SCIENCE
PROSPECTUS

FY93-FY94 ATLANTIC PROGRAM

Prepared from Original Proposals and Working Group Reports

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INTRODUCTION

This FY93-FY94 North Atlantic Science Prospectus presents the scheduled scientific operations for ODP Legs 149 through 158. These legs represent scientific cruises commencing March 1993 and continuing through November 1994.

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 may be subject to future changes.

Also enclosed with this document is information on how individuals can become involved with any of the above scientific programs. Please contact Dr. Jack Baldauf, the Ocean Drilling Program Manager of Science Operations, for additional information.

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.

OCEAN DRILLING PROGRAM SAMPLE REQUEST
FOR SHIPBOARD AND SHOREBASED CRUISE PARTICIPANTS

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

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

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.

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

2. Name(s), office address, telephone number, fax, email, BITNET (to facilitate contact between investigators), and telex number of investigator(s):

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.

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4. What is the specific cruise related research that you plan to accomplish for this cruise? 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 Initial Reports.

5. Please describe the proposed core sampling program in sufficient detail so that those who must carry it out onboard ship will understand your needs. Specify the size of samples (cubic centimeters); the number of samples to be taken from each section, core, and/or hole; particular stratigraphic or lithologic units to be sampled; and 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. You may choose to propose a two-stage sampling program (i.e. pilot study/follow-up study) now. Or you may elect to get samples only for the pilot study now, with the understanding that you will request additional samples later after you see what is recovered.

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. You must have publishable results within 16 months or less for samples taken on board the ship or during the first year post-cruise, as these must be worked up for the Part B volume.

8. In what condition will the samples be once your research is complete? Will they be useful to others? If so, for what kinds of research?

9. If you have ever before received samples from DSDP or ODP, please indicate the 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 four (4) reprints of each. 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 any other information which you feel would be useful in reviewing your request on an attached sheet.

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

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 (for example, refrigerated, refrigerated with blue ice, or frozen).

13. If your samples will require special storage or shipment (for example, frozen organic samples) please specify a destination airport which is near your institute. Specify the name, telephone number and telex number of someone who can: re-ice the shipment at the destination airport, clear the shipment from customs and provide transportation to the final destination.

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?

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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 (4) copies of reprints of all published works in the outside journals to the Curator, Ocean Drilling Program, Texas A&M 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 onboard 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 members 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 designed paleontological reference centers upon completion of the investigators' use of the materials.

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

All requests will be reviewed by the Assistant Curator, by the ODP Staff Scientist assigned to the leg, and by the Co-chief Scientists, 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 will have 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 this completed form to the Curator ***at least two months*** in advance of the cruise departure date. The Curator's address:

Curator
Ocean Drilling Program
Texas A&M University Research Park
1000 Discovery Drive
College Station, TX 77845-9547

bitnet: Chris@TAMODP
internet: Chris@nelson.tamu.edu
fax: (409) 845-4857
phone: (409) 845-4819

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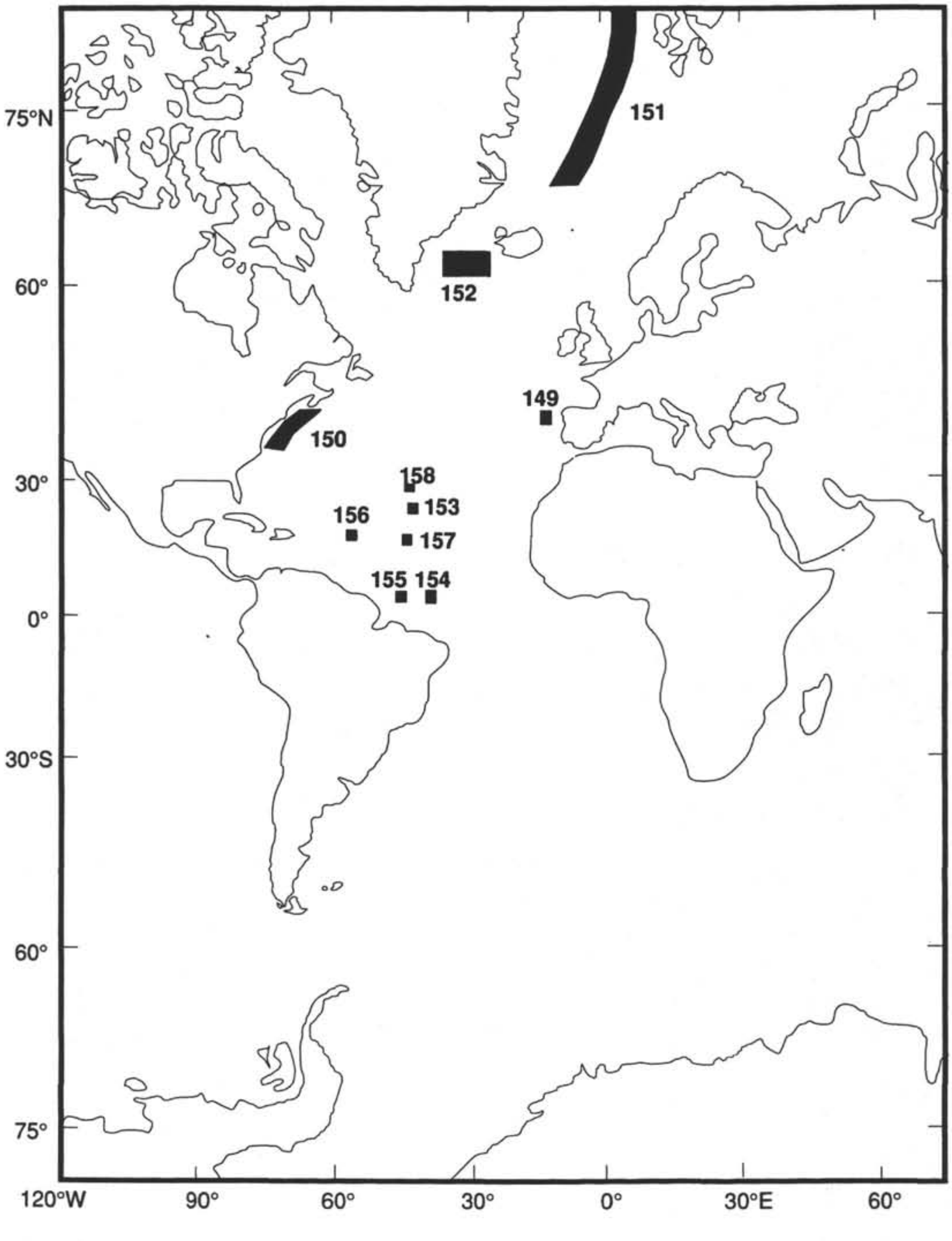

Location Map of Scheduled FY93-FY94 Atlantic Legs 149 through 158.

OPERATIONS SCHEDULE

LEG	PORT OF ORIGIN	CRUISE DATES	DAYS AT SEA	DAYS: TRANSIT/SITE (Estimated)
149A **Transit**	**Panama** **10 - 13 March 1993**	**14 March - 27 March 1993**	**13**	**13/0**
149B **Iberian Abyssal Plain**	**Ponta Delgada** **27 March 1993**	**28 March - 19 April 1993**	**22**	**4/18**
149C **Iberian Abyssal Plain**	**Lisbon** **19 April 1993**	**20 April - 25 May 1993**	**35**	**2/33**
150 **New Jersey Sea Level**	**Lisbon** **25 - 29 May 1993**	**30 May - 25 July 1993**	**56**	**16/40**
151 **Atlantic Arctic Gateways**	**St John's** **25 - 29 July 1993**	**30 July - 24 September 1993**	**56**	**14/42**
152 **East Greenland Margin**	**Reykjavik** **24 - 28 September 1993**	**29 September - 24 November 1993**	**56**	**9/47**
153 **MARK**	**Lisbon** **24 - 28 November 1993**	**29 November 1993 - 24 January 1994**	**56**	**12/44**
154 **Ceara Rise**	**Barbados** **24 - 28 January 1994**	**29 January - 26 March 1994**	**56**	**8/48**
155 **Amazon Fan**	**Recife** **26 - 30 March 1994**	**31 March - 26 May 1994**	**56**	**8/48**
156 **North Barbados Ridge**	**Barbados** **26 - 30 May 1994**	**31 May - 26 July 1994**	**56**	**1/55**
157 **DCS Engineering**	**Barbados** **26 - 30 July 1994**	**31 July - 25 September 1994**	**56**	**8/48**
158 **TAG**	**Barbados** **25 - 29 September 1994**	**30 September - 25 November 1994**	**56**	

LEG 149

OCEAN CONTINENT TRANSITION IN THE IBERIA ABYSSAL PLAIN

Modified From the ODP Leg 149 Scientific Prospectus

Dale S. Sawyer: Co-Chief

Robert B. Whitmarsh: Co-Chief

Adam Klaus: Staff Scientist

ABSTRACT

Leg 149 is scheduled to core a transect of holes across the ocean-continent transition (OCT) off western Iberia to determine the changes in the physical and petrological nature of the acoustic basement. Four sites that span the OCT have been chosen on basement highs to enable penetration of basement at each site to several hundred meters. It is anticipated that, at most, three of these sites will be drilled during Leg 149.

The west Iberia margin is an excellent example of a nonvolcanic rifted or passive continental margin. The OCT in the central Iberia Abyssal Plain segment of the margin has been located by seismic reflection and refraction profiles and by magnetic and gravity modeling. These independent measurements all support a single conceptual model of the crust and upper mantle within the OCT. Leg 149 will test part of this model.

Secondary objectives of Leg 149 include examining the depth of the ooze/chalk transition, the history of sediment deformation in the Cenozoic, the post-rift subsidence history of the margin, and the late Cenozoic turbidite succession with a view to testing whether the turbidites are triggered by changes in sea level and hence climatic changes.

The objective at a fifth and alternate site, proposed site GAL-1, located west of Galicia Bank, is to determine whether acoustic basement over a reflector called S', a possible lateral equivalent of the nearby S reflector, consists of continental crustal rocks. This site will be drilled only if the leg objectives can not be achieved at the other four proposed sites.

INTRODUCTION

The North Atlantic Rifted Margins Detailed Planning Group (NARM DPG) met in 1991 to plan a program to study the problems of rifted-margin formation and evolution. The group identified two important classes of rifted margins to be studied: margins in which magmatism has dominated the rifting process (volcanic margins) and margins in which magmatism seems to have been absent or incidental to the rifting process (nonvolcanic margins). The DPG recommended that ODP focus on a transect of each class and that each transect include a conjugate pair of margins. The criteria for selecting the locations of the two transects included (1) the existence of high quality geophysical data on the conjugate margins, (2) the presence of relatively thin sediment cover on the conjugate margins so that drilling to basement is possible using *JOIDES Resolution*, (3) the absence of salt, which could interfere with drilling, and (4) the absence of post-rift volcanism, which could have modified the divergent margin.

Leg 149 represents the first part of the program planned by the DPG for the study of nonvolcanic margins. The total program, probably requiring four 2-month legs, includes drilling of multiple sites in both the Iberia Abyssal Plain and the conjugate Newfoundland Basin, and one site on the Galicia Bank margin. Drilling on each of the margins should include sites that allow sampling of significant sections of basement with minimum sediment penetration, and sites that would sample thicker and stratigraphically more complete sequences of syn- and post-rift sediment. The program is also designed to allow assessment of the degree of symmetry in the structure and evolution of the conjugate margins. Characterization of crustal type within a wide zone of thin continental or oceanic crust in the Newfoundland Basin and Iberia Abyssal Plain and the position and nature of the OCT on the two margins are also important scientific objectives. Geophysical data suggest that seafloor exposures of mantle peridotite on the west side of Galicia Bank, to the north of this transect, extend into the Iberia Abyssal Plain. If such exposures are found during the proposed drilling, then they are clearly a feature of more than local significance. Sites designed to sample syn-rift sequences will constrain the timing of rifting and breakup, the rift environment, and possibly significant anomalous elevation and/or subsidence asymmetries which are strongly indicated by recently acquired seismic data. The subsidence histories of the conjugate margins will help to determine the relative importance of lithosphere-scale pure and simple mechanisms of shear extension.

STUDY AREA

Ocean-Continent Transition

The western continental margin of Iberia runs from Cape Finisterre in the north to Cape Saint Vincent in the south (Fig. 1). The continental margin has a straight narrow shelf and a steep continental slope. South of 40°N the slope is cut by numerous canyons. This simple picture is complicated by several offshore bathymetric features. The largest feature is Galicia Bank, a 200- x 150-km area within which the seafloor shoals to about 600 m water depth. Galicia Bank is characterized by a series of isolated seamounts on its southern edge (Vigo, Vasco da Gama, and Porto), and is separated from northwestern Iberia by a broad submarine valley. At 39°N, the Estremadura Spur extends east-west over 100 km offshore and forms a barrier between the Iberia and Tagus abyssal plains. Lastly, the east-northeast trending Gorringe Bank forms the southern boundary of the Tagus Abyssal Plain and marks the surface expression of the seismically active Eurasia/Africa plate boundary.

Like many rifted or passive margins, the Iberia margin had a long history of rifting before the separation of Iberia from the Grand Banks of North America. Three main Mesozoic rifting episodes affected the west Iberia margin. These episodes are recorded in the deposits of the Lusitanian Basin, which is probably continuous with the Interior Basin separating Galicia Bank from northeastern Iberia (Wilson *et al.*, 1989; Murillas *et al.*, 1990). A Triassic to Early Jurassic (Liassic) continental rifting phase gave rise to graben and half-graben structures in which evaporites were deposited. The second rifting phase consisted of extension in the Late Jurassic. The last phase of extension occurred in the Early Cretaceous (from Valanginian to early Aptian time), coincided with the south-to-north breakup of Iberia from the Grand Banks and has been well documented based on geological and geophysical data at sea (Boillot, Winterer, *et al.*, 1988; Whitmarsh *et al.*, 1990; Pinheiro *et al.*, 1992).

The rifting phases were accompanied by only minor volcanism (dikes and flows) within Iberia. Two phases of pre-breakup volcanism have been recognized by Ribeiro *et al.* (1979) and Martins (1991). A tholeiitic phase lasted from 190 to 160 Ma, and a second phase occurred from 135 to 130 Ma in the Lusitanian Basin, coeval with Late Jurassic rifting. This volcanism was relatively minor, and the west Iberia margin has essentially nonvolcanic characteristics. For example, there are clear tilted fault blocks and half grabens off Galicia Bank (Mauffret and Montadert, 1987), and there is no evidence of seaward-dipping reflectors or of substantial subcrustal underplating.

Parts of the west Iberia margin underwent two additional phases of deformation in the Eocene and the Miocene. The Eocene deformation was caused by the Pyrenean orogeny and the abortive subduction of the Bay of Biscay beneath the north Spanish margin; this deformation affected the margin adjacent to the Iberia Abyssal Plain and included the uplift of Galicia Bank and adjacent seamounts (Boillot *et al.*, 1979). The Miocene deformation accompanied the formation of the Rif-Betic mountains and led to the gentle folding of sediments in the Iberia and northern Tagus abyssal plains, as apparent on reflection profiles (Masson *et al.*, in press; Mauffret *et al.*, 1989).

Several plate-tectonic reconstructions attempted to show the original positions of North America, Iberia, and Europe (Le Pichon *et al.*, 1977; Masson and Miles, 1984; Klitgord and Schouten, 1986; Srivastava *et al.*, 1988, 1990a). The along-strike positions of the North American and European plates are poorly constrained because the Mesozoic magnetic quiet zone lies offshore of the Grand Banks and Iberia, and no large fracture zones occur at this latitude. The various fits differ by tens of kilometers in the north-south direction. The situation is further complicated by intraplate deformation and "jumping" plate boundaries, which imply that Iberia was alternately attached to Africa or Europe (Srivastava *et al.*, 1990b). The reconstruction by Srivastava *et al.* (1990a) is now regarded as the most closely constrained.

The western margin of Iberia comprises three segments (the Tagus Abyssal Plain, from Estremadura Spur to Vasco da Gama Seamount, and west of Galicia Bank), which appear to have experienced progressive breakup from south to north in Early Cretaceous times. Geological and geophysical studies of each of these segments have provided a conceptual model for the nature of the ocean-continent transition on this nonvolcanic rifted margin. These studies and the subsequent model are outlined below.

Magnetic models indicate that seafloor spreading in the Tagus Abyssal Plain began about 136 Ma (Valanginian; Harland *et al.*, 1990). A recent geophysical study of the Tagus Abyssal Plain (Pinheiro *et al.*, 1992), using seismic refraction, seismic reflection and magnetic profiles, showed that the oceanic crust adjacent to the OCT is unusually thin (2 km) and that there is a transitional region between thinned continental crust and the thin oceanic crust, which, although not truly oceanic (for example, it has no seafloor-spreading magnetic anomalies), has a magnetization far stronger than is usually associated with continental crust. The thin oceanic crust is underlain by a 7.6 km/s layer, which is probably serpentinized peridotite.

Whitmarsh *et al.* (1990; in press, 1992) studied the middle segment off Iberia (between 39° and 41°30'N) using seismic refraction and reflection profiles, gravity and magnetics. Magnetic models suggest that seafloor spreading began about 130 Ma (Barremian). They also found that the oceanic crust adjacent to the OCT is thin (4 km), and that the OCT appears to be an intermediate type of nonoceanic crust with a strong magnetization.There is also evidence of a widespread layer with 7.6 km/s velocity (possibly serpentinized peridotite at the base of the crust under the OCT). The intermediate OCT crust is associated with an unusually smooth acoustic basement between the apparently most seaward-tilted continental rift block to the east and a highly linear ridge to the west. If tentative extrapolations of basement morphology are correct, this ridge represents the southward continuation of a peridotite ridge drilled off Galicia Bank.

The western margin of Galicia Bank, the third of the three segments, has been studied with seismic refraction and reflection profiles, and has also been sampled extensively with dredges, submersibles, and by drilling (Horsefield, 1992; Mauffret and Montadert, 1987; Boillot, Winterer, *et al.*, 1988; Boillot *et al.*, 1988). A seismic refraction model across the margin shows a thinned continental crust at the OCT adjacent to a moderately thinned (5-km) oceanic crust, which thickens rapidly to the west. A layer with 7.2-7.3 km/s velocity underlies the thinned continental crust and may represent crustal underplating (Horsefield, 1992). In August 1992, a continuous gravity profile was obtained along an east-west seismic refraction line across the whole OCT. A complete crustal-density model across the OCT, constrained by seismic velocities, remains to be computed (J.C. Sibuet, personal communication). Because the Cretaceous quiet zone abuts the OCT at this margin, conventional seafloor magnetics can not date the beginning of seafloor spreading. However, the recognition of the paleomagnetic reversal period M0 below the breakup unconformity downhole at Site 641 (Ogg, 1988) indicates that breakup occurred about 120 Ma (Aptian). Sampling has shown unequivocally that a north-south basement ridge, which appears to coincide with an abrupt ocean/continent boundary, is composed of serpentinized peridotite.

The cumulative results from studies of these three segments of the west Iberia margin suggest that the following features are characteristic of the OCT in this region, and may exist elsewhere in similar settings: 1) abnormally thin oceanic crust (2-4 km) with a seafloor spreading signature underlies part of the OCT; 2) "intermediate", strongly magnetized, non-oceanic crust, capped by a smooth acoustic basement, exists immediately landward of the thin oceanic crust; 3) a subcrustal layer which has a velocity of 7.6 km/s and is probably serpentinized peridotite underlies much of the OCT; and 4) there may be a basement peridotite ridge within the OCT, as found west of Galicia Bank.

Presently, and pending the results of Leg 149 in particular, the explanation for the above characteristics of the OCT remains somewhat enigmatic. It seems likely that the thin oceanic crust represents the product of a transitional state between the slow, discontinuous extension of pure continental rifting and the faster, more continuous seafloor spreading which eventually replaces it. The presence of serpentinized peridotite at the base of the thin continental and oceanic crust may be explained by the improved access of seawater to the upper mantle, which is afforded by the thin crust, at least until the OCT is blanketed by thick sediments.

The S Reflector

A midcrustal (S) reflector is apparent on some multichannel seismic reflection profiles of the west Galicia margin. This reflector is either a single, strong reflector or a sequence of horizontal to gently dipping elementary reflectors (Hoffman and Reston, in press). In general, the reflector occurs at 0.6 to 1.6 s two-way travel time (twt) from the top of the acoustic basement (Mauffret and Montadert, 1987). Similar reflectors have been recognized on other rifted margins.

The origin of the S reflector is unknown. It has been tentatively interpreted as the seismic signature of a syn-rift detachment fault (Wernicke and Burchfiel, 1982; Boillot *et al.*, 1987; Hoffman and Reston, in press) and as décollement at the brittle-ductile transition within the thinned continental crust (de Charpal *et al.*, 1978; Montadert *et al.*, 1979; Sibuet, 1992). The S reflector may also represent the tectonic contact between continental crustal material and underlying serpentinized peridotite, marking a detachment fault that was rooted in the mantle (Boillot *et al.*, 1989, 1992). In any case, the reflector is clearly a structure related to the stretching of the lithosphere. The terranes located over, at the level of, and beneath the S reflector should be drilled and efforts made to clarify the relationship between these terranes and the ultramafic belt bounding the continental margin.

Unfortunately, the S reflector is deeply buried beneath sediments and continental basement (at least 3 km beneath the seafloor) in the region where it was first recognized. In order to sample these terranes, the reflector must be traced on seismic profiles to depths where drilling becomes feasible.

The northwestern edge of the deep Galicia margin (together with Galicia Bank) was uplifted during Cenozoic tectonic events, and the sedimentary cover was partly washed out by subsequent submarine erosion (Boillot *et al.*, 1979; Grimaud *et al.*, 1982; Mougenot *et al.*, 1984). New seismic reflection data were obtained during a 1990 Lusigal cruise to map the S reflector and surrounding terranes northward, from the region where the S reflector is deeply buried, to the uplifted area where the sediment thins. This approach was hindered by the occurrence of a Cenozoic transverse fault crossing the deep margin. This fault prevented continuous imaging of the reflector from the area where it was actually defined to the area where it is suspected to approach the seafloor. However, other arguments based on seismic velocities and attenuation coefficients suggest that such a correlation exists. This reflector at the northwestern edge of the Galicia margin is referred to as S', a possible lateral equivalent of the nearby S reflector.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To test a number of geophysically-based predictions about the nature of the OCT by determining the changes in the physical and petrological characteristics of the acoustic basement.

2) To examine the depth of the ooze/chalk transition.

3) To examine the history of sediment deformation in the Cenozoic.

4) To investigate the post-rift subsidence history of the margin.

6) To study the late Cenozoic turbidite succession with a view to testing whether the turbidites are triggered by changes in sea level and hence climatic changes.

7) To determine whether acoustic basement over a reflector called S', a possible lateral equivalent of the nearby S reflector, consists of continental crustal rock.

Specific Objectives and Methodology

Ocean-Continent Transition

The principal objective of Leg 149 is to sample the crust within the OCT of the Iberia Abyssal Plain to establish the nature of the upper crust and test some of the predictions based on geophysical observations. Naturally this bold objective must be tempered by the accessibility of the crust using current technology. In order to achieve significant progress within a single leg, four sites (IAP-2, 3C, 4, and 5) have been chosen. These proposed sites lie on basement highs situated at critical points within the OCT. Leg 149 is expected to drill three of these sites. The detailed objectives of each site are outlined below. In general, our aim is to penetrate several hundred meters into the acoustic basement, and to use cores and downhole logs from basement to determine its origin and history. This task will be accomplished through petrologic, mineralogic, chemical, physical, nuclear, electrical, and magnetic analyses of cores and boreholes drilled at each Leg 149 proposed site.

Sedimentary History

Secondary objectives of Leg 149 relate to the sediments themselves. One aim is to discover the history of turbidite sedimentation in the Iberia Abyssal Plain. Work done in the Madeira Abyssal Plain indicates that, in general, a single turbidite was deposited each time sealevel changed between glacial and interglacial periods (Weaver and Kuijpers, 1986). Attempts will be made to determine the extent to which the age and frequency of turbidites relates to past climatic changes. Another objective will be to date the deformation of the sediments and to relate these events to periods of deformation in Europe mentioned previously. An additional objective is to test estimates of the depth of the ooze/chalk transition made on the basis of seismic refraction measurements in the Iberia Abyssal Plain (Whitmarsh *et al.*, 1989) and to relate the velocity logs to these predictions.

Heat Flow

Heat flow will be measured at each of the Leg 149 sites, through measurements of thermal conductivities and thermal gradients. Thermal conductivity of the core samples will be measured routinely in the Physical Properties Lab. The thermal gradient will be determined by making ***in-situ*** temperature measurements in relatively shallow sediments (the upper 300-500 mbsf) at various depths with the APC tool and WSTP. Temperatures in open holes will be measured as part of most logging runs. Corrections for disturbances due to drilling and circulation may be applied to temperature logs based on results of successive runs in the same hole.

Late Post-Rift Subsidence

Attempts will be made to acquire data that can be used to estimate the late post-rift subsidence history of the Iberia Abyssal Plain. The depth, age, environment of deposition, and physical properties of each sedimentary unit will be observed and documented. The subsidence history of the Iberia Abyssal Plain is not anticipated to be precise at these sites because the basin was relatively sediment starved, and therefore continental slope conditions probably persisted throughout much of the post-rift period. Estimates of depths of deposition of continental-slope sediments from paleoenvironmental observations are accurate to 500 m at best.

S Reflector

On Leg 149 the S reflector problem may be addressed by sampling the "enigmatic terrane" rocks that overly the S' reflector. Petrologic, chemical, and structural descriptions of the rocks will be used to determine if they could be the intact hanging-wall block of a crustal detachment. If so, it may be possible and useful to core the S' reflector, a possible detachment fault, on a future leg.

DRILLING PLAN/STRATEGY

Up to three holes will be drilled at each site in the Iberia Abyssal Plain (proposed sites IAP-2, IAP-3C, IAP-4, IAP-5; Tables 1, 2). The first hole (hole A) will be cored using the RCB from the seafloor to bit destruction. It is anticipated that the first bit will penetrate the top of basement but not reach several hundred meters into basement. At this point the stability of the hole will be assessed:

> 1. If the sediments and upper basement are very stable, a free-fall funnel will be dropped, the RCB bit changed, and coring will be continued to the basement objective. The hole will be logged completely prior to abandonment.
>
> 2. If there are stability problems, hole A will be logged and abandoned. The ship will then offset and begin hole B, setting a reentry cone and casing this hole through the unstable material. The hole will be cored using one or more RCB bits to the basement objective. The unlogged part of the site will be logged in the reentry hole prior to abandonment.

In either case, depending on RCB core recovery and time remaining, an additional hole may be cored at the site, using the APC to refusal.

The WSTP will be used to measure *in situ* temperatures at depths of 50, 100, 150, and 200 m in the first RCB hole at each site. During APC coring, the APC temperature tool will be employed every 3-5 cores. The holes will be logged using the standard Schlumberger suite of logging tools, including the formation microscanner (FMS), and the Lamont temperature tool. The temperature tool will be run on at least the first and last logging runs affording the best chance to extrapolate equilibrium temperatures. A velocity survey may be done using a surface source in one or more holes to correlate depth in the borehole to seismic reflection time. The magnetic susceptibility tool may also be run in the sediments at one or more sites.

One hole will be drilled at proposed site GAL-1. The RCB will be used to core and drill from the seafloor into the basement. If a bit change is required and time is available, a free-fall funnel will be deployed. The RCB hole will be logged using the standard Schlumberger suite of logging tools. The temperature tool will be run on at least the first and last logging runs affording the best chance to extrapolate equilibrium temperatures.

It is anticipated that the sites drilled during Leg 149 will be, in order of priority and drilling, IAP-4, IAP-2, and IAP-3C. The full program can be achieved if free-fall funnels are used instead of reentry cones, or no change of RCB bits are required. Proposed site IAP-5 may be drilled third, instead of IAP-3C, if oceanic basement with no traces of continental lithosphere is encountered at proposed sites IAP-4 and IAP-2.

At each site, the uncased and cased RCB holes will have highest priority. APC coring will be given high priority at one of the sites (to be selected by the shipboard party). The APC coring will probably take place during intervals of two to three days prior to going into port (which happens twice during Leg 149), when deeper objectives cannot usefully be targeted.

Proposed site GAL-1 will be drilled only if time is available after completion of the drilling program at the IAP sites.

PROPOSED DRILL SITES

IAP-2 is situated over a basement high thought to be part of the most oceanward continental-rift block on this margin. The high has an irregular, possibly fault-controlled, surface and a trend just east of north, roughly parallel to the tectonic fabric of the oceanic crust to the west. The bounding faults of the block are not visible, nor does the block display any clear structure which might be used to indicate a direction of dip. About 850 m of sediment (Table 1), estimated to be as old as Santonian, overlies basement. Studies of the reflection profiles, and analogy with Site 398, suggest that the lithologies are ooze/chalk with turbidites overlying chalk, mudstone, and claystone. The post-Eocene unconformity lies at about 510 mbsf. Just east of the site a fault, or other tectonic disturbance, appears to pass up toward, but not reach, the seafloor. To the west of the site, about 1.5 s (1.6 km) of sediment overlies the acoustic basement, which is smooth and may be capped by, or composed of, lava or other igneous material. This is the "intermediate" crust in the conceptual model, which possesses relatively strong magnetization. To the east, the post-rift sedimentary section thickens to 2.2 s (2.8 km) and basement is expected to consist of pre-rift sediment or continental basement rocks.

IAP-3C is situated over a shallow basement high, which magnetic modeling and seismic refraction results indicate is part of the thin oceanic crust associated with the OCT. The basement high is strongly elongated in a direction just east of north and parallel with the general tectonic fabric of the oceanic crust in this area. The basement high has a rounded east-west cross section, and the overlying sediments are horizontal and undeformed. About 830 m of sediment, estimated to be as old as late Paleocene, overlies basement (Table 1). Studies of reflection profiles and analogy with Site 398, suggest that the lithologies are ooze/chalk with turbidites over chalk and mudstone. The post-Eocene unconformity lies at about 510 mbsf. The sediments thicken to about 2.0 s (2.4 km) in a basin to the west and to 1.8 s (2.1 km) to the east. The basement material is expected to be upper oceanic crust.

IAP-4 centers on a basement high which may be longitudinally continuous with the peridotite ridge drilled at Site 637 off Galicia Bank during Leg 103. This association is primarily based on basement morphology. The IAP-4 basement high occupies a critical location in our conceptual model of the OCT, lying precisely at the boundary between the intermediate crust and the thin oceanic crust apparently generated by seafloor spreading. The basement high is strongly elongated and trends just east of north. About 680 m of sediment, estimated to be as old as Maastrichtian, overlies basement. Studies of reflection profiles, and analogy with Site 398, suggest that the lithologies are ooze/chalk with turbidites overlying chalk, mudstone, and claystone. The post-Eocene unconformity lies at about 360 mbsf. The sediments are horizontal, but a low-angle, west-dipping structure can be seen on the east-west seismic profile across the site. The sediments thicken to 2.0 s (2.4 km) in a basin to the west and to 1.4 s (1.5 km) to the east. The acoustic basement to the east of the site is smooth and underlain by the intermediate crust described above. Although the acoustic basement may contain ultramafic rocks within a few hundred meters of the seafloor, it is uncertain that these ever actually cropped out. Thus the uppermost basement could be any mixture of lithology from continental basement rocks to igneous intrusive/extrusive material to tholeiitic lavas of the upper oceanic crust.

IAP-5 is centered over the next most oceanward basement high on profile Lusigal 12 and is situated east of proposed site IAP-2, and is an alternate for proposed site IAP-3C. The basement high appears to be more or less circular in shape with the suggestion of a northwest-dipping internal interface. About 980 m of sediment, estimated to be as old as early Paleocene, overlies basement. Studies of reflection profiles, and analogy with Site 398, suggest that the lithologies are ooze/chalk with turbidites overlying chalk, mudstone, and claystone. The post-Eocene unconformity lies at about 560 mbsf. The sediment basins to east and west do not have a clear base, and the reflectors are indistinct in this region. The basement at this site is expected to be continental in character with little or no igneous intrusive material.

The objective of drilling at GAL-1 is to sample the acoustic basement (enigmatic terrane) which overlies the S' reflector and underlies about 550 m of Cenozoic sediments. The basement rocks may contain crucial information about timing, pressure, temperature, and kinematic conditions of their metamorphism and deformation during the rifting stage of the margin. Sampling the terrane overlying S' may constrain models of rifted-margin formation. The goals of drilling are:

- Petrologic identification of the rocks overlying S'. Currently, it is suspected that the enigmatic terrane covering S' is continental basement, whereas the underlying rocks probably are serpentinized peridotite, with S' being the crust/mantle boundary (Moho). The S reflector may be a target for a future ODP leg.

- Absolute timing of events. It may be possible to use geochronological dating of minerals which crystallized after metamorphism, after ductile deformation, and possibly after brittle deformation of the sampled rocks, to establish the order and age of individual tectonic episodes.

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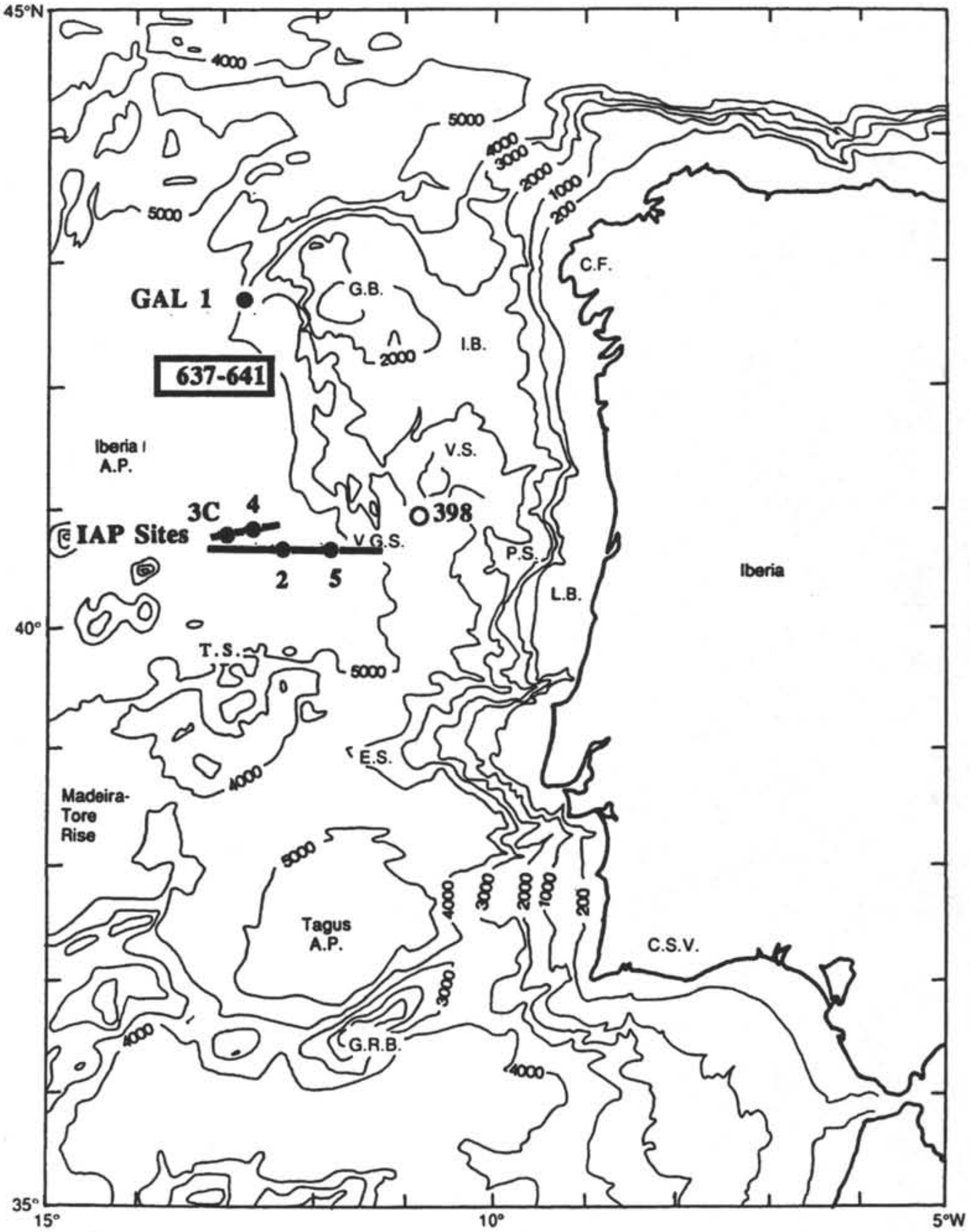

Figure 1. Bathymetry of the west Iberia margin (contours in meters) showing location of Leg 149 proposed drill sites, DSDP Leg 47 Site 398 and ODP Leg 103 Sites 637 to 641.

C.F.=Cape Finisterre; V.S.=Vigo Seamount; P.S.=Porto Seamount; V.G.S.=Vasco da Gama Seamount; C.S.V.=Cape Saint Vincent; G.R.B.=Gorringe Bank; G.B.=Galicia Bank; L.B.=Lusitanian Basin; I.B.=Interior Basin; E.S.=Estremadura Spur; T.S.=Tore Seamount.

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: IAP-2 **PRIORITY:** 1 **POSITION:** 40°41.0'N, 12° 07.1'W
WATER DEPTH: 5250 m **SEDIMENT THICKNESS:** 850 m **SEDIMENT DEPTH** (TWT s): 0.88
SEISMIC COVERAGE: Sonne 75 Line 17 (see related Lines 18 and 22); Lusigal Line 12

Objectives: Sample the crust within the OCT to establish the nature of the upper crust and test geophysical predictions. Determine history of turbidite sedimentation. Date Cenozoic deformation. Measure heat flow. Estimate late post-rift subsidence.

Drilling Program: 1) RCB core to bit destruction in basement. If hole is stable, drop FFF, RCB core in basement to TD, log entire hole, and abandon. If hole unstable, log sediments in initial hole, offset and start new hole, set casing through unstable part of the hole, RCB core in basement to TD, log basement, and abandon; and 2) APC core to refusal, and abandon (if time is available and RCB core is inadequate for sedimentary objectives).

Logging and Downhole Operations: Standard strings (Geophysical, Geochemical, and FMS). Four WSTP measurements in first RCB hole. Magnetic susceptibility log may be run.

Nature of Rock Anticipated: Pelagic clay, sand/silt/clay turbidites, ooze and chalk, mudstone, claystone, continental crust modified by rifting.

SITE: IAP-3C **PRIORITY:** 2 **POSITION:** 40°47.7'N, 12°44.1'W
WATER DEPTH: 5500 m **SEDIMENT THICKNESS:** 830 m **SEDIMENT DEPTH** (TWT s): 0.85
SEISMIC COVERAGE: Sonne 75 Line 16; Discovery 161 day 234

Objectives: Sample the crust within the OCT to establish the nature of the upper crust and test geophysical predictions. Determine history of turbidite sedimentation. Date Cenozoic deformation. Measure heat flow. Estimate late post-rift subsidence.

Drilling Program: 1) RCB core to bit destruction in basement. If hole is stable, drop FFF, RCB core in basement to TD, log entire hole, and abandon. If hole unstable, log sediments in initial hole, offset and start new hole, set casing through unstable part of the hole, RCB core in basement to TD, log basement, and abandon, and 2) APC core to refusal, and abandon (if time is available and RCB core is inadequate for sedimentary objectives).

Logging and Downhole Operations: Standard strings (Geophysical, Geochemical, and FMS). Four WSTP measurements. Magnetic susceptibility log may be run.

Nature of Rock Anticipated: Pelagic clay, sand/silt/clay turbidites, ooze and chalk, claystone, altered oceanic crust.

SITE: IAP-4 **PRIORITY** 1 **POSITION:** 40°50.3'N, 12°28.5'W
WATER DEPTH: 5450 m **SEDIMENT THICKNESS:** 680 m **SEDIMENT DEPTH** (TWT s): 0.70
SEISMIC COVERAGE: Sonne 75 Line 16; Lusigal Lines 04 and 15.

Objectives: Sample the crust within the OCT to establish the nature of the upper crust and test geophysical predictions. Determine history of turbidite sedimentation. Date Cenozoic deformation. Measure heat flow. Estimate late post-rift subsidence.

Drilling Program: 1) RCB core to bit destruction in basement. If hole is stable, drop FFF, RCB core in basement to TD, log entire hole, and abandon. If hole unstable, log sediments in initial hole, offset and start new hole, set casing through unstable part of the hole, RCB core in basement to TD, log basement, and abandon; and 2) APC core to refusal, and abandon (if time is available and RCB core is inadequate for sedimentary objectives).

Logging and Downhole Operations: Standard strings (Geophysical, Geochemical, and FMS). Four WSTP measurements in first RCB hole. Magnetic susceptibility log may be run.

Nature of Rock Anticipated: Pelagic clay, sand/silt/clay turbidites, ooze and chalk, claystone, serpentinized peridotite and/or continental crust and/or volcanic flows and sills.

SITE: IAP-5 **PRIORITY:** 2 **POSITION:** 40°40.9'N, 11°37.0'W
WATER DEPTH: 5100 m **SEDIMENT THICKNESS:** 980 m **SEDIMENT DEPTH** (TWT s): 0.98
SEISMIC COVERAGE: Sonne 75 Line 21 (see also related Lines 20 and 22); Lusigal Line 12

Objectives: Sample the crust within the OCT to establish the nature of the upper crust and test geophysical predictions. Determine history of turbidite sedimentation. Date Cenozoic deformation. Measure heat flow. Estimate late post-rift subsidence.

Drilling Program: 1) RCB core to bit destruction in basement. If hole is stable, drop FFF, RCB core in basement to TD, log entire hole, and abandon. If hole unstable, log sediments in initial hole, offset and start new hole, set casing through unstable part of the hole, RCB core in basement to TD, log basement, and abandon; and 2) APC core to refusal, and abandon (if time is available and RCB core is inadequate for sedimentary objectives).

Logging and Downhole Operations: Standard strings (Geophysical, Geochemical, and FMS). Four WSTP measurements. Magnetic susceptibility log may be run.

Nature of Rock Anticipated: Pelagic clay, sand/silt/clay turbidites, ooze and chalk, claystone, continental crust.

SITE: GAL-1 **PRIORITY:** 3 **POSITION:** 42°40.0'N, 12°48.0'W
WATER DEPTH: 4500 m **SEDIMENT THICKNESS:** 550 m **SEDIMENT DEPTH** (TWT s): 0.50
SEISMIC COVERAGE: Lusigal Line 06 (see also related Line GP03).

Objectives: Determine lithologic composition of the "enigmatic terrane" above the S' reflector which appears to crop out to the west of the site.

Drilling Program: RCB core to bit destruction in basement or 100-m basement penetration, log entire hole, and abandon.

Logging and Downhole Operations: Standard strings (Geophysical, Geochemical, and FMS).

Nature of Rock Anticipated: Pelagic clay, sand/silt/clay turbidites, ooze and chalk, claystone, continental crust.

TABLE 2

DRILLING TIME ESTIMATES

Site	Priority	Drilling Option[1]	Time (days) Drilling[2]	Time (days) Logging[3]	Total Days
IAP-4	1	Two RCB holes	21.0	2.8	23.8
		One RCB hole	12.0	1.7	13.7
		APC hole	3.5	---	3.5
IAP-2	1	Two RCB holes	21.0	2.9	23.9
		One RCB hole	13.6	1.8	15.4
		APC hole	3.5	---	3.5
IAP-3C	2	One RCB hole	13.5	1.6	15.1
		APC hole	3.5	---	3.5
IAP-5	2	One RCB hole	13.5	1.7	15.2
		APC hole	3.5	---	3.5
GAL-1	3	One RCB hole	9	1.3	10.3

[1] Drilling options

Two RCB holes:	First RCB hole cored to refusal (bit destruction) in basement, with logging in sediment section. Offset reentry hole cased through sediment, with drilling, coring, and logging in basement. Drilling time estimates assume 200 m of basement penetration in reentry holes.
One RCB hole:	Single RCB hole cored to refusal (bit destruction) in basement, followed by emplacement of free-fall funnel. One or more bit trips then allow additional penetration in basement (200 m assumed in time estimates) followed by logging through entire section.
APC hole:	APC core to refusal, assumed in time estimates to penetrate 300 mbsf.

[2] Drilling times include 4 WSTP runs in all RCB sediment holes.

[3] Logging includes standard three strings (geophysical, geochemical, and FMS) in open RCB holes, with the side-entry sub (SES); standard three strings in reentry basement holes, without SES.

TABLE 3

LEG 149 SCHEDULE

Leg 149A begins with port call Panama 10-13 March, departing Panama 14 March 1993.

			Time on Site (days)	Transit Time (days)
Transit from Panama to Ponta Delgada				13.0
(end Leg 149A)				
Arrive	Ponta Delgada	27 March		
(end Leg 149A, begin Leg 149B)				
Depart	Ponta Delgada	28 March	1.0	
Transit from Ponta Delgada to IAP-4 (first visit)				2.6
Arrive	IAP-4	30 March	17.0[1,2]	
Leave	IAP-4	16 April		
Transit from IAP-4 to Lisbon				0.8
Arrive	Lisbon	17 April	1.0	
(end Leg 149B, begin Leg 149C)				
Leave	Lisbon	18 April		
Transit from Lisbon to IAP-4 (return)				0.9
Arrive	IAP-4	19 April	6.8[1,2]	
Leave	IAP-4	26 April		
Transit from IAP-4 to IAP-2				0.3
Arrive	IAP-2	26 April	23.9[2]	
Leave	IAP-2	20 May		
Transit from IAP-2 to IAP-3C				0.3
Arrive	IAP-3C	20 May	4.0[3]	
Leave	IAP-3C	24 May		
Transit from IAP-3C to Lisbon				1.0
Arrive	Lisbon	25 May 1993		
(end Leg 149C)				
		Total Time (Legs 149A, 149B, 149C)		72.6
		Total Time (Legs 149B and 149C)		59.6

[1] Operations at proposed site IAP-4 split between port call for crew change. Exploratory RCB hole is to be cored and logged before port call; reentry hole will be started before port call, then completed and logged after port call.

[2] Drilling times for IAP-4 and IAP-2 assume two holes per site: RCB single-bit and full reentry. Drilling (and logging) times may be reduced significantly if conditions allow use of free-fall funnels in single RCB holes at each site. Time for 4 WSTP runs are included in each RCB single-bit hole.

[3] As much time as is available at the end of the leg will be devoted to coring a single-bit hole at Site IAP-3C, with the hope of recovering and characterizing basement at this site. Additionally, an APC hole may be drilled at one or more sites, depending on recovery, core quality, and time required during RCB and reentry work.

LEG 150

UPPER PALEOGENE TO NEOGENE DEPOSITIONAL SEQUENCES ON THE U.S. MIDDLE ATLANTIC MARGIN: THE CONTINENTAL SLOPE AND RISE

Modified From Proposals 348 and 348B

Gregory S. Mountain: Co-Chief **Kenneth G. Miller: Co-Chief**
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ABSTRACT

The New Jersey Sea Level Project is an integrated transect of boreholes in the U.S. mid-Atlantic region. The objective is to document the continental margin record of the Oligocene-Holocene "Icehouse World" by determining the age of major unconformities, acquiring a database needed for modeling the amplitude of relative sea-level variations, and documenting facies variations associated with oscillations of sea-level.

This transect requires drilling in three settings: 1) the continental slope to date sequence boundaries at their correlative conformities in the deepest paleodepth possible (where biostratigraphic correlation will be optimized); 2) the continental shelf to recover the most complete record of relatively shallow-water facies; and 3) the onshore coastal plain to update upper Oligocene to lower Miocene sequences and to provide facies information on sequences landward of the clinoform break point (shelf break of Vail *et al*., 1977). Onshore drilling at Island Beach, Atlantic City, and Cape May, New Jersey is scheduled to begin in Spring 1993 and conclude by Fall 1993.

Leg 150 proposes to drill five sites on the continental slope (4) and continental rise (1). Although slope-drilling alone does not constitute a sea-level program, this comparatively deep-water record is a critical component of the sea-level project. The upper Paleogene to Neogene section of the mid-Atlantic region is ideally suited for the study of relative changes of sea level recorded in passive margin sediments and the upper Oligocene to Miocene record is particularly promising. A number of features are unique to this area during this time period, including rapid sedimentation that provides an unusually high-resolution record during a time of known glacio-eustatic change, tectonic stability that simplifies subsidence considerations, a mid-latitudinal setting that optimizes biostratigraphic control, provides magnetostratigraphic potential, and yields sufficient carbonate for Sr-isotope stratigraphy; and an abundance of prior studies (seismic, logs, boreholes and outcrops) that can guide efforts to concentrate on features most likely to record sea-level change.

INTRODUCTION

Past fluctuations of global (eustatic) sea-level have had profound impact on a wide range of disciplines within the earth sciences and extensive data must still be gathered if knowledge of the timing and magnitude of past eustatic changes is to be improved. These fluctuations can be measured in either of three independent ways: 1) from foraminiferal $\delta^{18}O$ records which reflect ice-volume and temperature fluctuations (e.g., Shackleton and Opdyke, 1973; Miller *et al.*, 1987a); 2) from the analysis of sea-level changes relative to carbonate platforms and atolls, both of which behave like oceanic dip-sticks (e.g., Fairbanks and Matthews, 1978; Halley and Ludwig, 1987); and 3) from the analyses of sea-level relative to continents (e.g., Sloss, 1963; Hallam, 1984; Vail, 1987). The oxygen isotope record is largely restricted to the past 100 m.y. and contains no information about tectonically induced sea-level changes. The platform and atoll records also extend back only a few tens of millions of years. By contrast, the record of sea-level fluctuations observed on continents and their margins spans a much larger time interval, certainly back to the beginning of the Paleozoic and, with limited resolution, into the Precambrian.

This continental margin record of sea-level change can be deciphered in either of two ways: 1) through observations of transgressions/regressions of the shoreline or of changes in water depth inferred from facies successions (e.g., Bond, 1978; Hancock and Kauffman, 1979); or 2) by analyzing regional unconformities either through physical and seismic stratigraphy (e.g., Vail *et al.*, 1977; Vail, 1987; van Wagoner *et al.*, 1987) or through chronostratigraphy (e.g., Aubry, 1985; Miller *et al.*, 1985a, b). The chief advantage of the sequence stratigraphic approach is that the formation of major stratal discontinuities requires the lowering of depositional base level, and is therefore less sensitive to variations in sediment supply than is the position of the shoreline (Christie-Blick *et al.*, 1989). This approach provides a great deal of information about the timing of relative sea-level changes, but less certain information about their magnitudes. Nonetheless, it is crucial to assess timing before magnitude to ensure that a given sea-level oscillation is of global rather than local origin.

Determining the influence of sea-level fluctuations on passive margin stratigraphy poses a paradox. Shallow-water (neritic) sections are most sensitive to sea-level changes, but are often difficult to correlate a standard chronostratigraphy because of rare zonal marker plankton and discontinuous deposition. Conversely, deep-sea (bathyal) sections often are better constrained and more complete, but the link between deep-sea deposition and sea-level fluctuations is complex and incompletely understood (Tucholke, 1981; Farre *et al.*, 1983; Farre, 1985; Mountain, 1987). The best solution to this problem is to develop chronostratigraphic standards using deep sea sections (e.g., Berggren *et al.*, 1985), monitor sea-level changes in shallow, passive, continental margin sequences (e.g., Aubry, 1985; Olsson and Wise, 1987), and use facies-independent means (seismic, Sr-isotope, magnetostratigraphy) for correlating the two regions (Miller and Kent, 1987). Thus, determining relative sea-level and eventually recognizing eustatic changes requires the integration of studies from nearshore to deep-sea environments. ODP Legs 80, 93, and 95 focused on the deep-water end of this spectrum.

The Oligocene to Miocene is an interval in which eustatic estimates derived from patterns of coastal onlap may be directly compared with eustatic estimates obtained from $\delta^{18}O$ studies. Oxygen isotope records and glacio-marine sediments indicate the presence of large continental ice sheets on Antarctica since at least the earliest Oligocene (Miller at al., 1987a). These ice sheets waxed and waned numerous times during the Oligocene to modern "ice house world", resulting in sea-level changes up to 100 m (Miller *et al.*, 1987a, in prep.). Benthic foraminiferal $\delta^{18}O$ maxima at ca. 35, 33, and 23 Ma can be directly linked with $\delta^{18}O$ increases in subtropical planktonic foraminifera and maxima in ice sheet development inferred from glacio-marine sediments. These were three major eustatic lowerings which may be compared with depositional history on passive margins.

The early to middle Miocene ice volume signal has not been isolated previously, in part because of problems correlating the numerous benthic $\delta^{18}O$ records that are available. Early to middle Miocene correlations of benthic $\delta^{18}O$ records with low-latitude western equatorial planktonic foraminiferal records (Miller *et al.*, in prep.) shows remarkable agreement in timing and amplitude of $\delta^{18}O$ variations with associated eustatic lowerings of greater than 50 m (based upon calibrations discussed in Miller *et al.*, 1987a, Miller *et al.*, in prep.) at about 16.5, 14.5-13.5 Ma, and 10 Ma. The low frequency sampling (~ 50 k.y.) of these records does not represent the high frequency components (10-100 k.y.) embedded in the ice volume record. Nonetheless, the observed changes occur in benthic and planktonic records from different locations with different sampling intervals, and hence the similar patterns observed are likely to be an artifact of signal aliasing. Ongoing stable isotope studies by various investigators using recently recovered ODP samples will provide additional documentation of the oxygen isotope proxy for sea-level change for this critical Oligocene-Miocene interval.

STUDY AREA

Oligocene to Miocene rock and seismic disconformities are known on the U.S. middle Atlantic (New Jersey-Delaware-Maryland) margin (Kidwell, 1984; Miller *et al.*, 1985b; Olsson *et al.*, 1987; Greenlee *et al.*, 1988). Two types of data are required to evaluate the link between $\delta^{18}O$ increases and these stratigraphic breaks: 1) the timing and amplitude of the Oligocene-Miocene western equatorial planktonic $\delta^{18}O$ and benthic $\delta^{18}O$ fluctuations need to be firmly resolved; and 2) high-resolution seismic and chronostratigraphic studies of the middle Atlantic margin must be acquired to refine stratal geometry and age estimates of these sequences.

A survey cruise was funded for summer 1990 to address the latter need. The U.S. middle Atlantic margin represents an especially suitable area for the study of sea-level changes during the critical upper Oligocene to Miocene "ice house" interval. Paleocene-Eocene sections onlap landward of the modern outcrop belt, and stratal geometrics of the Paleocene-Eocene therefore cannot be resolved fully; furthermore, the lower Oligocene section is largely missing. In contrast, upper Oligocene to Miocene shelf sequences are relatively complete. Features that make this location especially valuable include:

1) sediments prograded across the margin throughout the Miocene and accumulated at rates high enough (tens to hundreds of m/m.y.) to resolve stratal relationships in usually great detail (Poag, 1977; Schlee, 1981; Greenlee *et al.*, 1988);

2) the middle Atlantic margin's mid-latitude setting ensures good biostratigraphic control (Poag, 1985a, b; Olsson and Wise, 1987; Poore and Bybell, 1988; among others). Oligocene-Miocene sediments of this region have adequate carbonate to utilize Sr-isotope correlation techniques (Burke *et al.*, 1982; DePaolo and Ingram, 1985; Hess *et al.*, 1986; Miller *et al.*, 1988). Although the Eocene pelagic carbonate sediments of this area are not suitable for magnetostratigraphy (Miller and Hart, 1987), the shelf sediments of this margin have proven to be suitable for magnetostratigraphy (Miller *et al.*, in press);

3) the eastern U.S. is an old, stable margin, and throughout the Cenozoic, its tectonic subsidence has been along the relatively well-defined, nearly linear part of the thermal subsidence curve (Steckler and Watts, 1982);

4) because of these relatively slow Cenozoic subsidence rates (< 10 m/m.y.), any eustatic effects on lateral facies changes and coastal onlap have been at their maximum expression (Mitchum *et al.*, 1977); and

5) a substantial body of useful data including seismic, wells, and outcrops already exists on this margin (Hathaway *et al.*, 1976; Poag, 1978, 1980, 1985a, b, 1987; Kidwell, 1984, 1988; Olsson *et al.*, 1987; Greenlee *et al.*, 1988; among others) and allows a well-constrained study to focus on the crucial, testable issues (Fig. 1).

The nature and timing of sea-level events recorded in the Oligocene to Miocene sediments of the middle Atlantic margin remain poorly constrained in several critical intervals due to the spatially and temporally limited distribution of borehole and seismic data. The only continuously cored Cenozoic offshore wells are from the coastal plain (e.g., ACGS #4; Owens *et al.*, in press) and the continental slope (DSDP Site 612; Poag, Watts, *et al.*, 1987). The intervening shelf has either been discontinuously cored to only 300 m subbottom (AMCOR) or has not been cored at all (COST wells). No DSDP site on the slope or upper rise has yet recovered anything from between the lowermost Oligocene and upper Miocene, and sampling on the shelf is seriously limited by discontinuous coring.

Seismic studies have shown that more than 2 km of Neogene sediments account for the general shape of the rise off the eastern U.S. Three widespread reflectors, A^u, Merlin, and Blue, have been traced along the rise and subdivide this thick interval (Mountain and Tucholke, 1985). Each of these reflectors provides evidence for deep-sea erosion resulting from strongly circulating deep waters originating in the high latitude North Atlantic or nordic Seas (i.e. Northern Component Water, NCW, analogous to modern North Atlantic Deep water). While their exact ages are uncertain, it is clear that A^u is latest Eocene to earliest Oligocene, Merlin is late middle Miocene, and Blue is Pliocene, more precise dates are needed. Reflector A^u is a distinct seismic disconformity that is overlain by a seismic unit of hummocky, discontinuous reflectors, although exceptions are found along the foot of the slope where acoustic stratification indicates deposition may have been dominated by down-slope processes. Reflector Merlin has been traced as a chronostratigraphic surface as much as the data will allow, independent of the seismic facies (Mountain and Tucholke, 1985). Hence, in places this marker rests directly on the top of the hummocky seismic facies. Elsewhere, it is shallower. Locally, Merlin is clearly an erosional unconformity. Acoustically stratified sediment or migrating waves usually rest directly on Merlin. Like Merlin, Reflector Blue shows local erosion and is overlain by sediment waves. However, on the upper rise acoustic stratification indicates control by downslope transport and deposition. Mountain and Tucholke (1985) have interpreted these seismic features as elements of current-controlled deposition.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To extend the DSDP transect onto the continental slope.

2) To determine the age and geometry of Oligocene and Neogene depositional sequences.

3) To evaluate the role of relative sea-level changes in a developing sedimentary record.

4) To evaluate a possible causal link with ice-volume (glacio-eustatic) changes inferred from the deep-sea $\delta^{18}O$ record.

Specific Objectives and Methodology

The proposed drilling of the mid-Atlantic margin is a critical component to a comprehensive evaluation of global sea-level changes, potentially yielding excellent constraints upon the timing and amplitude of relative sea-level fluctuations, and in concert with drilling planned on other margins, will allow the eustatic issue to be properly addressed.

Leg 150 intends to build on the previous efforts of DSDP Legs 93 and 95 and NSF-funded projects (e.g. *Alvin* sampling and piston coring submarine canyon outcrops, multichannel seismic data acquisition, and re-examination of existing boreholes and wells for Sr-isotope stratigraphy) with an integrated program of sampling, chronostratigraphy, and seismic acquisition. This approach promises to constrain the timing of unconformities/sequence boundaries during a clearly testable period of known glacio-eustatic change.

The greatest potential for improvement over present biostratigraphic control is in the upper Oligocene to Miocene. Strata of this age crop out in slope canyons near DSDP Site 612. In 1989, these strata were thoroughly sampled in Lindenkohl Canyon using the *Alvin* and precision piston coring. Miocene strata are also well represented in the Atlantic coastal plain, and the physical stratigraphy of the classic Miocene outcrops of Calvert Co., Maryland (Shattuck, 1904; Kidwell, 1984) has been examined in detail. Kidwell (1984) described eight disconformable surfaces in the Miocene Calvert Cliffs and, in 1988, 21 samples spanning these disconformities were collected for Sr-isotope stratigraphy.

Additional surface and submarine outcrop studies are required to constrain the ages of Miocene and upper Neogene sequences in this region. Leg 150 will drill four sites on the continental slope, extending the data set for submarine samples. At present, biostratigraphic age assignments are controversial: while diatom biostratigraphy suggests a relatively complete middle Miocene section in the middle Atlantic coastal plain (e.g., Abbott, 1978), planktonic foraminifera delineate a gap between Zone N8 (~ 15 Ma, earliest middle Miocene) and Zone N16 (~ 10 Ma, earliest late Miocene; Olsson *et al.*, 1987). Furthermore, Melillo and Olsson (1981) suggest that the middle Miocene is largely missing in the New Jersey coastal plain. This latter point is in agreement with the seismic stratigraphic interpretation of Greenlee *et al.* (1988), who show that middle Miocene sequences (ca. 15.5-12.5 Ma) onlap or pinch out seaward of the modern shoreline. Olsson *et al.* (1987) noted eight Miocene hiatuses in the subsurface of Maryland, and suggested that these were partially equivalent to the disconformities mapped in outcrop by Kidwell (1984). However, some of these hiatuses were recognized by breaks within a foraminiferal zone, and are thus subject to interpretation.

Leg 150 also intends to drill a site on the continental rise to evaluate the source, age, and mechanism of Neogene deposition on the rise and to constrain the timing of deep-water circulation events that are potentially related to global sea-level changes. Numerous studies have suggested that increased sedimentation on the rise and abyssal plains was caused by increased terrigenous input during late Pleistocene lowstands (e.g., Weaver *et al.*, 1986). However, this conclusion has not been tested with samples from the older record. Due to site placement, Legs 93 and 95 did not recover Neogene sediments on the upper rise older than latest Miocene. Though Sites 105, 106, 388, and 603 cored a thick Miocene section, all were on the lower rise in water depths too deep for detailed biostratigraphic control. Thus previous seismic stratigraphic studies of the margin have been hampered by a lack of age and lithologic data (e.g., Tucholke and Mountain, 1979; Poag, 1985; Mountain and Tucholke, 1985; Poag and Sevon, 1987; McMaster *et al.*, 1989).

DRILLING PLAN/STRATEGY

Leg 150 will drill four sites on the continental slope and one site on the continental rise off New Jersey (Fig. 1, Table 1). A transect of boreholes is required for estimating both the ages of sequence boundaries and the amplitudes of relative sea-level change associated with the sequences. Only this array can sample the most complete section across a sequence boundary and thereby date it, account for the influence of lithospheric flexure in controlling sedimentation, and minimize errors in paleobathymetry.

Ages of the sequence boundaries are best determined at two locations: 1) at their deep water correlatives where biostratigraphic resolution is optimized (in this case, the continental slope, the focus of Leg 150); and 2) at the toe of each clinoform, where physical stratigraphy indicates that the hiatus is minimized. The proposed drilling focuses on upper Oligocene and Neogene sequences because of their high accumulation rates, accessibility, clear seismic geometry, and likely correlations to the history of glacio-eustatic forcing throughout this time interval.

PROPOSED SITES

Proposed site MAT-10 is located 1.8 km north of COST 3B where the first rotary core sample was recovered from below the Tuscan sequence boundary (10 ± 1 Ma). Drilling at this proposed site aims to penetrate the reflector Red-3 which was sampled on the continental. Greenlee and Moore (1988) have suggested that the Red-3 boundary correlates with the 49.5 Ma sequence boundary of Haq *et al.* (1987).

Proposed site MAT-11 is located 5 km upslope from COST 3B. Drilling at this proposed site will constrain the age of pelagic correlatives from the Yellow-2 (11.7 ± 1 Ma) to Red-3 (middle Miocene to the top of lower Eocene).

Drilling at proposed site MAT-12 will attempt to recover most of the 28 m.y.-hiatus from the upper Miocene to lowermost Oligocene encountered 1.8 km downslope at DSDP Site 612, determining the age of pelagic correlatives from the Pink-2 (?17.5 Ma) through Red-3 (?49.5 ma) sequence boundaries.

Proposed site MAT-13 is located approximately 35 km northeast of proposed sites MAT-10 to -12, in a region where the upper Neogene section above Pink-1 is considerable thicker and numerous sequence boundaries can be traced along MCS Line 1002 to the shelf. The age of the Pink-1 sequence boundary and the numerous unconformities that overlie it are poorly constrained. Greenlee and Moore (1988) speculated that Pink-1 correlates with the 5.5 Ma sequence boundary of Haq *et al.* (1987), although subsequent examination of all oil company wells in this region shows that the age of this reflector is unconstrained (Greenlee *et al.*, 1992).

Proposed site MAT-14 will be drilled to provide a record of coeval sediments on the continental rise that will address two major issues related to the response of continental rise sedimentation to sea-level changes. This site was designated as proposed site NJ-6 on Leg 95, but due to time constraints, was never drilled. The first issue to be evaluated at this site is how and when sediment was deposited on the continental rise, and the relationship of this history to relative sea-level change. Three problems need to be addressed: 1) is the transport of terrestrial sediments to the rise constant or episodic?; 2) what processes determine sediments accumulation on the rise?; and 3) what is the relative contribution of slope sediments to the rise?

The New Jersey transect will provide the relative sea-level signal from the coastal plain to the slope. MAT-14 will document the accumulation rate, source, and sedimentary structures of the coeval sediments on the rise and will provide both the biostratigraphic and lithostratigraphic control on the Miocene sections that will also be sampled on the shelf and slope.

MAT-14 will address a second important issue by evaluating the role of deep-sea currents in shaping the upper continental rise. Only the few hundred meters of stratified sediments at the base and at the top of the post-A^u interval at MAT-14 are predicted to be downslope-transported sediments. The rest of MAT-14 will sample the "hummocky" and "back-slope" acoustic facies of the Chesapeake Drift.

Thus MAT-14 will not only address the effects of sea-level change on continental rise deposition, but will also evaluate the timing and role of deep-water circulation changes in reshaping these deposits. While it is likely that pulses of NCW correlate with sea-level changes, sufficient age control to test this important linkage is lacking. MAT-14 will provide improved geochronology of the three marker horizons, A^u, Merlin, and Blue, and will allow an evaluation of the causal relationship between deep-water changes, glaciation, and sea-level (e.g., Broecker and Denton, 1989).

ADDITIONAL CONSIDERATIONS

Safety

No commercially valuable hydrocarbon shows have been encountered in the proposed drilling area, despite extensive searches during the 1970's. Interest was focused on three possible reservoirs; early drift-stage sandstones, lower to middle Cretaceous carbonates beneath the outer shelf and upper slope, and Cretaceous stratigraphic traps fringing a mid-shelf igneous intrusion. No safety problems at the proposed drilling targets are anticipated.

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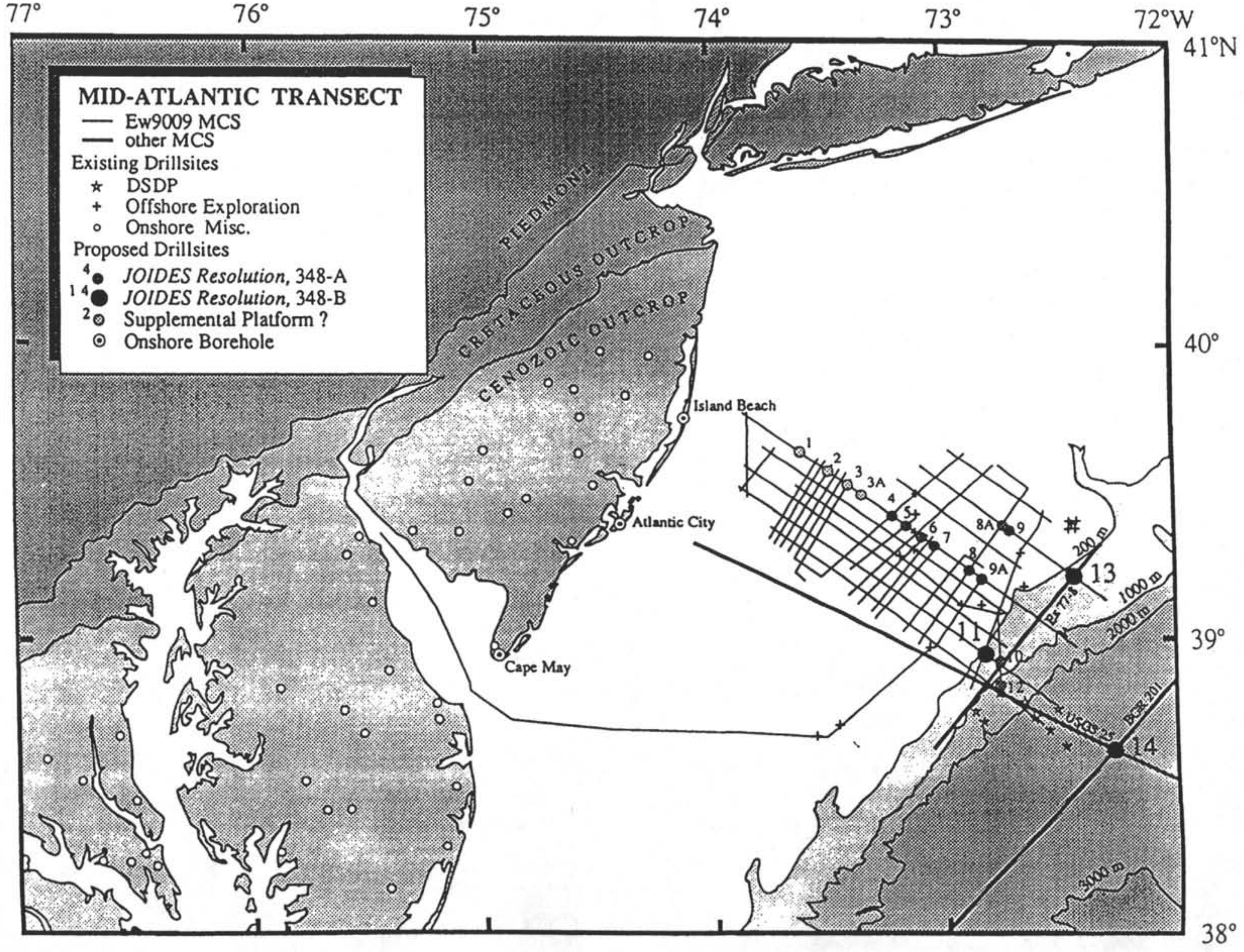

FIGURE 1: Location map of the Mid-Atlantic Transect (MAT-10 through MAT-14)

Miocene Biostratigraphy and Age Estimates

Sequence Boundaries & Ages	COST B-2 298' (91 m) 98' kb	SHELL 273-1 292' (89 m) 84' kb	EXXON 684-1 399' (122m) kb	EXXON 902-1 433' (132 m) 72' kb	COST B-3 2686' (819 m) 42' kb	Interpreted Age	δ¹⁸O Zones	
	Gt. plesiotumida 810[1] *B. elongata* 880[4]		*B. elongata* 1964[4]	*B. elongata* 2810[4]				
PINK-1 "5.5"	1345	1210	2365	2910	N.D.	?3 Ma ? 9-3 Ma		Pliocene?
				S. seminulina 2990[4] (N21; ~3 Ma)				
YELLOW-1 "6.3"	ONLAPPED OUT N.D.	1660	N.D.	3110	N.D.	?		upper Miocene
		Gt. margaritae 2220[4] (3.4 Ma) *B. elongata* 2220[4]						
RED "8.2"	ONLAPPED OUT N.D.	2430	N.D.	N.D.	N.D.	?	?Mi 7 (8.5 Ma)	
		Gt. mayeri 2640[4] (10.4 Ma)			Reflector M1 of Miller et al, 1987			
TUSCAN "10.5"	1500	2860	2810	3475	~3700?	10 Ma ~11-9 Ma	Mi 6 (9.6 Ma)	middle Miocene
	Gt. mayeri 1510[1] (10.4 Ma)	*Gt. fohsi lobata* 3030[4] (11.6 Ma)	*Gt. mayeri* 2940[4] (10.4 Ma)	*Gt. mayeri* 3590 (10.4 Ma) *Gt. fohsi robusta* 3650[5] (11.5 Ma)	*Gt. fohsi lobata* 3800[6] (11.6 Ma) *Gt. mayeri* 3800[4,7] *Gt. fohsi fohsi* 3990[4] (12.3 Ma)			
YELLOW -2 "DLS"	2000	3050	3230	3800	~4100	11.7 Ma 12.2-11.2 Ma	Mi 5 (11.3 Ma)	
	Gt. fohsi fohsi 2800[3] (12.3 Ma) *Gt. peripheroronda* 2860[1] (~N10; 14.6 Ma?)	*Gt. fohsi fohsi* 3120[4] (12.3 Ma)			*P. glomerosa* 4160[6] (~15 Ma)			
BLUE "12.5"	2920	3260	3330	4030	4335	13.5 Ma 14.9-12.8 Ma	Mi 4 (12.6 Ma)	
		Gt. peripheroronda 3420[4] (~14.6 Ma?)			*G'lla insueta* 4430[6] (~15 Ma)			
RED-2 "13.8"	3080	3470?	3445	4170	4480	14.5 Ma 15.3-13.5 Ma	Mi 3 (13.6 Ma)	
			Gt. peripheroronda 3630[4] (~14.5 Ma?)	*G'lla insueta* 4250[4] (~lower N9; ~15 Ma)	*C. dissimilis* 4490[6] (17.6 Ma)			
GREEN "15.5"	3280	3950	3640	4270	4650	16 Ma? ~19-14.8 Ma	Mi 2 (16.1Ma)	?
	C. stainforthi 3580[4] (~mid N7; ~17 Ma) *Gt. kugleri* 3610[1,2] (21.7 Ma) *P. opima opima* 3850[5] (28.2 Ma)	*G. ciperoensis* 3990[4] (~23 Ma) *P. opima opima* 4230[4] (28.2 Ma)	*P. opima* cf. *opima* 3690[4] (?28.2 Ma)	*Gt. peripheroronda* 4406[4] (~14.6 Ma) (premature LO ?) *P. opima opima* 4422[4] (28.2 Ma)	*Gt. kugeri* 4670[6] (21.7 Ma) *P. opima opima* 4760[8] (28.2 Ma)			up. Ol.- lo. Mio.

FIGURE 2: Miocene biostratigraphy and age estimates for five industry wells on the New Jersey continental shelf and slope. All depths are in feet below kelly bushing. The depth to sequence boundaries were derived from seismic well log ties and velocity surveys except for Tuscan at COST B-3. T="tops" (last occurrence). Oxygen isotope zones after Miller et al. (1991). (after Greenlee et al., submitted).

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: MAT-10 **PRIORITY:** 1 **POSITION:** 38°55.93'N, 72°46.05'W
WATER DEPTH: 806 m **SEDIMENT THICKNESS:** ~ 10 km **TOTAL PENETRATION:** 908 m
SEISMIC COVERAGE: Ew9009 Line 1027; misc. airgun, watergun; Exxon MCS

Objectives: Determine age of pelagic correlatives to sequence boundaries Tuscan (10 ± 1 Ma) to Red-3 (?49.5 Ma) sampled on the continental shelf.

Drilling Program: APC and XCB coring.

Logging and Downhole Operations: 1) Schlumberger suite: standard quad combo and geochemical log; 2) formation microscanner.

Nature of Rock Anticipated: Silty clays and pebbly mudstones (0-760 m), chalk (760-875 m), and porcellanitic limestone (875-908 m).

SITE: MAT-11 **PRIORITY:** 1 **POSITION:** 38°56.22'N, 72°49.00'W
WATER DEPTH: 430 m **SEDIMENT THICKNESS:** ~ 10 km **TOTAL PENETRATION:** 1271 m
SEISMIC COVERAGE: Ew9009 Lines 1005 & 1026; Ew9009 watergun; USGS 40-in^3 airgun; Exxon MCS

Objectives: Determine age of pelagic correlatives to sequence boundaries Tuscan (10 ± 1 Ma) to Red-3 (?49.5 Ma) sampled on the continental shelf.

Drilling Program: APC, XCB, and RCB coring.

Logging and Downhole Operations: 1) Schlumberger suite: standard quad combo and geochemical log; 2) formation microscanner.

Nature of Rock Anticipated: Silty clays and pebbly mudstones.

SITE: MAT-12 **PRIORITY:** 2 **POSITION:** 38°50.00'N, 72°44.98'W
WATER DEPTH: 1298 m **SEDIMENT THICKNESS:** ~ 10 km **TOTAL PENETRATION:** 477 m
SEISMIC COVERAGE: Ew9009 Line 1027; misc. airgun, watergun.

Objectives: Determine age of pelagic correlatives to sequence boundaries Pink-2 (?17.5 Ma) through Red-3 (?49.5 Ma) sampled on the continental shelf.

Drilling Program: APC and XCB coring.

Logging and Downhole Operations: 1) Schlumberger suite: standard quad combo and geochemical log; 2) formation microscanner.

Nature of Rock Anticipated: Silty clays and pebbly mudstones (0-250 m), chalk (250-450 m), and porcellanitic limestone (450-477 m)

SITE: MAT-13 **PRIORITY:** 2 **POSITION:** 39°12.50'N, 72°26.60'W
WATER DEPTH: 345 m **SEDIMENT THICKNESS:** ~ 10 km **TOTAL PENETRATION:** 937 m
SEISMIC COVERAGE: Ew9009 Line 1002; Exxon MCS Line 77-8, misc. watergun, airgun.

Objectives: To focus on upper Neogene sequence boundaries (especially post Pink-1, ? 5.5 Ma) and to provide groundtruth on pre-late Neogene sequences on the slope adjacent to MAT-8A and -9.

Drilling Program: APC, XCB, and RCB coring.

Logging and Downhole Operations: 1) Schlumberger suite: standard quad combo and geochemical log; 2) formation microscanner.

Nature of Rock Anticipated: Silty clays and pebbly mudstones.

SITE: MAT-14 **PRIORITY:** 2 **POSITION:** 38°37.00'N, 72°17.30'W
WATER DEPTH: 2761 m **SEDIMENT THICKNESS:** ~ 10 km **TOTAL PENETRATION:** 1300 m
SEISMIC COVERAGE: BGR 201; USGS 25 MCS; C2502 watergun; C1903 large watergun.

Objectives: To determine response of continental rise sedimentation to sea-level change during "ice-house" interval and to link deep sea record with shallow- and intermediate-water sea-level studies. Determine age of three major continental rise unconformities (reflectors Blue, Merlin, and A^u).

Drilling Program: APC, XCB, RCB coring and reentry.

Logging and Downhole Operations: 1) Schlumberger suite: standard quad combo and geochemical log; 2) formation microscanner.

Nature of Rock Anticipated: Silty clays and mudstones.

LEG 151

NORTH ATLANTIC - ARCTIC GATEWAYS 1

Modified From NAAG-DPG Report (Proposals 305, 320, and 336)
To Be Named: Co-Chief **Jörn Thiede: Co-Chief**
John Firth: Staff Scientist

ABSTRACT

The Arctic and sub-Arctic areas exert major influences on global climate and ocean systems. Understanding the causes and consequences of global climatic and environmental change is an important challenge for humanity. The high northern latitude oceans are of high relevance for this task since they directly influence the global environment through the formation of permanent and seasonal ice-cover, transfer of sensible and latent heat to the atmosphere, deep-water formation and deep-ocean ventilation which control or influence both oceanic and atmospheric chemistry. Thus, any serious attempt to model and understand the Cenozoic variability of global climate must take into account these paleoenvironmentally oriented topics.

Leg 151 is scheduled to drill a number of sites in four major geographic locations (the Northern Gateway Region, the East Greenland Margin, the Greenland-Norway Transect (Iceland Plateau), and the Southern Gateway Region) with the aim of reconstructing the temporal and spatial variability of the oceanic heat budget and the record of variability in the chemical composition of the ocean. Leg 151 will also undertake a study of circulation patterns in a warm ocean, and the mechanisms of climatic change in a predominantly ice-free climatic system. In addition, the proposed drilling includes a collection of sequences containing records of biogenic fluxes ($CaCO_3$, opal, and organic carbon) and stable-isotopic carbon and oxygen records which will address aspects of facies evolution and depositional environments and the carbon cycle and productivity. The drilling approach focuses on rapidly-deposited sediment sequences to be used for high-resolution, Milankovitch-scale paleoclimatic analysis. Most of the proposed sites are arrayed as either broad north-south and east-west transects to monitor spatial paleoclimatic variability or closely spaced suites of cores across a range of depths to monitor vertical variability. Other approaches include sites chosen for deep drilling that will better constrain the time of opening of Fram Strait, and sites placed to monitor downstream sedimentological effects of deep flow through narrow gateway constrictions. In addition to the paleoenvironmental objectives, a number of sites, in particular in the Fram Strait and Yermak Plateau area, will address the age and nature of basement rocks. The sites to the north of Svalbard also constitute the first drilling to be conducted in the Arctic Ocean proper.

INTRODUCTION

During the last decade it has been realized that much of the natural variance in the Earth's environment on timescales less than 1 million years originates from changes in the geometry of the Earth-Sun orbital system. The sensitivity of the Earth system to orbital forcing has been especially high over the last one million years. Both for understanding how this high sensitivity to external forcing has evolved from periods of less sensitivity and lower amplitude variation, and for understanding the way environmental change is forced both by this and other forcing mechanisms which operate on longer time scales (such as: plate reorganizations, orogeny, carbon cycle variations), it is necessary to obtain records that document how the climatically-sensitive, high-latitude regions have developed.

It follows that this focus on high northern latitude paleoenvironmental questions require deep-sea drilling in the areas north of the Greenland-Scotland Ridge. From south to north these seas consist of the Norwegian and Iceland Seas, the Greenland Sea and the Arctic Ocean, which together commonly are referred to as the Arctic Mediterranean (Sverdrup *et al.*, 1942) or the Nordic Seas (Hurdle, 1986).

The deep-water areas of the Nordic Seas have previously been drilled during DSDP Leg 38 which occupied 17 sites spread out over some of the major basins (Talwani, Udintsev *et al.*,1976), and ODP Leg 104 which occupied three sites on a transect across the Vøring Plateau in the eastern Norwegian Sea (Eldholm, Thiede, Taylor *et al.*, 1987). The sites from Leg 38 were almost exclusively chosen to meet structural and geophysical objectives, and thus did not retrieve complete stratigraphical sequences. In addition, the holes were rotary drilled and mostly spot cored. The quality and continuity of the Leg 38 material is therefore so poor that it is impossible to establish a chronologic resolution and precision which meet the requirements of modern paleoceanography. The Leg 104 sites were drilled with the Advanced Piston Corer (APC) with high recovery and very good sample quality. The sequences from Leg 104 document portions of the Neogene fairly well despite a number of hiatuses (Goll, 1989). The Paleogene intervals of these sites are either missing or seriously altered by diagenesis. Thus, no sequences are available to document the whole Cenozoic history of these oceans, and major portions of the Cenozoic are still unavailable for investigation by modern methods. Although especially the upper Neogene is rather complete on the Vøring Plateau, the location of the sites basically implies that they must be considered as a single sample point along the meridional and latitudinal transects herein advocated. The Leg 104 sites cannot on their own resolve the development of major regional differences and the evolution of environmental gradients and fronts.

No scientific drilling has so far been performed in the Arctic and, due to its inaccessibility, very limited material is available from conventional coring. Sediment cores from the areas north of 76°N, where DSDP Site 344 is located, represent less than 10% of the last 70 m.y., implying that virtually no knowledge exists of the paleoceanography of the Arctic Ocean. This stands in distinct contrast to its fundamental oceanographic and climatic influence. Although the ice cover prevents entry of the *JOIDES Resolution* to most parts of the Arctic Ocean, areas on the Yermak Plateau north of Svalbard and hence north of the gateway (Fram Strait) between the Nordic Seas and the Arctic Ocean are ice-free and accessible in late summer during normal ice years, and can be drilled by normal ODP methodology.

The conclusion is consequently that the presently available material is far from sufficient for solving the scientific objectives outlined above, and that a whole new program of APC/ XCB-drilling in various areas of the Nordic Seas is required for this purpose.

STUDY AREA

Oceanographic Setting

The series of interconnected basins comprising the Nordic Seas contain a total volume of roughly 10 x 106 km^3, if excluding the Amerasian Basin of the Arctic Ocean, or about 0.7% of the volume of the world ocean. The Eurasian basin of the Arctic Ocean makes up nearly 60% of this volume. Despite the small volume of these areas, they nevertheless act as a primary source of a large portion of deep, ventilated waters in the world ocean. The idea that deep waters are formed in the Norwegian-Greenland Seas (Helland-Hansen and Nansen, 1909), and that some of this newly formed water flows into the deep Atlantic across saddles on the Greenland-Scotland Ridge (see Warren, 1981; Mantyla and Reid, 1983 for reviews) was suggested a long time ago. Previous notions about the Arctic Ocean indicated that it has been a passive recipient of ventilated water from the south. In recent years, however, it has been demonstrated that the Arctic Ocean itself is an important contributor of deep waters which flow southward through the Fram Strait, and, after mixing with deep waters formed in the Greenland/Iceland Seas, pass further on into the world ocean (Aagaard, 1981; Aagaard *et al.*, 1985). The processes leading to the formation of dense deep-waters in the Arctic Ocean are thought to involve either intense cooling of Atlantic waters on the Barents Sea Shelf (Swift *et al.*, 1983), or an increase in salinity through salt release during sea-ice formation on the large Arctic shelves (Aagaard *et al.*, 1985). Smethie *et al.*(1988) suggest that both processes are in operation.

The chief components of the surface water systems of the Nordic Seas involve the influx of warm and relatively high-salinity waters via the North Atlantic Current, which continues its northward flow as the Norwegian Current, and outflow via the cold and low-salinity East Greenland Current. The Norwegian Current is sufficiently cooled to allow deep water formation within the cyclonic gyre of the Greenland Sea. Another branch of this current continues along the western margin of Svalbard as the West Spitsbergen Current, before entering the Arctic Ocean. Within the Arctic this relatively warm water mass mixes with low-salinity surface waters, sinks and flows as an intermediate water mass counterclockwise before being exported out of the Arctic via the Fram Strait along the Greenland Margin. The surface outflow from the Arctic Ocean sweeps the east margin of Greenland before entering the Irminger Sea of the North Atlantic via the Denmark Strait.

Aagaard *et al.* (1985) concluded that nearly 50% of the water volume in the Nordic Seas, including the Amerasian Basin, is potentially in communication with the world ocean (Fig. 1). The Nordic Seas might hence be characterized as the "lungs" of the present world ocean, implying that it is of fundamental importance to derive a detailed understanding of the timing and history of deep and shallow water exchange between the Nordic Seas and the remainder of the world ocean. The unique topographic constraints provided by a single deep, narrow passageway to the North (the Fram Strait), and a major submarine ridge system to the south (Greenland-Scotland Ridge) make it pertinent to address the question of the Cenozoic paleoceanography of the Nordic Seas as a gateway problem.

The Gateways and Paleoceanography

The tectonic development and the opening of the Fram Strait has determined the history of water mass exchange between the Arctic Ocean and the Greenland-Norwegian-Iceland Seas. Submergence below sea level of the southern gateway, or parts of it, has determined the possibilities for water mass exchange between the Nordic Seas and the Atlantic Ocean, and thus the world ocean.

The Fram Strait, with a present critical sill depth of 2600 m, represents the only deep connection between the Arctic Ocean and the global ocean. The initiation of this connection may have taken place as early as Anomaly 13 time, close to the Eocene/Oligocene boundary (Crane *et al.*, 1982; Eldholm *et al.*, 1987; see also reviews by Vogt, 1986a, b). The tectonic history of the Fram Strait area, however, is characterized by complex and, at present, vaguely understood processes, which might include stretching of the Svalbard continental crust and hotspot activity. When taking into account the strongly oblique opening of the Fram Strait and the nearness to surrounding land areas

(Greenland and Svalbard), it seems possible that a truly deep Arctic Ocean/Greenland-Norwegian Sea connection became established considerably later than Anomaly 13 time, perhaps as late as Anomaly 6 time. The history of water mass exchange between the Arctic Ocean and the world ocean via the Greenland-Norwegian-Iceland Seas is a key element in any large scale model of post-Eocene paleoceanography. However, the documentation of this history will depend on new drilling efforts to make available material from within and from both sides of the gateway.

There are few oceanic gateways that can compete with the Greenland-Scotland Ridge in having such a profound influence on the present world hydrography (Bott *et al.*, 1983). Overflow from northern sources occurs in the Faeroe-Shetland Channel, across the Iceland-Faeroe Ridge and in the Denmark Strait. Tracer studies indicate that the overflow waters originate from waters shallower than 1000-1200 m, probably to a large extent formed by deep convection in the Iceland Sea (Peterson and Rooth, 1976; Warren,1981; Aagaard *et al.*, 1985). Reconstructions of the subsidence history of the ridge system, suggest that its eastern parts sank beneath sea level probably sometime during middle Eocene times, and during early to middle Miocene times in the Denmark Strait area. The distribution of shallow water benthic foraminifera, however, indicates that the Nordic Seas were effectively isolated from any "deep" Atlantic influence until middle Miocene times (Berggren and Schnitker, 1983; Thiede, 1983; Thiede and Eldholm, 1983). The overflows have both influenced the Atlantic and global deep water masses through their contribution to North Atlantic Deep Water (NADW) production and to the formation of North Atlantic sedimentary records. Basic questions as to why and when NADW production was initiated, and how and why the chemical and physical signature of this major water mass has varied, remain to a large degree unanswered. Quite obviously the physical and chemical characterization of surface and deep waters through time directly in the main source regions, i.e. north of the Greenland-Scotland Ridge, will greatly improve the understanding of world ocean hydrography, global energy budgets and North Atlantic patterns of sedimentation and erosion.

The Nordic Seas are characterized by strong latitudinal gradients in the sea surface environment, but also by unusually strong meridional gradients due to the warm Atlantic influence in the east and the cold polar influence in the west. Strong seasonal variability is also a prominent feature of the surface environments, resulting in strong and rapidly migrating ocean fronts. The onset and subsequent variability of these fronts are almost totally unknown. Apart from the data obtained from the Norwegian Margin by ODP Leg 104, no high quality material exists which is older than a few hundred thousand years. Thus, to derive a comprehensive understanding of the whole ocean-climate system of the Nordic Seas, and the *modus operandi* of this, in a global perspective critical, system, it is necessary to obtain material that can document how sea-surface environments have changed and the underlying causes for these changes through late Paleogene and Neogene times.

Climate Evolution of High Northern Latitudes

A major element in the evolution of Cenozoic environments has been the transformation from warm Eocene oceans with low latitudinal and bathymetric thermal gradients into the later type of oceans characterized by strong thermal gradients, oceanic fronts, cold deep oceans and cold high latitude surface water masses (Shackleton and Boersma, 1981). This transformation is linked with the climatic transition into cold high latitude climates and the connection of both surface and deep-ocean circulation between high latitude regions and the lower latitude oceans. It is still not known what role the Arctic and sub-Arctic regions played in this transformation, or how and when climatic, tectonic and oceanographic changes in the Arctic contributed to the global ocean cooling and increased thermal gradients.

At present it is uncertain when cold climates evolved in the Arctic and surrounding regions. In order to understand the evolution of the global climate system it is necessary to clarify when the Arctic Ocean became ice-covered, and document the variability of ice cover in the Arctic. It has been proposed that the Arctic Ocean has been permanently ice covered since the late Miocene (Clark 1982). Other studies conclude that this event happened in the Matuyama or at the Brunhes/Matuyama boundary (Herman and Hopkins,1980; Carter *et al.*, 1985; Repenning *et al.*, 1987). This discrepancy in timing cannot be verified by the available material.

A major threshold of the climate system was passed with the inception of glaciers and ice-sheets in the northern hemisphere. Data from ODP Leg 104 document minor input of ice-rafted debris (IRD) into the Nordic Seas in the late Miocene and through the Pliocene, pointing to the existence of periods when large glaciers were able to form and reach coastal areas in some of the areas surrounding the Nordic Seas (Jansen and Sjøholm, 1991). The major shift to a mode of variation characterized by repeated large glacials in Scandinavia probably occurred at about 2.5 Ma and was further amplified at about 1 Ma (Jansen *et al.*, 1988; Jansen and Sjøholm, 1991). With the presently available material it is impossible to document clearly when glaciers started to evolve in the Arctic and high sub-arctic, and it is impossible to describe the glaciation history of the different individual areas, i.e. when was Greenland glaciated? What distinguished the climatic responses in the Arctic parts of this area (Greenland, Svalbard, and Arctic Ocean fringes) from those of the sub-arctic North European areas? Did the cooling and glacial inception of the high Arctic and Greenland take place at an earlier stage than in the sub-arctic? Terrestrial data indicate significant cooling on Iceland at about 10 Ma (Mudie and Helgason, 1983) and glaciation in elevated areas of Iceland in the latest Miocene and the Pliocene (Einarsson and Albertsson, 1988). Terrestrial evidence also indicates forested areas in the Arctic fringes, which are far north of the present forest-tundra boundary, until about 2 Ma (Carter *et al.*; 1985, Nelson and Carter, 1985; Funder *et al.*, 1985; Repenning *et al.*, 1987). The chronology from these land sites is, however, poorly constrained, and since this is only scattered evidence, there are no continuous records from land sites that document the climatic transition into a cold arctic climate. Both a clear documentation and a proper timing of the climatic evolution will therefore depend on the availability of new, continuous, deep-sea material.

Since the glacial and climatic history of the high northern latitudes are so poorly known, the ability to model and understand linkages between low and high latitude climates and between southern and northern hemisphere climates is limited.

The Norwegian-Greenland Seas and the Arctic Ocean are surrounded by landmasses that acted as loci for the late Cenozoic Northern Hemisphere ice sheets. Therefore these areas are key areas where northern hemisphere glacials can be documented in the form of input of IRD into the ocean. The history of large glaciations in the high northern latitudes has only been firmly documented back to approximately 2.5 m.y. (Shackleton *et al.*, 1984; Ruddiman and Raymo, 1988; Jansen *et al.*, 1988), although glaciation in some areas must have started earlier in the Neogene. This contrasts with the history of glaciation in the Antarctic which probably dates back at least to the early Oligocene, some 36 million years ago (Barron, Larsen, Baldauf, and Leg 119 Scientific Party, 1988). The apparent interhemispheric asynchroneity in the climatic evolution of high latitude regions on the southern and northern hemispheres is a major unresolved question for understanding Cenozoic paleoenvironments.

In addition to the above questions that address the magnitude of glaciations and the passing of certain climatic thresholds in the Earth's history, are the frequency components of the climatic, oceanographic, and glacial evolution of the Arctic and Sub-arctic which are of importance for assessing the climate system's response to external forcing. Results from DSDP Leg 94 sites in the North Atlantic have shown that sea-surface temperatures and ice volumes have a strong response to orbital forcing over the last 3 m.y. However, the amplitudes of climatic variation and the dominant frequencies have varied strongly, indicating variations in the way the climate system responds to external forcing (Ruddiman *et al.*, 1986; Ruddiman and Raymo, 1988; Raymo *et al.*, in press). Work is underway, based on Leg 104 material, to study the cyclicity of IRD input into the sub-arctic Norwegian Sea. This can aid in understanding the controlling factors for sub-polar ice-sheet variations. However, presently available data does not permit extending this type of high-resolution study on orbital time scales to other parts of the Arctic Ocean and Nordic Seas.

Some models constructed to investigate and explain the evolution and operation of the global climate system include variations in the magnitude and mode of thermohaline ocean circulation, (e.g. Barron and Washington, 1984; Broecker *et al.* 1985; Mix and Pisias, 1988; Boyle 1988). Further improvements of such models will thereby partly depend on records that can assess the actual climatic and oceanographic evolution of this particular region.

Sediment Budgets

The rates at which the various deep-sea sediment types accumulate are essential to the global geochemical balances, because mass accumulation rates of biogenic carbonate, opaline silica, organic matter, and non-biogenic sediment components determine the internal cycling of matter in the oceans and are therefore linked to the chemical state of both the oceans and the atmosphere (Broecker and Peng, 1982). Accumulation of biogenic matter and carbonate are, for example, closely linked with atmospheric CO_2 levels. Biogenic sediment components, which account for more than 50% of the deep-sea sediments, accumulate at rates which are determined by the productivity rates in the surface waters and the dissolution of these components at depth.

The availability of nutrients determines the productivity rates which, therefore, also are dependent on the ocean circulation (e.g. vertical mixing, upwelling), and on climate as a driving force for the circulation. Dissolution of biogenic carbonate is basically a function of the degree of calcite saturation in sea-water at the sediment/water interface. Averaged globally, the degree of calcite saturation varies in order to balance the total carbonate budget. The ocean circulation, and the underlying causes for its development and change, is thus a key factor among the dissolution-related parameters.

ODP Leg 104 documented a major deepening of the calcite lysocline at about 10 Ma in the Norwegian Sea. This was followed by a series of low frequency variations in carbonate deposition/dissolution and opaline silica preservation. This 10 Ma-event presumably reflects the cumulative effect of a large set of changes occurring in the global sediment budgets and paleoenvironment at around the middle/late Miocene transition, such as an increase from 5 to 10% in the recycling rate of the total sediment mass on earth (Hay, 1985), the beginning of a remarkable decrease in the global organic carbon reservoir (Shackleton, 1987), or the substantial increase in latitudinal temperature gradients (Shackleton and Kennett, 1975; Thierstein and Berger, 1978). Concomitant changes induced by tectonic forcing also belong in this picture, where the activation of new ocean circulation patterns through newly formed gateways must be an important factor contributing to the large scale changes in the global climate-ocean-sediment system. It follows that many possible cause and effect relationships can be inferred to explain, for example, the deepening of the Norwegian Sea lysocline at 10 Ma. Yet, this shows that global patterns are preserved in the sediments of the Nordic Seas.

Biological Evolution

The coring program envisaged herein will recover high quality APC/XCB sediment material reflecting a wide variety of paleoenvironmental conditions in the Nordic Seas, and it is anticipated that the material also will be used to address a wide array of significant scientific questions which have not been specifically mentioned in the three main themes.

Studying biological evolution is one such additional scientific problem. Such studies will allow the assessment of the response of oceanic biota to changes in climate, ocean circulation, and ocean chemistry. Cores from high northern latitudes, and particularly the Arctic Ocean, will provide the northern hemisphere end-member for examining topics such as patterns and modes of speciation, bipolar evolution, Arctic fauna and flora, and Arctic/sub-Arctic environmental influence on intra- and inter-specific morphological variation.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

Cenozoic Paleoceanography of the Nordic Seas

1) To study the timing and history of deep and shallow water exchange between the Arctic Ocean and the Norwegian-Greenland Sea via the Fram Strait (Northern Gateway).

2) To study the timing and history of deep and shallow water inflow and outflow between the Norwegian-Greenland Sea and the North Atlantic across the Greenland-Scotland Ridge (Southern Gateway).

3) To investigate water mass evolution, particularly addressing the initiation and variability of east-west and north-south oceanic fronts in surface waters, the initiation and variability of northern source deep-water formation, and the history of vertical physical and chemical gradients.

Cenozoic Evolution of Climate in High Northern Latitudes: Cenozoic Cooling, Sea-Ice and Continental Ice-Sheet Formation, and Deposition of IRD

1) To investigate the timing and development of polar cooling and the evolution of low to high latitude thermal gradients in the northern hemisphere.

2) To establish the temporal and spatial variation of sea-ice distribution, the glacial history of the circum-Arctic, Greenland and Northern Europe, and the history of IRD sedimentation in the Arctic.

3) To investigate variations in climatic zonality and meridionality through time as response to tectonic forcing.

4) To establish the history of the higher frequency components of the climatic and glacial evolution of the Arctic and sub-Arctic areas.

5) To identify ocean-atmosphere interactions associated with northern Hemisphere deep-water formation and the interhemispheric couplings and contrasts in climatic evolution.

Sediment Budgets

1) To investigate fluxes of biogenic carbonate, opaline silica, organic matter, and non-biogenic sediment components through time.

2) To study bathymetric variability through time of the CCD and lysocline.

3) To establish the spatial and temporal history of silica preservation.

4) To investigate Arctic and sub-arctic oceanic influence on global biogeochemical cycles.

Specific Objectives and Methodology

Surface Water Mass Evolution

The Norwegian-Greenland Sea links the cold Arctic Ocean with the warm-temperate North Atlantic Ocean via northern and southern "gateways" (Fig. 1). Fram Strait in the north is the single passage to the Arctic Ocean through which surface and deep waters are exchanged. Similar exchanges occur farther south at both the Denmark Strait, Faeroe-Shetland Channel, and Iceland-Faeroe Ridge.

The Nordic Seas are characterized by strong oceanographic gradients not just latitudinally but also meridionally, due to the northward flow of warm Atlantic water in the east and southward flow of cold polar water and ice in the west. Strong seasonal variability also results in rapid migrations of sharply defined fronts. Apart from material obtained from the Norwegian margin by ODP Leg 104, the history of these surface-ocean gradients is almost totally unknown prior to the last few hundred thousands years. ODP drilling will provide material from the colder western regions for tracing the spatial evolution of surface-water environments and thus enhancing the understanding of climatic change.

Temporal and Spatial Variation of Sea-Ice Distribution

The present Arctic climate is strongly influenced by its sea ice cover, which greatly increases the regional albedo and reduces heat and gas exchange with the atmosphere. Very little is known about how this ice cover first developed and subsequently varied. Although prevented from drilling within the permanent pack ice in the Central Arctic, *JOIDES Resolution* drilling along the present ice margins will provide better constraints on the history of sea-ice extent just north of a key Arctic gateway and southward into Nordic Seas.

The Gateway Problem

The gateways in the north (Fram Strait) and south (Greenland-Scotland Ridge) are among the most important submarine topographic constrictions to global oceanic circulation. Opening of Fram Strait and subsidence of the Greenland-Scotland Ridge below critical levels are necessary conditions for deep water exchange between the Nordic Seas and Atlantic Ocean, although other tectonic changes may also play a role in determining the subsequent long-term evolution of meridional exchanges across these former barriers. The history of these gateways is thus a key component in understanding the long-term evolution of both Northern Hemisphere and global climate.

Leg 151 focuses on two key objectives not addressed in previous drilling: 1) constraining the tectonic history of opening of these barriers, primarily by drilling to obtain basement ages; and (2) defining the subsequent history of surface and deep-water exchange across these barriers, based both on proxy watermass indicators and on current-sculpted features on the sea floor.

Deep Water-Mass Evolution

At present, deep waters of the sub-Arctic North Atlantic form partly from dense saline waters cooled in the Greenland and Iceland Seas, and partly from deep waters flowing out of the Arctic Ocean. Because of their rapid formation and short residence times, these deep waters are rich in O_2 but poor in CO_2 and nutrients. The deep water spills over the Greenland-Scotland Ridge and mixes with warmer North Atlantic waters to form southward-flowing North Atlantic Deep Water (NADW). NADW helps to oxygenate the deep ocean and transfers heat and salt to the Antarctic. Glacial/interglacial changes in deep-water formation in the Nordic Seas are implicated in conceptual models of atmospheric CO_2 variations.

ODP drilling in the Nordic Seas will improve the understanding of deep-water evolution by providing: spatial/vertical transects that constrain the development of physical/chemical gradients in deep waters; sites located in regions where vigorous deep-water outflow has altered normal pelagic sedimentation; and evidence of surface ocean climate changes in regions of deep-water formation.

History of Mountain Glaciers and Ice Sheets around the Nordic Seas

Results from ODP Leg 104 trace the glacial history of the Fennoscandian Ice Sheet back to 2.57 Ma. Sporadic earlier occurrences of minor quantities of ice-rafter debris in various North Atlantic drill sites indicate a still earlier onset of limited glaciation around the Nordic Seas. Both the location and kind of ice remain uncertain. Were there mountain glaciers that reached the sea, or small ice sheets? Were they located on Greenland, on Svalbard, or over the Barents Sea? It is thus a primary drilling objective to obtain sediments from sites adjoining these regions to assess their glacial histories individually.

Sediment Budgets

In order to derive a broad understanding of global sediment budgets, it is necessary to integrate biogenic (and lithogenic) flux data from all ocean basins. The present coverage of high-quality material from the Nordic Seas is insufficient both regionally (no sites in the central, western, or northern parts) and vertically (lack of deeper sites). The proposed drill sites cover the major water masses and depth gradients and will permit calculation of burial fluxes of opal, $CaCO_3$, and organic carbon, as well as deductions about the intensity of $CaCO_3$ dissolution through time.

DRILLING PLAN/STRATEGY

Most of Leg 151's objectives require drilling long sequences of rapidly deposited (>20 m./m.y.) sequences, with double APC coring to refusal (or occasional triple HPC coring as necessary). This approach permits retrieval of continuous sections for high resolution analysis of the higher frequency (orbital-scale or higher) variations of the climate system. At the same time, it also provides sequences spanning millions of years, during which the long-term baseline climatic state may evolve toward generally colder conditions, as may the spectral character of orbital-scale variations. In the following discussion of objectives, references to the history, evolution, or development of key components of the Arctic/Nordic climate system should thus be understood to include both orbital-scale and tectonic-scale changes.

Leg 151 constitutes a series of proposed sites drilled to form a north-south transect, an east-west transect, and a bathymetric transect. The sites should be double, or even triple, APC/XCB cored in order to achieve 100% recoveries. The north-south transect extends from the Arctic Ocean (the Yermak Plateau) via the Fram Strait, the Greenland and Iceland Seas into the north-western North Atlantic. It can thereby tie into existing North Atlantic (DSDP Leg 81, 94), and Labrador Sea (ODP Leg 105) high resolution stratigraphies. This transect will cover the major ocean basins of the region and provide sites on both sides of the two important gateways (the Fram Strait) and the Greenland-Scotland Ridge, and it will address the evolution of north-south environmental gradients from the Arctic to the temperate North Atlantic.

The east-west transect will use the Leg 104 sites on the Vøring Plateau as its eastern tie-point and will extend across to the areas immediately off east Greenland. The main intention of this transect is to sample the strong environmental gradient between the polar regions off east Greenland and the temperate Atlantic waters off Norway, in order to study the inception and evolution of the strong mid to high latitude east-west gradients and oceanic fronts, and to investigate differences in the oceanic and glacial evolution between Greenland and Northern Europe. Additionally it is necessary to include a central sample point along this transect in order to obtain clean pelagic records from the central portions of the basin.

Two bathymetric transects are also proposed in order to study sediment budgets, lysocline/ CCD-variability, and bathymetric gradients in ocean chemistry: one on the Yermak Plateau in the Arctic and the other on the slope between the Iceland Plateau and the Aegir Ridge (extinct axis) in the Norwegian Basin. This area is located centrally in the Norwegian Sea and will not be influenced by continental margin effects.

PROPOSED SITES

The Yermak Plateau (YERM)

The Yermak Plateau is a topographic high due north of Svalbard. The Morris Jesup and northeastern Yermak Rises are a pair of plateaus rising to crestal depths of 0.5 to 1 km, which apparently were formed in Paleocene-Oligocene time by excess, Iceland-like volcanism along the southwestern Nansen ridge. The southern part of the Yermak Plateau may be thinned continental crust (Jackson *et al.* 1984). There is thick sediment draping on both the western and eastern flanks. Gravity and piston cores show that the present sediment cover contains some biogenic calcareous components and document normal pelagic sedimentation rates.

Drilling in this area will enable a study of environmental responses pre- and postdating the opening of the deep gateway into the Arctic. It will document the timing of this event, the physical and chemical nature of the water masses associated with the gateway opening and its influence on ocean circulation and climate. It will furthermore provide a check for the theory linking this event with changes in the relative plate motion starting at about Anomaly 13 time, and the possible global impacts of the establishment of a deep connection between the Arctic Ocean and the World Ocean. The other main achievement from drilling this area is that it should provide a continuous late Neogene record from the Arctic Ocean of the same quality as is available from lower latitude areas. This will make it possible to identify the onset of permanent ice cover in the Arctic, test models of the pre-glacial ice-free Arctic, and the magnitude of glaciation and ice-sheets in the Arctic areas by identifying the onset and variation of IRD input into the Arctic Ocean. It should further enable studies of Milankovitch cyclicity in Arctic Ocean climates and circulation and how this cyclicity has evolved with time.

The area forms the most northernmost end member of a north-south transect of drill sites that ties into the other oceans. This would be the first scientific drilling in any part of the Arctic. It will be the northernmost control point for stratigraphic/chronostratigraphic studies, a reference area for Arctic studies, and a northern tie point for studies of the evolution of global thermal gradients. A series of sites in this region has been proposed for three reasons: 1) the necessity to drill more than one site to recover a complete stratigraphic section from the time period of interest; 2) the area lies in the marginal ice-zone, and especially the northern and western sites are only accessible during favorable ice years, and, for this reason it is necessary to have a series of proposed sites to choose between, should one of them not be accessible; and 3) it is desirable to obtain a bathymetric transect of sites in the Arctic to monitor depth gradients in sediment accumulation and water mass properties.

Proposed site YERM 1 is located on the eastern flank of the Plateau and is designed as a deep target site (Fig. 2, Table 1).This site has been proposed to document the subsidence history of the Yermak Plateau and its control on the watermass exchange through the Arctic gateway, and to determine the age and nature of basement. Furthermore it will provide records of surface and deep-water communication between the Arctic and the Norwegian Sea and the IRD-sedimentation history of the Arctic.

Proposed site YERM 2 might, in part, serve as an alternate site for YERM 1 (Fig. 2, Table 1). YERM 2 is located deeper than proposed site YERM 1 on the southwest slope of the Plateau. Besides being an alternate site for YERM 1, this site is designed to study the Neogene glacial history of the Arctic, the history of North Atlantic surface water influx to the Arctic, and to be an intermediate member of a bathymetric transect. Basement is considered to be oceanic crust. Proposed site YERM 3 is located on a thick sequence of draping sediment cover on the eastern flank of the Plateau (Fig. 2, Table 1). It is planned as a site to study Neogene variations in climate and oceanography, and will specifically address the Neogene Arctic glacial history, the Neogene variations in Atlantic water influx to the Arctic and is also the shallow-water member of the bathymetric transect.

Proposed site YERM 4 is located on the thick draping sediment sequence on the western flank of the plateau (Fig. 2, Table 1). The objectives are the same as for proposed site YERM 3.

Proposed site YERM 5 is located at 2850 m on a conformable draping sediment sequence on the lower western slope of the Plateau (Fig. 2, Table 1). The site will be used to document the glacial history of the Arctic Ocean for the Neogene, the history of sea-ice cover, the history of Atlantic water influx, deep water variations and will serve as the deep end member of the bathymetric gradient.

The Fram Strait (FRAM)

Proposed site FRAM 1 is located in the Fram Strait on a gentle elevated area northeast of the Hovgaard Ridge (Fig. 2, Table 1). Two alternate proposed sites FRAM 1a and 1b are proposed in order to have a back-up site in case of problematic ice conditions. Proposed site FRAM 1a is the highest priority, but both sites are located in the same area, and the MCS records provide an easy tie between these alternate sites and shows the same features on both of them. The site is designed to document the timing of the opening of a deep passageway through the Fram Strait and the history of deep and shallow water exchange between the Arctic and the world ocean. It will also provide records of Arctic glacial history and the climatic evolution of the Arctic region. The sites are located west of the complex spreading center, on post-Anomaly 13 crust. MCS and 3.5 kHz lines document a gently draped sediment cover. The area is elevated with respect to the surrounding regions and should be protected against turbidites and slumps originating from the continental margins. A number of piston cores from this area document normal pelagic sedimentation rates and pelagic sediments with good isotopic and biostratigraphic age control for the Quaternary.

Proposed site FRAM 2 is situated on the crest of the Hovgaard Ridge (Fig. 2, Table 1). It is proposed in order to (1) determine the age and lithology of the sedimentary processes immediately postdating the opening of the Fram Strait, and (2) investigate the watermass exchange in and out of the Arctic Ocean. The Hovgaard Ridge is a topographic high which is thought to be a continental fragment severed off Svalbard during the early rifting phase (Eldholm and Myhre, 1977; Myhre and Eldholm, 1987). A few small sediment basins are located on the ridge, which potentially contains sediments documenting the early history of sedimentation after the ridge subsided below sea-level. This site should potentially be able to document the earliest post-opening events, whereas proposed site FRAM 1 is better suited to document the Neogene sections.

The East Greenland Margin (EGM)

The proposed sites on the East Greenland Margin (Figs. 3 and 4, Table 1) are located on a north-south transect paralleling the path of the East Greenland Current (EGC). The objectives are to date the onset of the EGC, monitor deep-water formation and surface-water paleoenvironments in the

Greenland Sea, determine their influence on the variability of the polar front and on the northern hemisphere paleoclimate, decipher the evolution of the Greenland Ice Sheet, monitor contour current activity and sediment drift deposition in the Greenland Basin, and study Paleogene paleoceanography.

Proposed site EGM 2 is located on the lower slope of the east Greenland continental margin and is the northern end of a N-S transect along the margin. It is proposed in order to document the history of the EGC and of deep water flow out of the Arctic downstream from Fram Strait. Proposed sites EGM 1 and EGM 3 are alternate sites.

Proposed site EGM 4 is situated on the lower slope of the Trough Mouth Fan at Scoresby Sund. It is intended for high-resolution studies of the late Neogene history of IRD input and evolution of the Greenland Ice Sheet. It is also located where intermediate and deep waters from the Greenland Sea flow towards Denmark Strait. The Trough Mouth Fan of Scoresby Sund was surveyed by the Greenland Geological Survey (GGU), the Bundesanstalt für Geowissenschaften (BGR), and Polarstern (ARK/V).

The Iceland Plateau (ICEP)

The sites proposed for this area comprise a bathymetric transect of three sites as well as a site in the central Iceland Sea designated to be a part of the east-west transect (Fig. 5, Table 1).

Proposed site ICEP 1 represents the mid-point in the east-west transect located in the southern Nordic Seas, and is proposed in order to (1) monitor the history of oceanic and climatic fronts moving east and west across the Iceland Plateau, (2) derive an open ocean record of IRD and carbonate, and (3) determine the history of the formation of northern source deep waters. As mentioned above, the Leg 104 sites, being located close to the Norwegian coast, suggest local influence on the IRD records and possible increased dissolution and dilution of carbonate along the continental margin. It is thus of crucial importance to drill a good, open-ocean site isolated from such influence and where sub-arctic IRD and environmental changes can be properly assessed.

The Iceland Sea is the final station for deep water production and modification of deep waters formed in the Greenland Sea and in the Arctic Ocean, before the deep waters are exported into the North Atlantic. Results from this drill site are considered necessary in order to determine the timing, evolution, and variations of these water masses.

The proposed site is located on middle Miocene crust and is overlain by about 360 m of sediment allowing high resolution studies throughout the past 10-12 m.y. Piston cores document Pleistocene pelagic carbonate sequences with pronounced glacial-interglacial cycles and ash-layers. DSDP Site 348 was spot-cored (RCB) about 40 nmi due south of proposed site ICEP 1, and contained biogenic sediments throughout the middle Miocene through Quaternary interval. The results from Site 348 clearly indicate that this area on the Iceland Plateau holds excellent promise for solving the problems addressed at proposed site ICEP 1. These problems can not be solved using the Leg 38 material due to poor recovery and poor quality.

Proposed sites ICEP 2, 3, and 4 form a bathymetric transect from the Iceland Plateau down toward the Norway Basin along Conrad Line 209. As a southern end-member of the north-south transect, these sites will enable a study of the oceanic response to different stages in the opening of the Greenland-Scotland gateway north of the ridge. They will also provide a continuous high-resolution pelagic upper Neogene record. The bathymetric transect enables documentation of CCD and carbonate preservation as well as biogenic silica budgets and their response to changing oceanic and climatic conditions. As a key location for the east-west transect they will enable a study of variations in surface currents and oceanic fronts. They will also provide a record of pelagic IRD input well away from the ice sheets, thereby avoiding strong continental influence. This will ensure a more complete biogenous record than is available from locations closer to the coasts.

The area is ideally suited for studies of the chemical characterization of intermediate and deep waters through time. In turn this will have a profound influence on the understanding of the initiation and variation in NADW and global ocean circulation.

The basement is of Anomaly 23-24 age and is overlain by 700-800 m of sediment on an evenly draped gentle slope. The proposed sites are located to the south on the flanks of the Jan Mayen Ridge. This location makes it possible to avoid disturbances caused by the large vertical movements of the Jan Mayen micro-continent during the Paleogene.

Northern Iceland-Faeroe Ridge (NIFR)

The proposed area for drilling north of the Iceland-Faeroe Ridge (Fig. 6, Table 1) holds key information on the early spreading stages of the southern Norwegian Sea and the subsidence history of the Iceland-Faeroe Ridge. Compared with selected sites south of the Iceland-Faeroe Ridge, lithological and biological facies changes may indicate the development of the complex current systems that have crossed the ridge since its initiation in Early to Middle Neogene times. This area holds the unique opportunity to describe the developments of Paleogene environments and to determine exactly the early phases of warm surface-water inflow from the North Atlantic, as a key parameter for northern hemisphere climate.

Southern Iceland-Faeroe Ridge (SIFR)

The area south of the Iceland-Faeroe Ridge covers the key position for data on the origin and early subsidence history of the Iceland-Faeroe Ridge as the major gateway responsible for northern hemisphere climate development. Since the warm North Atlantic Current advected this area also during Early to Middle Neogene times, lithological and biological facies changes from the ridge into the southern Norwegian Sea may help to clarify the onset of surface- and bottom-water exchanges over the ridge. The location of the proposed area (Fig. 6, Table 1) provides the opportunity to determine the age and nature of the Iceland-Faeroe Ridge and of the overlying sediments, which will provide crucial information about the early history of the ridge. Drilling in this area can also determine if a stepwise or more sudden exchange of surface- and bottom-water occurred across the Iceland-Faeroe Ridge during the Early Neogene.

ADDITIONAL CONSIDERATIONS

Sea-Ice

The proposed YERM sites, and to a large extent also the proposed FRAM sites, are located in a region with close to year-around sea-ice cover. Sea-ice is thus the potentially largest operational concern for drilling the proposed sites. From studies of the average August and September sea-ice conditions and a report prepared by Dr. T. Vinje of the Norwegian Polar Research Institute on expected sea-ice hazards, it appears that, in the worst ice years, all proposed sites from the FRAM and YERM areas might potentially be affected by ice. However, the likelihood for ice concerns in the August-mid-September window is low and close to being negligible for the FRAM 1 and the YERM 2 proposed sites. In the normal ice years, also the FRAM 2 and the YERM 3 and 4 proposed sites should be accessible by *JOIDES Resolution.* The YERM 1 and 5 proposed sites will only be accessible during favorable ice years.

From this it is concluded that the major portions of the drilling program can be accomplished in normal years, including some of the Arctic sites, and all sites can be drilled in good ice years. Thus the chances of success are good, and the importance of drilling these frontier regions for the first time certainly makes it worthwhile. In order to drill under the most optimal sea-ice conditions, an ice forecast/ice surveillance program will be implemented and an ice picket boat employed.

Weather

Although the proposed sites are located in high latitude areas, weather conditions in the summer weather window (May-September) are not particularly adverse, and do not pose any threat to the success of the drilling program. Both DSDP Leg 38 and ODP Leg 104 were carried out without weather problems. Recent drilling in the Southern Ocean has proven the capabilities of *JOIDES Resolution* to provide excellent results under much harder weather conditions than those expected for the summer season in the Nordic Seas.

Heat Flow

An extensive survey of heat flow measurements on the Svalbard Margin has shown a zone of anomalously high heat flow along a northwest trend off Svalbard. Only proposed sites YERM 3 and 4 lie within the zone of highest heat flow. Both of these are shallow target sites. The proposed deep target sites, YERM 1 and 2, are both located in areas with less heat flow.

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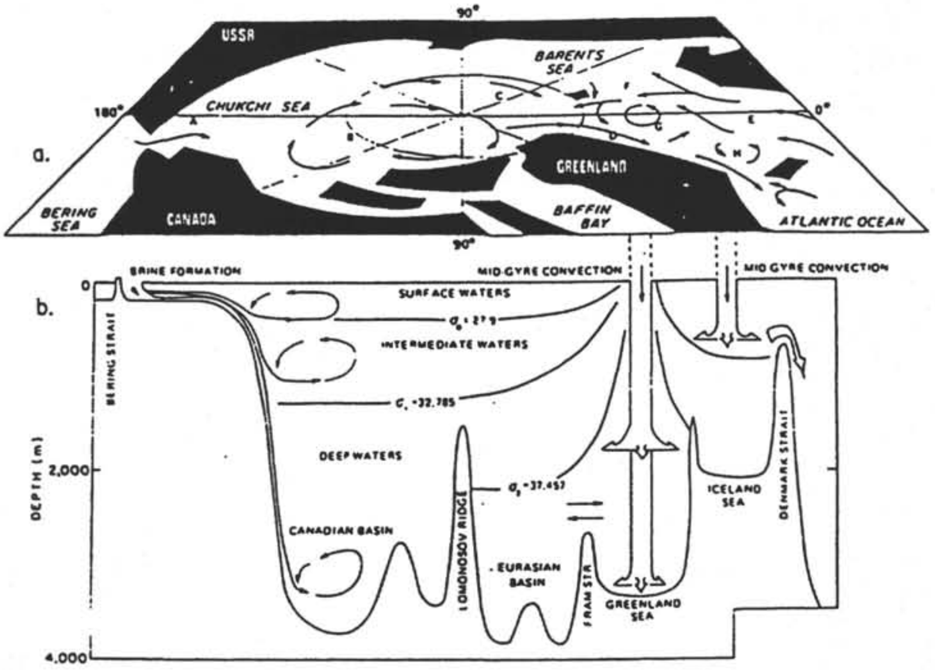

Figure 1. Schematic illustration of ocean circulation in the Arctic Ocean and Nordic seas (from Aagaard *et al.*, 1985).

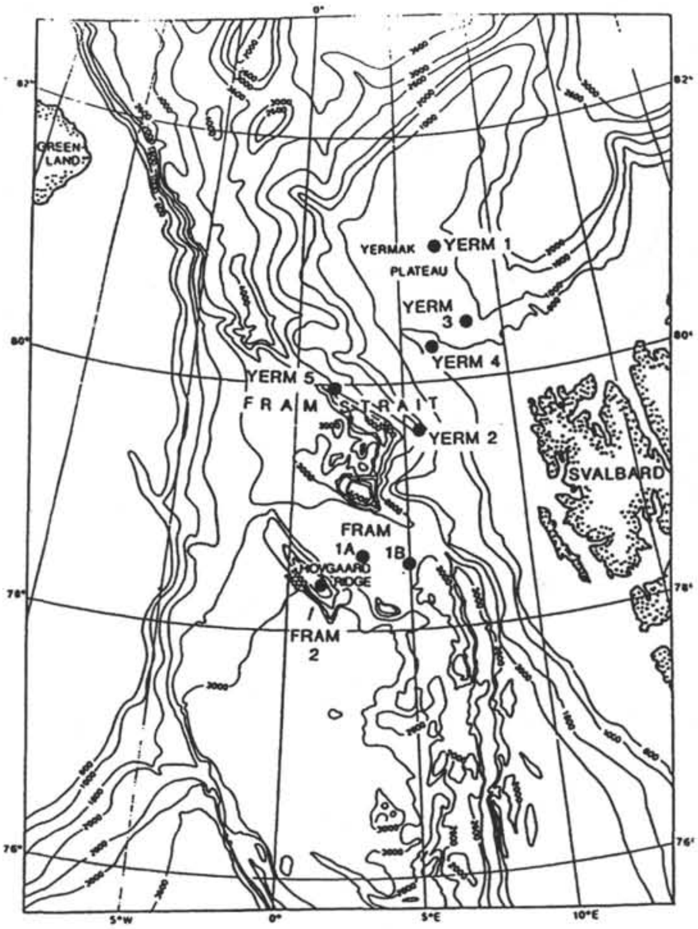

Figure 2. Bathymetry in meters and location of proposed FRAM and YERM sites.

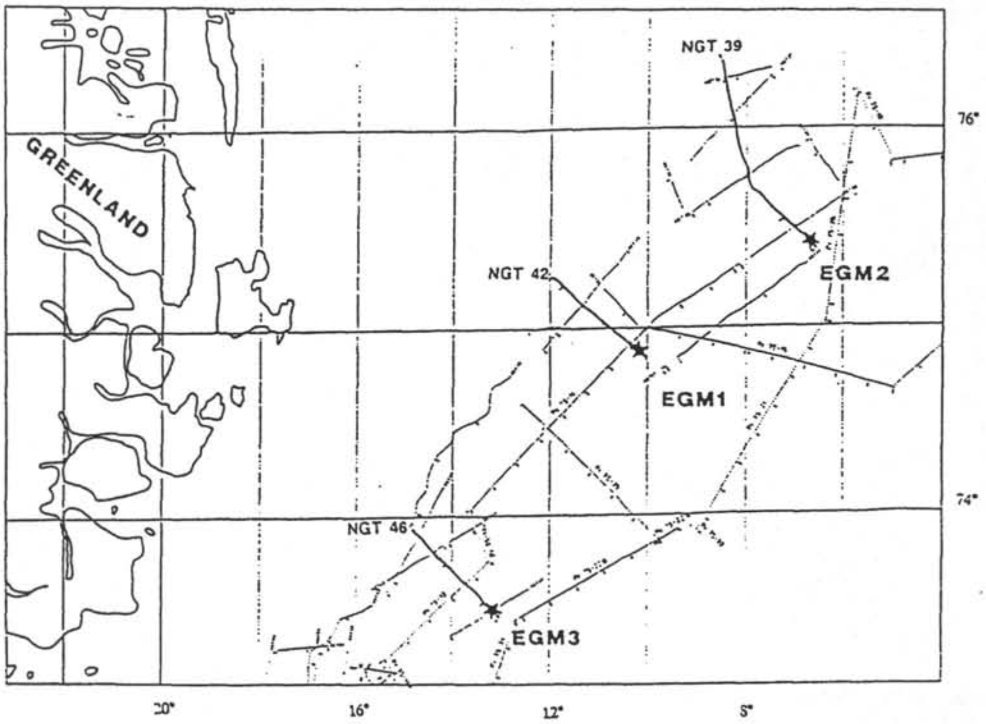

Figure 3. Multichannel seismic profiles on the East Greenland Continental Margin (BGR-Hannover, FRG) showing the location of proposed sites EGM 1, EGM 2, and EGM 3.

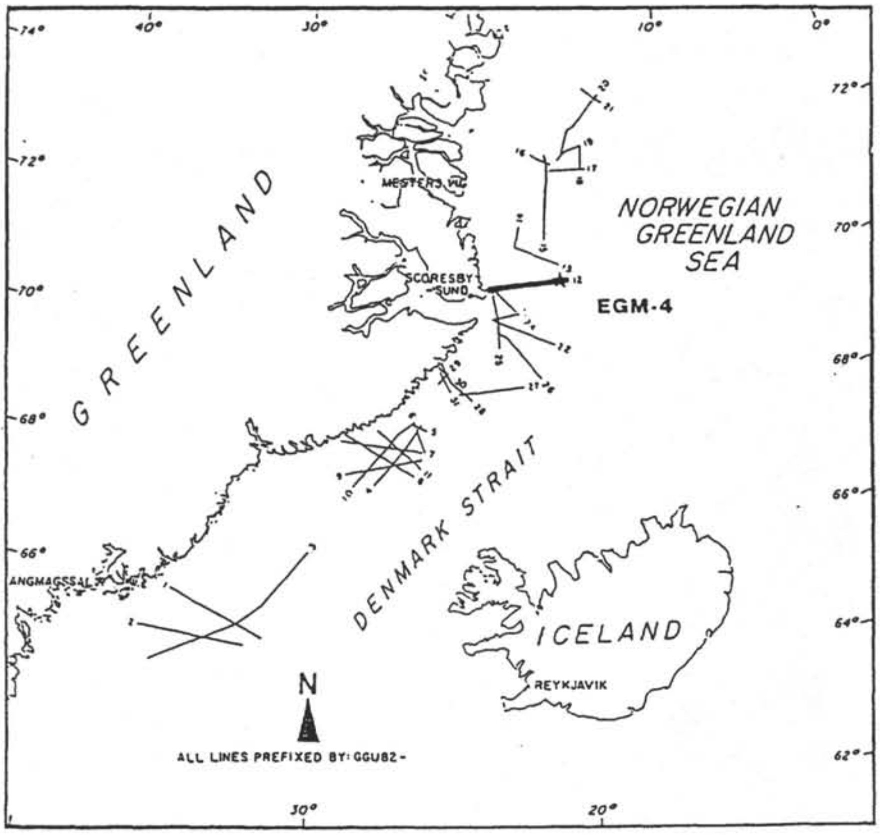

Figure 4. Trackchart of CGU multichannel seismic lines off Scoresby Sund, showing location of proposed site EGM 4.

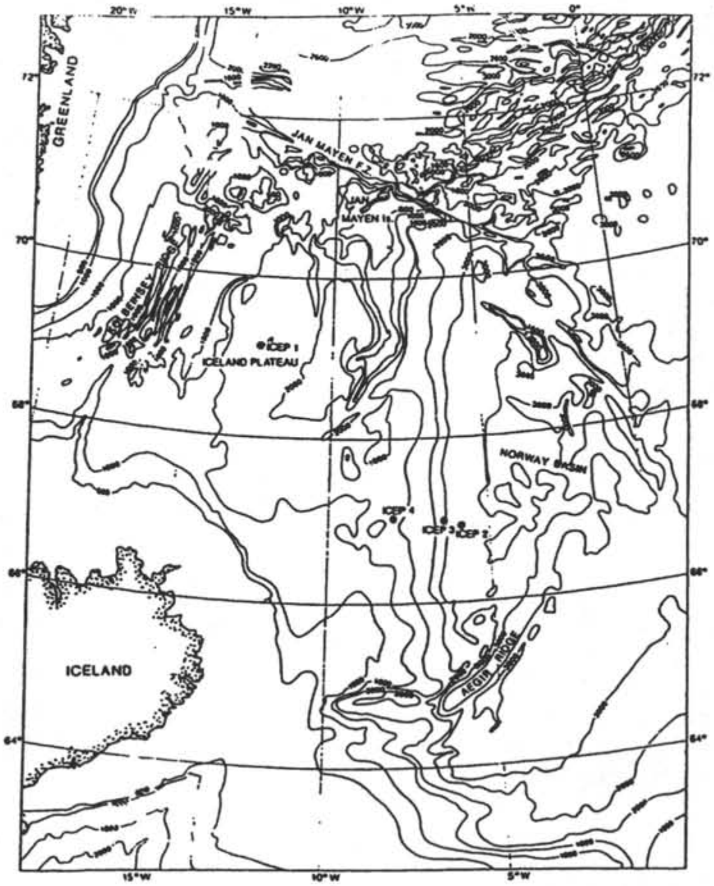

Figure 5. Bathymetry in meters and location of proposed ICEP sites.

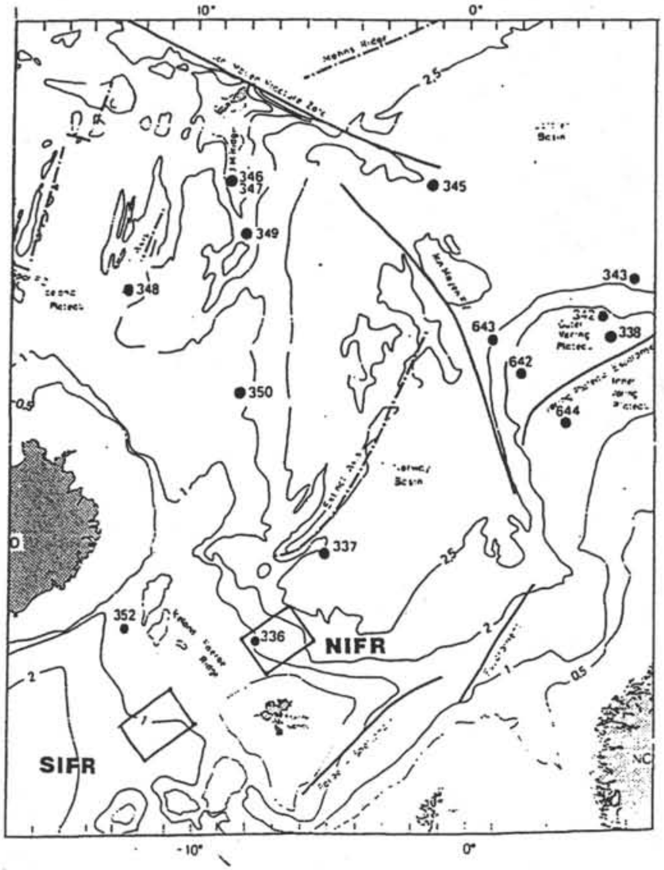

Figure 6. Location of proposed sites NIFR 1 and SIFR 1.

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: YERM 1 **PRIORITY:** 1 **POSITION:** 81°06'N, 7°E
WATER DEPTH: 900 m **SEDIMENT THICKNESS:** 680 m **TOTAL PENETRATION:** 730 m
SEISMIC COVERAGE: BU 79-9 SP 390, BU 79-2 (x-ing)

Objectives: To study the subsidence history of the Yermak Plateau and its control on watermass exchange through the Arctic Gateway. To identify the nature and age of basement. To study the history of surface and deep-water communication between the Arctic and the Norwegian-Greenland Sea. To study the history of IRD sedimentation in the Arctic.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine muds, mudstones, sands, and basalts.

SITE: YERM 2A **PRIORITY:** 2 **POSITION:** 79°38'N, 5°35'E
WATER DEPTH: 1900 m **SEDIMENT THICKNESS:** 1.3 km **TOTAL PENETRATION:** 1000 m
SEISMIC COVERAGE: SVA-13 SP 703, SVA-9 (x-ing).

Objectives: To study the history of surface and deep water communication between the Arctic Ocean and the Norwegian-Greenland Sea. To investigate the Neogene glacial history of the Arctic. To study the history of North Atlantic water influx into the Arctic. To form an intermediate-member of a bathymetric transect of sites. To study the subsidence history of the Yermak Plateau and its control on watermass exchange through the Arctic Gateway and identify the nature and age of basement if this site is chosen as an alternate site to YERM 1.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine muds, mudstones, sands, and basalts.

SITE: YERM 3 **PRIORITY:** 1 **POSITION:** 80°25.5'N, 8°13'E
WATER DEPTH: 975 m **SEDIMENT THICKNESS:** 1.7 km **TOTAL PENETRATION:** 500 m
SEISMIC COVERAGE: BU 77-1 SP 1550, BU 79-12, 79-11, 79-2, 79-3 (x-ing).

Objectives: To investigate the glacial history of the Arctic Ocean for the Neogene. To study the history of influx of North Atlantic surface water into the Arctic Ocean. To form the shallow water member of a bathymetric transect to study depth gradients in sediment accumulation.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments, hemipelagic muds.

SITE: YERM 4 **PRIORITY:** 2 **POSITION:** 80°16'N, 6°38'E
WATER DEPTH: 600 m **SEDIMENT THICKNESS:** > 2 km **TOTAL PENETRATION:** 500 m
SEISMIC COVERAGE: BU 77-3 SP 50.

Objectives: To study the glacial history of the Arctic Ocean for the Neogene. To investigate the history of the influx of North Atlantic water into the Arctic Ocean. To form the shallow member of a bathymetric transect to study depth gradients in sediment accumulation.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments.

SITE: YERM 5 **PRIORITY:** 1 **POSITION:** 79°58.5'N, 1°42'E
WATER DEPTH: 2850 m **SEDIMENT THICKNESS:** > 2 km **TOTAL PENETRATION:** 600 m
SEISMIC COVERAGE: BU 77-18 SP 80.

Objectives: To study the glacial history of the Arctic Ocean for the Neogene. To investigate the history of the influx of North Atlantic water into the Arctic Ocean. To form the deep end-member of a bathymetric transect to study depth gradients in sediment accumulation.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments.

SITE: FRAM 1A **PRIORITY:** 1 **POSITION:** 78°36'N, 3°E
WATER DEPTH: 2590 m **SEDIMENT THICKNESS:**>945 m **TOTAL PENETRATION:** 675 m
SEISMIC COVERAGE: BU 81-20 SP 465 (MCS), BU 81-25 (x-ing), BU 81-26 (x-ing)

Objectives: Timing of the opening of the Fram Strait and the history of deep and shallow watermass exchange between the Arctic and world's oceans. To study the glacial history and climatic evolution of the Arctic Ocean

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine hemipelagic muds/ooze (calcareous/siliceous).

SITE: FRAM 1B **PRIORITY:** 1 **POSITION:** 78°33'N, 5°E
WATER DEPTH: 2500 m **SEDIMENT THICKNESS:** 1 km **TOTAL PENETRATION:** 810 m
SEISMIC COVERAGE: BU 81-34 SP 1380, BU 81-20 (x-ing)

Objectives: Timing of the opening of the Fram Strait and the history of deep and shallow watermass exchange between the Arctic and world's oceans. To study the glacial history and climatic evolution of the Arctic Ocean

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine and hemipelagic muds and biogenic oozes.

SITE: FRAM 2 **PRIORITY:** 2 **POSITION:** 78°22'N, 1°25'E
WATER DEPTH: 1290 m **SEDIMENT THICKNESS:** 360 m **TOTAL PENETRATION:** 360 m
SEISMIC COVERAGE: BU 81-24 SP 1315, BGR 31 (x-ing), BU 81-26 (x-ing).

Objectives: To determine the lithology and depositional history of the sedimentary units in the basins of the Hovgaard Ridge crest. To investigate the timing and variations of watermass exchange in and out of the Arctic Ocean.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Glacial marine and hemipelagic muds and biogenic oozes.

SITE: EGM 1 **PRIORITY:** 2 **POSITION:** 74°52'N, 10°06.5'W
WATER DEPTH: 3250 m **SEDIMENT THICKNESS:** 850-900 m **TOTAL PENETRATION:** 900 m
SEISMIC COVERAGE: MCS NGT 42, BGR 75-14, BGR 88-13 (regional) and NGT 42, BGR 75-14

Objectives: To date the onset of the East Greenland Current, monitor the development of deep-water formation in the Greenland Sea, and document the history of IRD inputs.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Seismic stratigraphy tools and geochemistry.

Nature of Rock Anticipated: Glacial marine and biogenic sediments, terrigenous mud.

SITE: EGM 2 **PRIORITY:** 1 **POSITION:** 75°25'N, 7°20'W
WATER DEPTH: 3400 m **SEDIMENT THICKNESS:** ~ 750 m **TOTAL PENETRATION:** 750 m
SEISMIC COVERAGE: NGT 39, NGT 41 (regional) and NGT 33

Objectives: To date the onset of the East Greenland Current, monitor the development of deep-water formation in the Greenland Sea, and document the history of IRD inputs.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Seismic stratigraphy and geochemistry.

Nature of Rock Anticipated: Glacial marine and biogenic sediments, terrigenous mud.

SITE: EGM 3 **PRIORITY:** 2 **POSITION:** 73°28.5'N, 13°9'W
WATER DEPTH: 2650 m **SEDIMENT THICKNESS:** ~ 1000 m **TOTAL PENETRATION:** 900 m
SEISMIC COVERAGE: NGT 46 (regional) and NGT 47.

Objectives: To date the onset of the East Greenland Current, monitor the development of deep-water formation in the Greenland Sea, and document the history of IRD inputs.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Seismic stratigraphy and geochemistry.

Nature of Rock Anticipated: Glacial marine and biogenic sediments, terrigenous mud.

SITE: EGM 4 **PRIORITY:** 1 **POSITION:** 70°30'N, 18°20'W
WATER DEPTH: 1500 m **SEDIMENT THICKNESS:** 1000 m **TOTAL PENETRATION:** 800 m
SEISMIC COVERAGE: GGU 82-12 (regional)

Objectives: To monitor the history of the Greenland ice sheet and study the latitudinal development of the EGC.

Drilling Program: Triple APC, and XCB or RCB coring.

Logging and Downhole Operations: Seismic stratigraphy and geochemistry.

Nature of Rock Anticipated: Glacial marine sediments.

SITE: ICEP 1 **PRIORITY:** 1 **POSITION:** 69°10'N, 12°25'W
WATER DEPTH: 1950 m **SEDIMENT THICKNESS:** 360 m **TOTAL PENETRATION:** 360 m
SEISMIC COVERAGE: Vema 29-10 (Aug. 18, 1530 hr), GC Leg 38, CP-108, RC 202, RC 204.

Objectives: To monitor the formation and variations of oceanic and climatic fronts (proposed site is midpoint in E-W transect). To obtain an open ocean record of IRD. To study the history of formation and chemistry of northern source deep waters.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Siliceous and calcareous muds and oozes.

SITE: ICEP 2 **PRIORITY:** 3 **POSITION:** 66°54'N, 5°56'W
WATER DEPTH: 3250 m **SEDIMENT THICKNESS:** 650 m **TOTAL PENETRATION:** 650 m
SEISMIC COVERAGE: RC 209 SP 7075, Vema 2304 (Oct. 4, 2000 hr).

Objectives: To document the oceanic response to different stages of the opening of the Greenland-Scotland Gateway. To form the deep end-member of a bathymetric transect of sites for monitoring the history of CCD, carbonate preservation, and biogenic silica sedimentation as a response to changing climatic and oceanographic conditions. To study the Neogene climate history of the Nordic seas. To form the east end-member of an E-W transect to study inception and changes in oceanic and climatic fronts.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments, carbonaceous and siliceous muds and oozes.

SITE: ICEP 3 **PRIORITY:** 1 **POSITION:** 66°56'N, 6°27'W
WATER DEPTH: 2807 m **SEDIMENT THICKNESS:** 800 m **TOTAL PENETRATION:** 300 m
SEISMIC COVERAGE: RC 209 SP 6690.

Objectives: To document the oceanic response to different stages of the opening of the Greenland-Scotland Gateway. To form an intermediate-member of a bathymetric transect of sites for monitoring the history of CCD, carbonate preservation, and biogenic silica sedimentation/accumulation as a response to changing climatic and oceanographic conditions.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Glacial marine sediments, carbonaceous and siliceous muds and oozes.

SITE: ICEP 4	**PRIORITY:** 3	**POSITION:** 67°2'N, 7°58'W
WATER DEPTH: 1800 m	**SEDIMENT THICKNESS:** 520 m	**TOTAL PENETRATION:** 520 m
SEISMIC COVERAGE: RC 209 SP 5500.		

Objectives: To document the oceanic response to different stages of the opening of the Greenland-Scotland Gateway. To form a shallow end-member of a bathymetric transect of sites for monitoring the history of CCD, carbonate preservation, and biogenic opal sedimentation/accumulation as a response to changing climatic and oceanographic conditions. To study the Neogene climatic evolution in high northern latitudes.

Drilling Program: Triple APC and XCB coring.

Logging and Downhole Operations: Standard logging.

Nature of Rock Anticipated: Glacial marine sediments, carbonaceous and siliceous muds and oozes.

SITE: NIFR 1	**PRIORITY:** 3	**POSITION:** 63°50'N, 7°05'W
WATER DEPTH: 2000 m	**SEDIMENT THICKNESS:**	**TOTAL PENETRATION:** 1000 m
SEISMIC COVERAGE: Poseidon 1988, Poseidon 1989, SeaBeam (Polarstern/Aegir Ridge)		

Objectives: To determine age and nature of Iceland-Faeroe Ridge, document Paleogene environmental situations in the southern Norwegian Sea, and monitor the early phases of warm water inflow into the Norwegian Sea.

Drilling Program: Triple APC, and XCB or RCB coring.

Nature of Rock Anticipated: Hemipelagic biogenic muds.

SITE: SIFR 1	**PRIORITY:** 3	**POSITION:** 62°N, 9°W
WATER DEPTH: 1500 m	**SEDIMENT THICKNESS:**	**TOTAL PENETRATION:** 500 m
SEISMIC COVERAGE: Poseidon 1988		

Objectives: To reconstruct the early subsidence of the Iceland-Faeroe Ridge, document onset of Neogene surface water exchange over the Iceland-Faeroe Ridge, and make a comparison of faunal assemblages north and south of the Iceland-Faeroe Ridge.

Drilling Program: Triple APC and XCB coring.

Nature of Rock Anticipated: Hemipelagic/pelagic biogenic muds.

LEG 152

NORTH ATLANTIC RIFTED MARGINS: EAST GREENLAND MARGIN

Modified From NARM-DPG Report

Hans-Christian Larsen: Co-Chief
Andrew D. Saunders: Co-Chief
Peter Clift: Staff Scientist

ABSTRACT

Divergent rifted margins are among the most prominent topographic features on our planet. One type of divergent rifted margin development that was discovered barely ten years ago, the so-called volcanic rifted margin, is now recognized as a common development along Pangea.

Leg 152 represents the second in an eight-leg program to investigate rifted margins. Four legs will be devoted to each margin type, volcanic and non-volcanic. Leg 152 will be the first leg to address processes at volcanic rifted margins by drilling a transect of proposed sites at 63°N, southeast Greenland.

The transect is located approximately 550 km south of the original center of the Iceland hotspot in a region of apparent structural simplicity, cratonic lithosphere, and conjugacy to the DSDP-drilled Rockall-Hatton margin, thus forming a complete conjugate margin study. This transect of four proposed sites is designed to constrain the timing of breakup, lithospheric deformation, magmatic processes, flexural deformation rates, emplacement mechanisms, geochemical and volumetric development of magmatism, spreading rate development prior to formation of magnetic isochrons, syn- and post-constructional subsidence of the volcanic carapace, and continuing subsidence of the spreading ridge. Proposed site EG63-1 will sample, through deep basement penetration, the initial volcanism while proposed sites EG63-2 and EG63-4 will sample the central part of the excessive volcanic phase in an area of interpreted steady state wedge formation. Proposed site EG63-2 is planned as a deep basement site in order to recover more rift-proximal deposits, cyclicities, and lava stratigraphy, which will bear on emplacement models, and to study flexural deformation and associated strain rates in detail. Proposed site EG63-3, a shallow basement well, will sample the phase of waning volcanism and increased subsidence. Proposed sites EG-1, EG-2, and EG-3 will provide a complete subsidence profile across a margin showing simple topography. Geochemical data from the Reykjanes Ridge at its intersection with the transect flowline will be used as a reference for the transect.

INTRODUCTION

Volcanic rifted margins (VRMs) are characterized by significant igneous-magmatic crustal accretion and substantial surface volcanism during continental breakup in which eruption occurs largely above sea level for some time after initiation of continental drift. Figure 1 shows the idealized zonation of a volcanic rifted margin into a three-fold division: a landward zone of plateau basalts, sills, and dikes; a central zone of baselap-free, seaward-dipping and offlapping lava flow units (seaward dipping reflector sequence; SDRS); and a seaward zone of seafloor spreading crust generated at increasing water depth. In contrast to non-volcanic rifted margins, the crust does not tend to significantly thin towards the ocean-continent transition (OCT), and a fairly thick crust (20-25 km) with high seismic velocities in the lower crust is observed around the transition zone.

Deformation of the lithosphere, in the sense of emplacement of volcanics, takes place over very large areas in connection with volcanic margin formation. Volcanic rifted margins commonly extend for more than 2000 km along strike and associated CFBs (continental flood basalts) may reach as far inland as 1000 km from the line of continental breakup (Paran and Deccan traps). The surface expressions of any tectonic deformation affecting the pre-existing lithosphere seem much more limited and are mainly found close to the line of breakup.

Evidence for significant tectonic stretching and thinning of the crust and lithosphere (e.g. basement-involved normal faulting) is presently scarce and inconclusive, but could be masked by the CFBs and/or the feather edge of the SDRS. However, the existence of extensive crustal normal faults below several important CFBs (Columbia River, Deccan and East Greenland) recently has been refuted (Hooper, 1990 and Larsen and Marcussen, in press), but is suggested to occur below others (Paran, Peate *et al.,* 1990; Vøring Basin, Skogseid and Eldholm, 1989). On the other hand, CFBs show marked faulting and downflexing along narrow, margin-parallel deformation zones relatively close to the line of breakup. (e.g., western Ghat flexure, the Lembobo flexure, and the East Greenland coastal dike swarm and flexure). These flexures seem to mark the transition from relatively non-deformed lithosphere seaward into deformed and downflexed continental lithosphere below the onlapping feather edge of the SDRS. Clearly, the effective elastic thickness and flexural rigidity of this downflexed continental lithosphere is very much reduced. At present, there is no strong evidence for this weakening of the lithosphere being caused by extensive normal fault thinning of the crust and lithosphere, nor is there any indication of a reactivation of this kind of extensive fault failure later in the breakup process. This suggests different thinning processes of the lithosphere prior to, and during, breakup. Excessive heating from below could be an explanation.

The emplacement mode of the volcanics and the syndepositional subsidence pattern associated with volcanism is clearly different in zones I and II (Fig. 1). A fairly simple concordant infill and subsidence pattern is present within zone I, in strong contrast to the non-concordant, offlapping infill pattern and associated flexural subsidence pattern within zone II (SDRS). This peculiar structure caused an intense debate on the emplacement mode and crustal heritage of the SDRS (Hinz, 1981; Mutter *et al.*, 1982; Smythe, 1983; Roberts *et al.*, 1984; Larsen and Jacobsdottir, 1988; Eldholm *et al.*, 1989). There is now a general consensus, however, that the kinematic model for crustal accretion in Iceland (Palmason 1973, 1980) can qualitatively explain the structure as a continuous process of volcanic accretion emanating from a central linear rift zone. Larsen and Jacobsdottir (1988) demonstrated the potential quantitative applicability of this model using input parameters based on seismic stratigraphy.

A most striking feature of volcanic margins is the rather thick crust and high velocity lower crust found below the outer continental crust and the oldest oceanic crust. It has been suggested that crustal thickening is due to magmatic underplating (White and McKenzie, 1989). The combination of little flexural strength and a thick crust is partly enigmatic but may be compatible with the underplating model.

In terms of asthenospheric processes, explanations for the development of VRMs fall into three different categories: 1) the impact of a transient broad head of a narrow mantle plume at the base of the lithosphere (Richards *et al.*,1989; Griffiths and Campbell, 1990; Duncan and Richards, 1991); 2) lithospheric extension over a pre-existing steady-state mantle plume with a large thermal head (e.g. White and McKenzie, 1989); and 3) convective overturn of asthenospheric mantle ("secondary convection") close to the conjugate trailing edges of the pre-existing thick and cold lithosphere (Mutter *et al.*, 1988).

In the first model a convective instability develops at the base of the lower mantle and eventually becomes detached and rises to the surface. The resulting plume has a large, hot head on top of a narrow stem and it is the impingement of this head on the lithosphere which both triggers continental rupture and accounts for the excess volcanism at a VRM.

The second model proposes build-up of a plume-fed, thermal anomaly beneath pre-rift lithosphere which by itself does not cause excessive extrusive volcanism. However, heating could soften and uplift the lithosphere and predispose it to rupture during a subsequent episode of extension. Adiabatic upwelling of anomalously hot asthenosphere following extension and rupture results in excessive melting and anomalous volcanism and the development of a VRM.

In the third model, convective overturn of the asthenosphere within convection cells of lithosphere thickness at the developing passive margin allows large volumes of mantle to rise toward the surface and melt by adiabatic decompression. The excess magmatism in this case results from the processing of larger volumes of mantle than would be the case at a non-volcanic margin.
These models are not mutually exclusive and components of all three may contribute to the formation and petrological characteristics of VRMs. The first model can be viewed as active rifting with plate tectonic strain transmitted from the plume to the lithospheric plates. The second model has both passive and active elements, and the last model is purely passive (plate-drag).

No model has been published to explain the apparent predominance of flexural deformation over fault failure within the upper lithosphere at volcanic margins. On the basis of NARM-DPG discussions, it has been suggested that the lithosphere is weakened, mainly by heat, to the extent that faults can hardly nucleate, and not more than a thin elastic thickness is maintained within the upper lithosphere at the high strain-rates occurring at volcanic margins. Upper lithospheric deformation is balanced at depth by rapid (lateral?) flow. The zone of viscous material may correspond to underplated bodies.

STUDY AREA

Continental breakup and seafloor spreading started in the NE-Atlantic during late Paleocene time (Fig. 2). The first datable seafloor spreading anomaly is Anomaly 24 and spreading was originally believed to have started just prior to Anomaly 24 (Talwani and Eldholm, 1977). However, the up-to-100 km broad zone of a SDRS landward of Anomaly 24 suggests the existence of an intense period of igneous crustal accretion prior to Anomaly 24 (Mutter *et al.*, 1982, Larsen and Jacobsdottir, 1988). As yet, it is not known exactly when this early and anomalous accretion of igneous crust started and if there are regional variations in the start of volcanism along the line of breakup. However Anomaly 25N has not been identified anywhere, and the pre-Anomaly 24 SDRS is generally associated with a broad magnetic low.

The SDRS is present along the entire northeast-Atlantic conjugate margin pairs. The zone of SDRSs broadens from south to north and toward Iceland, and thus progressively overlaps younger anomalies toward the Faeroe-Iceland-Greenland Ridge. The distribution of SDRSs north of Iceland is more complex due to the more complicated spreading history, but in this region SDRSs formed prior to Anomaly 24 (Eldholm *et al.*, 1989).

Breakup and seafloor spreading was initiated within two different zones of lithosphere. South of Iceland, the line of breakup was a linear, non-segmented rift zone within old cratonic lithosphere; the present spreading axis still follows this simple pattern (Reykjanes Ridge). North of Iceland, breakup took place in lithosphere which was affected by the Caledonian orogeny, followed by Devonian through Cretaceous rifting and basin formation. Several transform faults developed in this region. North of Iceland, spreading later ceased along the Aegir Ridge, and correspondingly the Kolbeinsey Ridge propagated northward. Spreading adjustments also occurred farther north causing local duplication of Anomaly 24 on the Vøring Margin, and a corresponding absence of it and some younger anomalies on the conjugate Greenland margin.

The Iceland hotspot was centered in east Greenland during breakup. The imprint of the Iceland hotspot onshore in east Greenland is recorded in intense plutonism and volcanism in this region (Brooks, 1973, Larsen, 1978, Brooks and Nielsen, 1982, Larsen and Watt, 1985). During mid-Tertiary time the Icelandic spreading center propagated northward and into the Greenland continent forming oceanic crust above, or close to, sea level (Larsen, 1988).

The present effect of the Icelandic hotspot is obvious in seafloor topography as noted by many authors (Morgan, 1983; Vogt *et al.*, 1980; Vogt, 1983). Its modern geochemical effect is traceable along the spreading ridges north and south of Iceland (Schilling *et al.*, 1983). However, the surface expression of the Iceland hotspot seems affected by lithospheric structure; depths of oceanic crust and ridges vary significantly across transform faults and enriched mantle material from the supposed mantle plume below the hotspot seems to spread over a great distance only south of Iceland where no major transform faults are present. However, the higher asthenospheric temperature recorded by basalt chemistry seems to have a more symmetric distribution north and south of Iceland.

In describing the interplay between breakup and the Icelandic hotspot, it is necessary to distinguish between thermal and source compositional effects. It is also expected that lithospheric structures shaped the surface expression of the plume/hotspot during breakup as they do now. Furthermore the thermal and compositional structures may have deformed differently during breakup, and may have differed from present steady-state conditions. The source compositional effect could have been more far-reaching during breakup than at present, but the opposite could also be hypothesized. There is little doubt that the thermal anomaly was more widespread than at present, given the fact that the earliest ocean crust formation took place above sea-level along the entire northeast Atlantic rift zone (White and McKenzie, 1989). But did the rift zone at that time show the same elevation profile as today? Probably not, as this would require the early rift zone to have been elevated to about 3-4 km above sea level close to the center of the hotspot on the Faeroe-Iceland-Greenland Ridge. Such an elevation is not substantiated by any data from either the Faeroes, the Iceland-Greenland Ridge or east Greenland where volcanism preceding subaerial plateau emplacement was in fact submarine (Nielsen *et al.*, 1981).

The east Greenland volcanic sequence is a major CFB province extending from south of Kangerdlugssuaq northward to Shannon Island. The lavas were erupted during magnetic Anomaly 24 (Larsen *et al.*,1989; Upton *et al.*,1980). They may thus overlap in time with the SDRS formed at the same latitude and with CFBs from the Faeroe Islands on the eastern side of the rifted continent (Waagstein, 1988; Gariepy *et al.*,1983).

The lavas are dominantly tholeiitic with the youngest lavas grading towards alkaline compositions. This reflects declining degrees of mantle melting as onshore volcanism waned. Several volcanic cycles can be recognized within the lava sequences and can be related to cycles of fractional crystallization, replenishment, and mixing in crustal magma reservoirs (Larsen *et al.*,1989). The lavas generally resemble Icelandic basalt chemically and isotopically. Some isotopic variation in early lavas from the lower part of the sequence may reflect continental lithospheric contamination (Holm, 1988). The distinctly different Zr/Nb ratios of the various lava formations point to variations in degree of melting and/or slight variations in source composition. It is important to note that the thicknesses of major lithostratigraphic units and minor subunits are on the order of hundreds of meters and several tens of meters, respectively, suggesting that long continuous cores are required to constrain such variations.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To constrain the SDRS emplacement mechanism and the geochemical composition and variation across an archetypal SDRS.

2) To investigate the temporal development of volcanism.

3) To quantify vertical and horizontal crustal accretion rates.

4) To understand and quantify lithospheric deformation, i.e. syn-constructional flexuring, strain rate, subsidence of the shallow igneous crust and deformation of its deeper stratum (continental

lithosphere and new igneous lithosphere) as well as the regional post-constructional subsidence of the new, thick igneous crust.

5) To identify possible source compositional influence from the Iceland hotspot, relating it to temperature, productivity, and spreading rate anomalies.

Specific Objectives and Methodology

Deformation of the Lithosphere

A first order objective is to determine whether rifting is active or passive. Does significant lithospheric deformation (e.g. thinning) take place prior to major volcanism and is it a prerequisite as suggested by one model (White and McKenzie, 1989), or is the lithospheric deformation a consequence of hot asthenospheric material rising to shallow, crustal levels (active rifting) as suggested by other models (Duncan and Richards, 1991)?

Flexure rather than localized fault failure seems to prevail. Deep (500-1000 m) basement samples can constrain both overall timing of this deformation as well as detailed imaging and high-resolution, relative timing of local flexural response from which strain rate, effective elastic thickness of the lithosphere, flexural rigidity and possible lateral flow of material at deeper levels can be calculated. Such data would help to describe asthenosphere-lithosphere interaction, and especially the overall thermal regime. The relative timing of tectonic and volcanic events and the spreading rate during the early phase of spreading, prior to the first datable seafloor spreading anomalies, can be established through drilling. Together with geochemical data, these drilling-based data will help considerably in resolving the controversy between active and passive rifting.

The question of symmetric or asymmetric breakup can be addressed by drilling on either side of the steeply-dipping seaward termination of the wedge. If a syn-constructional fault was active at this position, it might be indicated by dominance of erosional products, derived from a more slowly-subsiding block, which were deposited between the flows of the outermost wedge.

Emplacement and Underplating

Emplacement history, location, and the possible role of underplating can be detailed and investigated by deep (500-1000 m) basement drilling. The drilling data and calibrated seismic 3-D mapping will allow calculation of flow volumes, variations in magma production rates with time, and variations in residence time in shallow crustal magma chambers (primitive versus fractionated magmas, aphyric versus porphyritic). They will also provide data with which to evaluate whether extrusive rocks forming the SDRSs and associated rock units were emplaced during the late stage of rifting, or at breakup and during the initial period of seafloor spreading, and hence where the OCT lies. The data will be used to investigate possible cyclicities, to verify original flow directions, and to analyze for possible anatectic reactions suggesting underplating.

Subsidence of the SDRS

Maximum syn-constructional subsidence (down-flexing) seem to occur on the order of 5 km/m.y. Post-constructional subsidence of the whole SDRS seem to occur on the order of 2.5 km in 50 m.y. Drilling the post-SDRS marine sediments will detail early subsidence history. Syn- and post-constructional subsidence can then be quantitatively compared and will elucidate changes in thermal stage and rheology. On the southeast Greenland margin, no significant elevation difference is present between the main SDRS and "normal" oceanic crust; however, the Vøring Marginal High, with a maximum relief of ~ 3 km, forms a major boundary between the SDRS and "normal" oceanic crust. Drilling data will constrain models which must account for these differences in relative elevation.

Subsidence of Oceanic Rift Zone

Subsidence of the oceanic rift zone (Mid-Atlantic Ridge, or MAR) can be determined from the stratigraphy and subsidence history of sediment at the seaward end of the SDRS. Estimates of when the MAR reached its present "normal" water depth will reveal when the anomalous thermal and dynamic regime abated and when it reached present conditions.

Timing

Timing and duration of volcanism can be constrained by radiometric dating of volcanic rocks; ^{40}Ar-^{39}Ar laser dating of phenocrysts, for example, can yield uncertainties lower than one percent, provided suitable material is available (M. Pringle, pers. comm.). Drill samples can also provide material for tephrochronologic studies incorporating onshore NAVP data as well. Paleo-secular variation of the magnetic field measured from oriented cores would provide high-resolution relative dating on the order of 5-10 .k.y. Late Paleocene and early Eocene biostratigraphy south of the Faeroe-Greenland Ridge should also be precise (W. Berggren, pers. comm.).

Origin of Intra-Basement Reflections

Analysis of drilling data from ODP Site 642 suggests that individual flows and sediment layers are not sufficiently thick to produce the observed dipping reflections. It is more likely that superimposed signals from composite rock units are the cause. Detailed seismic modelling will be possible when drilling data from several deep (500-1000 m) sites in the SDRSs are available. This, in turn, may yield correlations between dipping reflection characteristics and emplacement parameters, e.g., production rates and constructional environment.

Magmatism: Relative Impact of Different Models

Because the parental magma of basalts in the three different models originates at different mantle depths and follows a different time-temperature path, petrological and geochemical studies of drill-core samples and estimates of magma production rates will constrain the relative contributions of the three processes.

The transient plume head and steady-state plume models (models 1 and 2) would predict similar, although not identical magma chemistries. Both are likely to be characterized by initially strong thermal and source composition anomalies over a large region. Offshore and onshore volcanic sequences would show evidence of high mantle temperatures and therefore onset of melting at great depth; in the case of the plume head model, inferred mantle temperatures may be extremely high. Magnesium-rich picritic liquids formed by extensive melting may be common. In addition, alkaline magmas formed by lower degrees of melting at great depth may occur. With time, these thermal effects may be expected to dissipate, particularly in the case of the plume head model in which a great deal of the thermal energy will be used in melt formation at an early stage of rifting.

Both models predict an associated source composition anomaly near the locus of plume upwelling; depending on where in the mantle these plumes originate, they may also show different enriched chemical signatures. For the transient plume head model, at points distant from the locus of plume upwelling, samples of progressively younger SDRS should show a concomitant diminution of inferred mantle temperature and source composition anomalies. In addition, mixing of lower mantle with entrained upper mantle in the plume head may produce rapid fluctuations in magma composition reflected, for example, in variations in trace element and isotopic systematics with stratigraphic height in the volcanic sequence. Significant contamination of the earliest emplaced basic lavas could be a hallmark of this model because the mantle melts have to actively rift and traverse a thick and only moderately fractured crust. For the steady-state plume model, however, at points distant from the locus of plume upwelling, the SDRS may show a decoupling between the thermal and source composition effects, as is presently seen along the Reykjanes Ridge.

The two plume models will also differ in the relative timing of magmatism and rifting. In the case of the plume head mode, the impact of the plume head drives rifting, and one would expect that magmatism and rifting would be closely associated in time. In the case of the steady-state plume, however, the pre-existing plume may simply act to weaken the pre-rift lithosphere and voluminous volcanism may both precede and follow rifting.

Convective Overturn

The convective overturn model should produce offshore volcanic sequences whose composition remains essentially constant with time and shows evidence for shallow melting. In the extreme case, i.e., in the absence of an associated thermal anomaly, all of the offshore volcanic rocks would approach N-MORB compositions, because only shallow, depleted mantle sources would be involved. The transient phase of excess volcanism would be relatively short and show rather non-systematic variation along rifted margins compared to models including a plume component.

Plume Components

Plume components from deep mantle sources in the VRM sequences can be identified and quantified by geochemical studies. Although plumes differ from one another in source composition, they commonly show enrichments in trace elements (e.g. light rare earth elements, or LREE, barium, thorium) and distinct radiogenic isotopic ratios of strontium, neodymium, and lead (e.g., Sun *et al.*, 1975; Zindler and Hart, 1986). In addition, modelling of major element variations in oceanic tholeiites has shown that variations in sodium content and CaO/Al_2O_3 ratios are particularly sensitive to the extent of melting and FeO is sensitive to the pressure of melting (Klein and Langmuir, 1987; McKenzie and Bickle, 1988).

Temporal and Geographical Variations

Systematic temporal and geographical variations in source composition and in extent and pressure of melting can be expected to be discerned in the volcanics drilled at VRMs. These can only be documented by a comprehensive drilling program consisting of several, longitudinally-spaced transects encompassing a few deep holes penetrating at least 500 m into basement. The longitudinal spacing is required to study any effects related to distance from the plume center. Transects are designed to resolve long-term petrogenetic trends across, and along, margins. Deep holes in turn will allow assessment of shorter-term variation and cyclicity in source composition, mixing processes, crustal residence time, and production rate.

DRILLING PLAN/STRATEGY

Transect EG63 (Fig. 3) is located approximately 550 km south of the original center of the Iceland hotspot close to 63°N in an area of cratonic basement that suffered little or no tectonic stretching prior to breakup (Larsen 1988,1990). However, earlier rifting occurred in the Rockall Trough 500-700 km east of the initial line of breakup (Joppen and White, 1990) and minor rifting in the Rockall Basin 200-300 km east of the breakup line could also be present (M. S. Andersen, pers. comm., and drilling proposal 394).

The location of the hotspot center is particular well-constrained in east Greenland (Brooks, 1973; Brooks and Nielsen, 1982; Nielsen *et al.*, 1981; Larsen, 1988). The landward part of the OCT is developed as a coast-parallel, intense dike swarm and crustal flexure of the cratonic basement rocks (Nielsen, 1978; Meyers, 1980). This structure can be followed along the inner to mid shelf (Larsen, 1978) southward to the location of the southeast-Greenland transect at about 63°N.

The drilling transect starts on the mid to outer part of the narrow shelf only about 40 km offshore. The inner to mid shelf is floored by basement rocks with a thin Quaternary cover. The outer shelf is floored by the landward feather edge of the southeast-Greenland SDRS covered by thin Paleogene and thicker Neogene sediments. The planned drilling transect extends seaward across the wide southeast-Greenland margin for about 150 km and terminates in oceanic crust of Anomaly 24 age close to the seaward end of the SDRS. The seafloor spreading anomaly pattern is simple and well developed in this region and allows easy determination and precise estimates of spreading rates. Spreading rates from late 24R time to Anomaly 23R time seem to have been anomalously high around 3 cm/yr (half rate, Larsen, 1980) compared to present day values close to 1 cm/yr. The seaward termination of the southeast-Greenland SDRS is diachronous, with termination prior to Anomaly 24B in the very south and progression of the SDRS onto slightly younger crust further north and much younger crust close to the Iceland hotspot.

The SDRS is particularly simple and well developed in the region of the main transect. It attains a uniform geometry and steady state development from around 25-40 km seaward of its feather edge and the landward part of the OCT, and maintains the same architecture until its termination. The SDRS is seismically imaged to great depth (5-7 km, Larsen and Jacobsdottir, 1988) and is, quite uniquely, mappable along strike for very long distances. The along strike study of individual SDRS units bound by particularly strong reflectors shows that the southeast-Greenland SDRS indeed comprises wedge-shaped units which continue rather uniformly along strike for more than 100 km parallel to the OCT and the seafloor spreading anomalies. These observations and application of the kinematic model for crustal accretion in Iceland (Palmason, 1973 and 1980) led Larsen and Jacobsdottir (1988) to conclude that the southeast-Greenland SDRS consist of mainly subaerial erupted basalts that originated form narrow (5 km) and very long (100-200 km or more) fissure zones or small rifts parallel to the seafloor spreading isochrons. These fissures or rifts probably showed little faulting and relief across the rift zone and little topographic variation along strike. The average volcanic productivity rate was likely to exceed present day levels from Iceland by a factor of three at minimum. Seafloor spreading in the sense of new igneous crustal and lithosphere accretion took place at similar high rates during most of the SDRS formation. The total stratigraphic thickness of the whole SDRS, summing maximum thicknesses at depth, is about 50 km (Larsen and Jacobsdottir, 1988). The simplicity of the southeast-Greenland SDRS formation is also reflected in the very smooth basement topography across and along the SDRS making the area an ideal place for regional subsidence studies.

PROPOSED SITES

The transect strategy is to first drill the oldest part of the SDRS (feather edge) to provide overall control on the timing of the SDRS (proposed site EG63-1) and the initial geochemical signature as well as the initial volcanic productivity rate. Basement penetration to 500 m is suggested (Table 1).

The second site (proposed site EG63-2) is approximately in the center of the SDRS (Table 1). This site is the ideal place for a deep well into the wedge, because the wedge is well developed and well imaged here (including along strike data) and a steady state development clearly has been established. Furthermore, this is a natural place to test the geochemical shift from initially more anomalous, and perhaps also quite variable, compositions towards less anomalous and stable conditions that are likely to have taken place. It is suggested to penetrate basement to 500 m and deepen the proposed site to 1000 m, if required by initial results (deformation studies, strain rate, cyclicities). A strong thermal anomaly, however, still must be expected to be present.

The third site (proposed site EG63-3) is placed at the seaward end of the SDRS in a position where some deep SDRS units still can be discerned at depth but the shallow igneous crust has lost this typical development. This position most likely represents the transition to submarine volcanism. Although the spreading center probably did not subside rapidly to present normal depths and still was fairly shallow, this change signals increased subsidence of the system, and therefore may show a geochemical gradient toward more typical N-MORB compositions and a less pronounced thermal anomaly. Basement penetration to 150 m or bit destruction is suggested (Table 1).

The fourth site (proposed site EG63-4) is placed landward of proposed site EG63-2 and is contingent upon the results EG63-2 (Table 1). If proposed site EG63-2 shows a dramatic change from proposed site EG63-1, then there is a need for further locating and detailing this change. Basement penetration to 150 m or bit destruction is suggested. Proposed site EG63-4 is located 20 km landward of proposed site EG63-2 making a stratigraphic overlap between the two sites possible if proposed site EG63-2 is deepened to about 1000 m into basement. If required, proposed site EG63-4 also can be deepened to 1000 m (not proposed as yet) and the two sites will recover a total 2000 m continuous SDRS stratigraphy. This recovery is measured at the top of the SDRS with the thinnest development of stratigraphic units. The total recovery by such deep offset drilling equate about 10 km coverage at depth or roughly 20% of the total estimated stratigraphic thickness of around 50 km. A possible deepening of proposed site EG63-1 would further increase the stratigraphic coverage to about 30%. At present, only deepening of proposed site EG63-2 is considered high priority and has been included in the drilling plan. It is important to obtain at least one really deep basement well because the emplacement model predicts that biased sampling towards rift-distal flows will be a consequence of shallow basement sampling only (Palmason, 1980; Larsen and Jacobsdottir, 1988).

The four proposed sites together will provide extremely good control on the subsidence history across this margin for integration with the seismically-documented facies developments on the shelf, slope, and abyssal plain which, in turn, have clear bearings on the overflow history of the Faeroe-Iceland-Greenland Ridge and formation of regional North Atlantic unconformities (Miller and Tucholke, 1983; Miller *et al.*, 1985; Larsen, 1990). An east Greenland regional shelf unconformity separating the strongly prograding clinoform sequence from overlying concordant and horizontal strata above will be sampled at proposed site EG63-1. This striking unconformity was suggested by Funder and Larsen (1989) and Larsen (1990) to reflect an approximately 1-2 Ma old, complete glaciation of the shelf by a grounded shelf ice. Drilling will test this hypothesis and determine how the shelf became a deep water shelf in the very recent.

In addition, the transect is located along the 61°N flowline (61°N at the Reykjanes Ridge) which, according to isotopic and LREE data, is within the distal portion of the source signature from the Icelandic plume. Formation of the SDRS wedge terminated between Anomaly 24B and 24A along this transect and flowline.The transect will show whether the source compositional anomaly extended farther south during breakup than it does at present. If the composition of the older part of the SDRS on the main transect is similar to basalts recovered from the conjugate Hatton margin farther south (i.e. N-type MORB from around the 58°N flowline) and from the MAR around 58°N, substantial decoupling of the thermal and source compositional anomaly during breakup is suggested. If, on the other hand, the older portion of the SDRS displays a source compositional anomaly (i.e. Icelandic or transitional compositions), then somewhere along the flowline (i.e. along-transect) there must be a change in composition toward N-type MORB. In either case, important information will be obtained about the spatial and temporal extent of the compositional versus thermal plume components during breakup.

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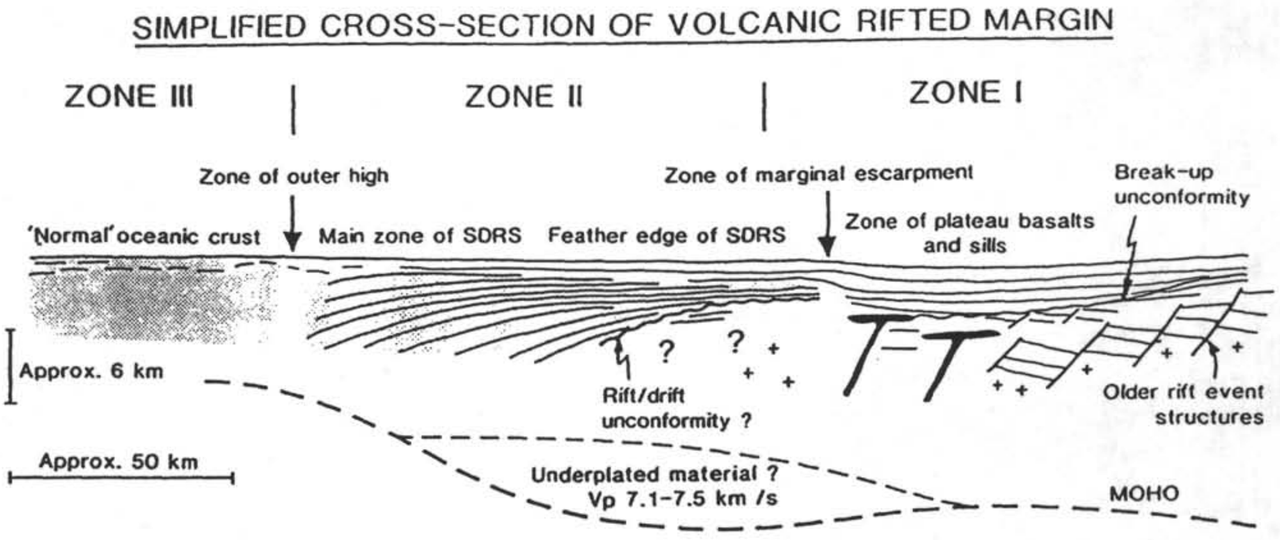

Figure 1a. Idealized zonation of a volcanic rifted margin. Zone I may be a 'sedimentary equivalent' to the Zone II volcanic edifice and may, or may not, be floored by older rift basins. If break-up takes place in a cratonic area as in SE Greenland, Zone I may develop only very little or no pre- to syn-rift sediments and merely is a gentle basement arch.

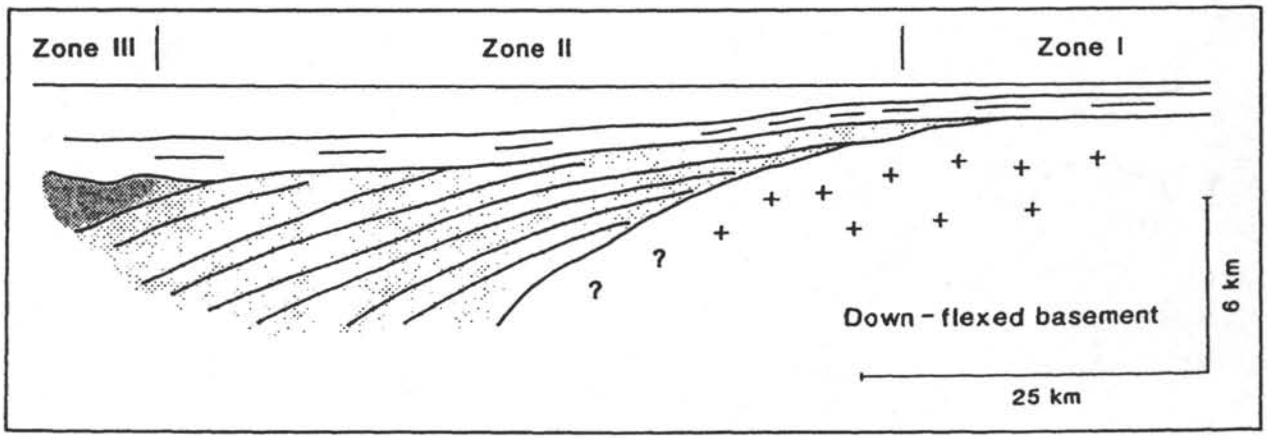

Figure 1b. Schematic cross section of a volcanic margin development in a cratonic area. However, some syn-breakup sediments are likely to occur between basement and onlapping SDRS wedge. Also some fault failure within the continental basement may occur although overshadowed by the significant flexural deformation. A CFB may build up within Zone I. Note the differences from Fig. 1a. Most real examples show variations between these two different developments.

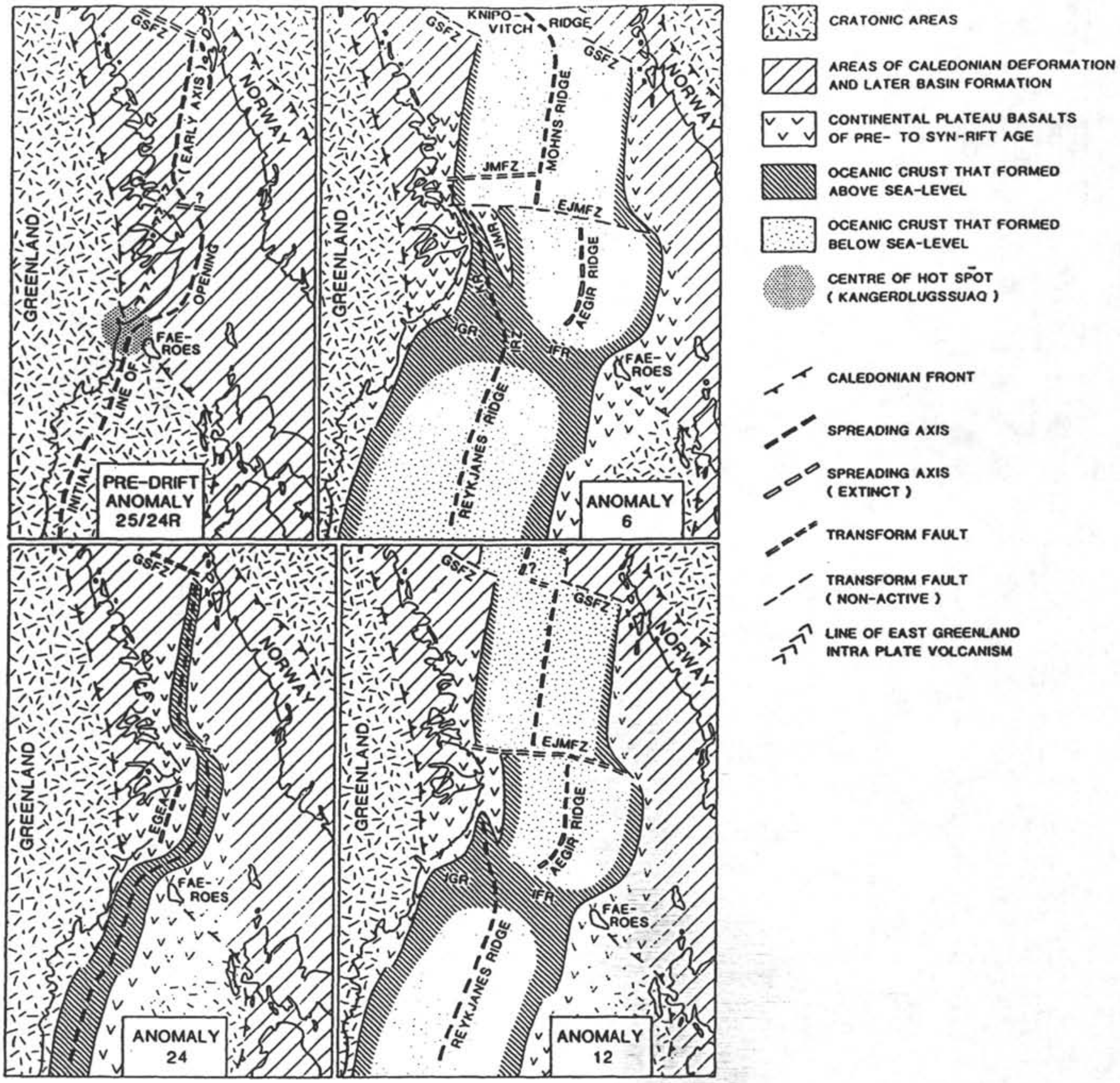

Figure 2. Opening of the NE-Atlantic. Note the mid Tertiary development of a spreading axis propagating northward from Iceland causing a secondary SDRS wedge to form. This wedge is much less well developed than the early Tertiary breakup wedge. From Larsen, 1988.

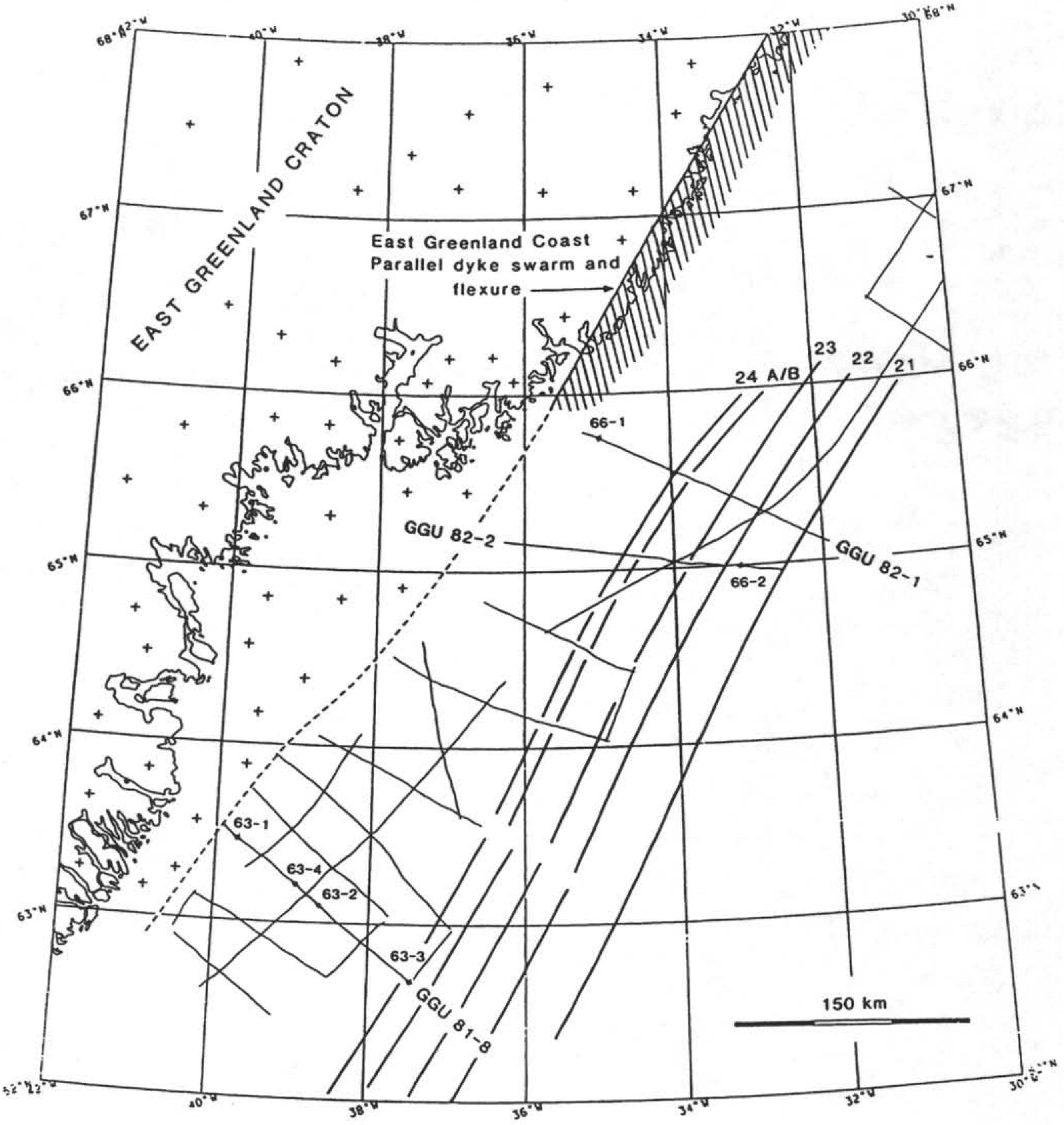

Figure 3. Position of proposed Southeast Greenland sites, Leg 152 transect at 63°N.

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: EG63-1	**PRIORITY:**	**POSITION:** 63°27.46'N, 39°43.30'W
WATER DEPTH: 520 m	**SEDIMENT THICKNESS:** 440 m	**TOTAL PENETRATION:** 940 m
SEISMIC COVERAGE: MCS Line GGU81-08 SP 320		

Objectives: To determine the age, magnetic polarity, composition, lava stratigraphy, volcanic productivity rates, cyclicities, possible continental lithospheric contamination, and geochemical signature of the continental feather edge of the marginal seaward dipping volcanic sequence. To determine the vertical movements of the inner part of the wedge. To constrain timing of overflow of the Iceland Greenland Ridge and of the extensive late Neogene to Quaternary unconformity by radiometric and biostratigraphic age determination.

Drilling Program: APC, XCB, and RCB coring.

Logging and Downhole Operations: Standard strings plus FMS and core orientation.

Nature of Rock Anticipated: Glaciomarine on Paleogene shelf sediments and basalt with some interbedded sediments.

SITE: EG63-2	**PRIORITY:**	**POSITION:** 63°05.52'N, 38°38.10'W
WATER DEPTH: 1875 m	**SEDIMENT THICKNESS:** 1220 m	**TOTAL PENETRATION:** 1720 m
SEISMIC COVERAGE: MCS Line GGU81-08 SP 1682		

Objectives: To determine the age, composition, and geochemical signature (and its variation) of basalts in the middle zone of the seaward dipping reflector sequences. To investigate the subsidence of basalts during and after deposition.

Drilling Program: APC, XCB, and RCB coring and reentry. Deepening to 1 km dependent upon the results from this site and EG63-1.

Logging and Downhole Operations: Standard strings plus FMS and core orientation.

Nature of Rock Anticipated: Pelagic Neogene (contourites?) on Paleogene shelf sediments and basalts with some interbedded sediments.

SITE: EG63-3	**PRIORITY**	**POSITION:** 40.45'N, 37°27.26'W
WATER DEPTH: 2095 m	**SEDIMENT THICKNESS:** 1420 m	**TOTAL PENETRATION:** 1470 m
SEISMIC COVERAGE: MCS Line GGU81-08 SP 3233		

Objectives: To determine the geochemical signature (plume components in particular) of the basement rock. To investigate the increased subsidence within the system reflected by the presumed transition to submarine spreading. To investigate the deepening of the basin south of the Iceland Greenland Ridge, the overflow of this ridge and the regional North Atlantic unconformity formation.

Drilling Program:APC, XCB, and RCB coring.

Logging and Downhole Operations: Standard strings plus FMS.

Nature of Rock Anticipated: Pelagic Neogene (contourites?) on Paleogene shelf sediments and pillow basalts, hyaloclastics with thin interbedded sediments.

SITE: EG63-4 **PRIORITY:** **POSITION:** 63°12.43'N, 38°56.42'W
WATER DEPTH: 1840 m **SEDIMENT THICKNESS:** 1180 m **TOTAL PENETRATION:** 1470 m
SEISMIC COVERAGE: MCS Line 81-08 SP 1291

Objectives: To determine the age, composition, and geochemical signature (and its variation) of the oldest deep-water section of basalts in the seaward dipping reflector sequences.

Drilling Program: APC, XCB, and RCB coring and reentry. 150 m penetration into basement or bit destruction. Possible deeper penetration is warranted by initial results.

Logging and Downhole Operations: Standard strings plus FMS and oriented cores.

Nature of Rock Anticipated: Pelagic Neogene (contourites?) on Paleogene shelf sediments and basalts with thin interbedded sediments.

LEG 153

GENERATION OF OCEANIC LITHOSPHERE AT SLOW-SPREADING CENTERS: DRILLING IN THE WESTERN WALL OF THE MARK AREA

Modified From Proposal 369-Rev 2

Jeffrey A. Karson: Co-Chief **Mathilde Cannat: Co-Chief**
To Be Named: Staff Scientist

ABSTRACT

Leg 153 is scheduled to drill the lower crust and upper mantle created at a slow-spreading ridge. Two sites have been selected in the MARK area of the Mid-Atlantic Ridge to achieve deep penetration into: 1) an exposed gabbro massif (as well as possible penetration of a master fault along which the gabbro has been unroofed during amagmatic extension); and 2) an exposed residual mantle section along strike to the south of the gabbroic massif.

Both proposed sites are along the western rift valley wall and the peridotite is an example of a mantle exposure in a non-transform setting. Studies at these proposed sites will address multiple objectives and a variety of tectonic, petrological, hydrothermal, and geophysical problems that are contingent upon the penetration of a long gabbro section and a long mantle section in slow-spreading lithosphere. The area and the gabbro site also have the future potential to achieve complete penetration of the gabbro "layer" through an offset strategy as well as penetration of the "petrologic", and possibly the "seismic", Moho transition as the crust appears somewhat thinner in this region, based on seismic and gravity evidence and the occurrence of peridotite exposures at the surface along strike.

In addition, major tectonic questions concerning the mechanisms responsible for deep crustal and upper mantle exposures along the rift valley wall and the formation of rift valleys by symmetrical or asymmetrical extension may also be addressed. In magma-starved regions like the MARK area, drilling of the deep crust and upper mantle could also lead to modification of the traditional seismically-based concepts of the architecture of slow-spreading crust and upper mantle.

INTRODUCTION

Two categories of data are critical to an understanding of oceanic spreading dynamics: 1) data on the magmatic processes which govern the formation of the oceanic crust (partial melting of mantle rocks, melt segregation and pooling, magmatic differentiation); and 2) data on the tectonic processes associated with the rise of new asthenospheric material, and with the stretching of the lithosphere, in the axial domain. These data may be derived from geophysical experiments, mechanical modelling, and submersible and sampling surveys. To some extent, the understanding of oceanic ridge dynamics is also based on data acquired in ophiolitic massifs; but the relevance of such field results to mid-oceanic ridges is often questionable, as it is difficult to ascertain the geological context in which these ophiolites were formed (large or small, fast- or slow-spreading oceanic basin, marginal basin, subduction zone?).

To understand the processes occurring in the lower crust and the mantle, direct information is essential and can be obtained from drill cores. The study of plutonic rocks is fundamentally stratigraphic. To date, however, most available oceanic rock samples have been dredged or collected by submersible, providing no stratigraphic information such as the spatial relationships and nature of the contacts (tectonic, cumulative, intrusive) between the various rock types and the geometry of the internal structure displayed by the rocks (foliations, lineations, fractures, veins, dikes). Drilling provides relatively continuous cores and therefore allows for a good assessment of lithological and structural relationships. Drilled samples are also oriented. The attitude of the vertical is known, and the dip of the various sets of structures may be measured. In addition, there are ways to constrain the azimuth of the observed structures, either by using paleomagnetic data, or by matching the cores with the images obtained with the FMS logging tool (formation microscanner). A variety of other potential logging experiments (e.g., geochemical, sonic, in-situ stress evaluation) may produce an even better assessment of their lithological and structural context.

Recent studies of slow-spreading ridges suggest that magma chambers are not permanent and that spreading mechanisms are controlled by periods of magma production followed by amagmatic extension. A consequence of this intermittent magma production is the absence of a permanent magma chamber. The study of gabbros drilled at Site 735B (Leg 118) suggest that they formed in a chamber filled with crystal mush rather than liquid, which can be easily deformed (Dick *et al.*, 1991). Igneous stratigraphy is complicated by injections of crystal mush (Dick *et al.*, 1991; Bloomer *et al.*, 1991). Early deformation provides channels for early seawater penetration in the lower crust, before the end of magmatic crystallization (Cannat *et al.*, 1991; Mével et Cannat,

1991) which contribute to the cooling and thickening of the lithosphere. The interplay between magmatism, deformation, and hydrothermalism is therefore typical of accretion at slow-spreading ridge. As a result, the ridge morphology is characterized by the almost ubiquitous presence of a well defined axial valley bordered by walls generally 1000 to 1500 m high, as opposed to fast-spreading ridges. The origin of this axial valley is interpreted as the response of surface topography to mantle dynamics and magma budget. However, the mechanism leading to the formation of the axial valley is not well understood and two main hypotheses have been proposed: 1) the mechanism is symmetrical and the valley is bordered by normal faults on each side, and 2) the mechanism is asymmetrical and the axial valley is created by asymmetrical detachment faulting along low-dipping normal faults. These detachment faults form during amagmatic stages, when the magma supply is low and spreading causes the stretching of the lithosphere. Asymmetrical stretching seems to characterize the areas in the vicinity of major transform faults.

Another characteristic of slow-spreading ridges is the common exposure of rocks of deep origin (gabbros and mantle peridotites) in the axial valley walls and even within the axial valley. Although the mechanism responsible for the emplacement of these rocks at the surface is certainly linked with the formation of the axial valley, particular environments may favor this process. This is particularly true for mantle peridotites which, in a so-called normal oceanic crust, should come from more than 5 km depth. Different mechanisms have been proposed to explain the presence of mantle rocks outcropping on the seafloor, such as 1) very high extension of normal crust related to detachment faulting during amagmatic spreading, 2) very thin crust related to low magma budget, and moderate extension, and 3) serpentinite diapirism related to penetration of seawater down to the mantle along major fault planes. The proximity of a major transform fault may also favor the exposure of rocks of deep origin by the formation of intersection massif.

Petrological and geophysical studies suggest that magmatic accretion at slow-spreading ridges varies, not only with time, but also along axis and is therefore a three dimensional process (Dick, 1090; Lin *et al.*, 1990) related to the segmentation. Segments are defined by non-transform and transform discontinuities. Mantle upwelling occurs at discrete centers and magma production varies along axis. Therefore, crustal thickness is likely to vary along axis.

All these considerations suggest that the lithosphere created at slow-spreading ridges may not correspond to the simple layered model, but is complicated by focused magmatic accretion and by tectonism related, in part, to amagmatic extension.

To better understand the processes involved in the formation and evolution of this oceanic lithosphere, two holes have been proposed, one in the lower crust and one in the shallow mantle, exposed along strike in the western wall of the M.A.R. (Figs 1 and 2). It may be argued that a major drawback of drilling directly in exposed gabbros and peridotites is that the processes of emplacement of such deep rocks in the seafloor probably left their imprint. The gabbroic or mantle rocks found in the upper levels of the oceanic lithosphere may therefore not be representative of "normal" mid oceanic lower crust and upper mantle. However, based on the large number of places where gabbros or ultramafics crop out directly on the seafloor in the Mid-Atlantic Ridge domain, in a slow-spreading environment the processes leading to the emplacement of deep rocks on the seafloor are actually inherent to spreading dynamics and it is possible to separate the successive events with a careful study of the samples.

STUDY AREA

Regional Setting

Two drill sites are proposed along the western wall of the MARK area (Mid-Atlantic Ridge/Kane fracture zone) where low angle normal faults as well as gabbros and peridotite outcrops have been documented by both the *Alvin* (Karson and Dick, 1983; Karson *et al.*, 1987) and the *Nautile* (Mével *et al.*, 1991) dives.

The MARK area is certainly the most studied portion of the Mid-Atlantic Ridge. Its surface geology and crustal structure are constrained by SeaBeam bathymetric mapping (Detrick *et al.*, 1984), SeaMare imaging (Kong *et al.*, 1988), seismic surveys (Cormier *et al.*, 1984; Purdy and Detrick, 1986; Detrick *et al.*, 1989), magnetic surveys (Schulz *et al.*, 1988), gravity surveys (Morris *et al.*, 1991), submersible studies with the *Alvin* (Karson and Dick, 1983; Karson *et al.*, 1987) and the *Nautile* (Mével *et al.*, 1989, 1991) and previous DSDP (Site 395, Shipboard Scientific Party, 1977) and ODP (Sites 648, 649 and 670, Shipboard Scientific Party, 1990) drilling.

A SeaBeam map of the MARK area was produced during the survey preliminary to Leg 106 (Detrick *et al.*, 1984) and allowed morphological and structural investigations (Kong *et al.*, 1988; Pockalny *et al.*, 1988). The MARK area ridge segment is relatively linear with no major offset. The rift valley varies in width from 10 to 17 km. The inner floor deepens towards the north from 3500-4000 to 6100 m in the nodal basin marking the intersection with the Kane Fracture Zone. The ridge/transform intersection is characterized by a strong topographic asymmetry (Karson and Dick, 1983); the inside corner is a topographic high (1300 mbsl) contrasting strongly with the much lower outside corner (3500 mbsl).

Cormier *et al.* (1984) suggested that the crustal thickness decreases towards the transform intersection. A seismic line along axis distinguished two domains with contrasting deep crustal structure; the northern cell which extends from the nodal basin down to 23°18'N and possesses a seismic crustal thickness of 4-5 km, and the southern cell which possesses a seismic crust 6-7 km thick (Purdy and Detrick, 1986). A wide transition zone (23°18'N to 23°05'N) separates these two cells. This transition zone corresponds with both a probable offset of magnetic anomalies (Schulz *et al.*, 1988) and a change of rift valley morphology (Kong *et al.*, 1988) and has been interpreted as a zero offset transform fault (Purdy and Detrick, 1986).

The morphology of the inner floor is well constrained by SeaBeam bathymetric mapping (Detrick *et al.*, 1984), SeaMarc I imaging (Kong *et al.*, 1988), and *Alvin* (Karson and Dick, 1983; Karson *et al.*, 1987; Karson and Brown, 1988; Brown and Karson, 1988) and *Nautile* (Mével *et al.*, 1988; Gente *et al.*, 1991) dives. A band of small volcanoes forms the axial topographic high of the southern cell. In the zero offset transform domain, the axial high is offset to the west, and the thick sediment cover suggests no recent volcanic activity. However, transverse structures are scarce. In the northern cell, a continuous neovolcanic ridge forms the axial high. The Snake Pit hydrothermal field (ODP Leg 106 Scientific Party, 1986) is located on this ridge.

Lower crustal and upper mantle rocks crop out on the western wall of the axial valley and are documented by previous dive and drilling programs.

Dredges as well as *Alvin* (Dick *et al.*, 1981; Karson and Dick, 1983) and *Nautile* (Mével *et al.*, 1991) dives identified a section of gabbros and metagabbros, metabasalts, metadiabases, and basalts on the inside of the intersection massif. These rocks are cut by moderately dipping, east-facing faults and the collected samples often display slickensides. Some fault planes can be followed for several hundred meters and may correspond to "master faults". These older structures are sometimes cut by higher angle faults. The gabbroic samples collected from this massif vary from olivine gabbros though gabbronorites and ferrogabbros to plagiogranites. The most differentiated gabbros were collected closer to the transform fault (Marion *et al.*, 1991; Marion, in prep). These gabbros display ductile as well as brittle deformations structures, which favor seawater penetration and hydrothermal recrystallization (Marion *et al.*, 1991). A drilling attempt in the gabbros at Site 669 (Leg 109) failed because of the lack of a guide base. A recent side-scan and video survey of the Kane transform wall at the inside corner of the RTI has identified layered gabbroic rocks along the wall and provides a three dimensional view of this extensive massif (Delaney and Karson, personal communication, 1992).

During the 1986 *Alvin* cruise, two serpentinite outcrops were discovered on the western wall of the axial valley (Karson *et al.*, 1987), one at 23°10'N in the domain of the zero-offset transform fault, and the other at 23°21'N at the limit of the northern cell. The southern outcrop was drilled during Leg 109. In 1988, three dredge hauls by the Akademik Mstislav Keldysh on the northernmost outcrop recovered more peridotites (Gente *et al.*, 1989). This outcrop was also explored during two dives of the *Nautile* (Mével *et al.*, 1991). Both sites are located in the area of the zero-offset transform fault. It is therefore possible that the emplacement of these mantle peridotites is linked with spreading processes specific to the transitional domain between the northern and southern segments. Normal fault planes also occur in the peridotite outcrops but they are not as low-dipping or as continuous as in the gabbros. Peridotites are predominantly serpentinized, clinopyroxene-bearing harzburgites (Juteau *et al.*, 1990; Tartarotti *et al.*, in prep.; Casey *et al.*, in prep.). Localized high temperature shear zones are underlined by synkinematic hornblende (Casey, 1986). Some zircon-bearing dikelets occasionally cross-cut the peridotites. Neither the lateral contact between the peridotites and the gabbros nor the contact between the peridotites and the overlying basalts have been observed.

A map of residual gravity anomalies calculated in the MARK area by Morris and Detrick (1991) shows a high beneath the discordant zone separating the northern from the southern cell. This is in accordance with the onbottom gravity measurements performed with the *Nautile* in 1988, which also showed the presence of a gravity high beneath the northern peridotite outcrop (Bergès, 1989). This high is interpreted by Morris and Detrick in terms of crustal thinning (1-2 km thinner than normal). Similar crustal thinning beneath non-offset discontinuities have been documented along the M.A.R. south of the Atlantis Fracture Zone (Lin *et al.,* 1990) and is attributed to focused magmatic accretion.

An offaxis bathymetry, gravity, and magnetics survey of the area was conducted with the *R/V Atalante* up to Anomaly 5 (Gente *et al.*, 1991). One spectacular result of the cruise was to show how segmentation varies with time. A series of elongated oblique depressions bound rhomboid- or lozenge-shaped domains which are interpreted to represent the evolution of segments with time. In terms of magma supply, the center of these lozenges may correspond to focused magmatic accretion. The magmatic crust should therefore be thick in the center and thin at the edges. The peridotite outcrops of the MARK area and DSDP Site 395 (where peridotites were drilled close to the surface) are located in one of these depressions, and therefore in an area where the magmatic crust is expected to be thin. Processing of the gravity and magnetics is in progress.

Petrologically, the MARK area appears to be a region along the M.A.R. that reflects a low degree of melting. For example, a simple plot of latitude versus unfiltered Na_2O (or Na8.0) and CaO/Al_2O_3 along the M.A.R. from the Azores to 10°N shows that Na_2O concentrations are generally highest, and CaO/Al_2O_3 ratios are generally low, in the MARK region, changing systematically towards the Azores plume region. These melt composition appear to indicate that subaxial mantle in the MARK region is characterized by a low degree of melting. This is also reflected in the composition of chrome spinel which display very low Cr/Cr+Al ratios of 0.2-0.3 (Juteau *et al.*, 1990; Casey *et al.*, in prep; Tartarotti *et al.*, in prep). This ratio can be used as an index of partial melting and also shows that the mantle is not extensively depleted by partial melting. The MARK area is not only characterized by slow-spreading, low degrees of melting and probable low magma supply, but also by N-type MORB. Thus the geochemical character of the MARK area provides one of the near-end member examples of the N-type (non-plume) crust in a slow-spreading environment.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

Leg 153 will investigate a number of petrological, hydrothermal, structural, and geophysical aspects of the gabbros at slow-spreading centers, including:

1) The basic structure and composition of the lower crust.

2) The nature of parental magma, the composition and periodicity of magma input, and fractionation and mixing events.

3) Magmatic evolution as defined by fine-scale studies of cryptic chemical variations through the crust.

4) The size, architecture, and longevity of the magma chamber.

5) Cumulate processes; in particular melt/rock ratios and melt migration paths within the cumulate rocks.

6) Structural changes throughout the lower crust; in particular the extent of deformation, localization of strain, etc.

7) Avenues for hydrothermal fluid penetration.

8) Physical properties in the plutonic part of the crust.

A study of the mantle peridotites will provide clues to:

1) The chemical nature and evolution of the upper mantle beneath the ridge.

2) The geometry of magmatic structures.

3) Deformation structures as related to asthenospheric flow and mantle incorporation into ridge axis lithosphere.

4) The extent to which ophiolites represent samples of ridge-generated lithosphere.

5) Symmetrical/asymmetrical axial lithosphere stretching, deviatoric stresses, and strain rates in axial regions, etc.

6) The mechanisms by which water penetrates the mantle and the role of serpentinite diapirism and swelling.

Specific Objectives and Methodology

A single hole drilled into the gabbro exposed at the intersection massif could address major questions concerning the nature of the plutonic levels at a slow-spreading crust. A number of recent investigations of slow-spreading crust appear to question the concept of a simple layer-cake stratigraphy and even the basic lithological and petrological organizations of crustal and upper mantle rocks. Drilling within a gabbroic complex along the rift valley could serve to clarify these long standing questions concerning the basic structure and composition of the lower crust.

Whereas knowledge of the shallow crust and basalt petrology is extensive at mid-ocean ridges, many of the hypotheses that have been proposed for the generation and evolution of basalts are conjectural and can be only tested, and concepts fundamentally advanced, by conducting detailed studies of long, continuous cores of cumulate mafic and cumulate and residual ultramafic rocks. Stratigraphic context is essential. Likewise, many of the alteration, structural, and physical property studies rely on stratigraphic context and continuity of section. Questions that will be addressed by drilling at the gabbroic site could not be completely addressed by conventional sampling techniques like dredging or submersible sampling because of a lack of stratigraphic continuity and/or complete exposure. For example, detailed mineral chemistry, whole rock and textural studies require continuous core in order to make fundamental advances. Studies of cryptic chemical variations in plutonic sections of ophiolites and core from Site 735B have shown that this data can yield information concerning the nature of parental magma and periodicity of magma input, fractionation, and mixing events within subaxial magma chamber, and can serve to define magma chamber boundaries where multiple chambers existed, to identify magma chamber and cumulate processes, and to define melt/rock ratios and melt migration paths within cumulate rocks. The scale of these variations can range from a centimeter to hundreds of meters and documentation clearly requires intensive sampling of continuous core. In addition to magmatic objectives, there are other general structural objectives that require continuous core recovery. Very little information exists on the structural changes that occur through the lower crustal section. It is not known if the lower crust is penetratively deformed or locally deformed, how strain is localized in the crust, how structures are oriented, and how structural style and orientation change with depth. Nor is there a clear picture of the relationships between fluid penetration and the evolution of ductile structures, the mechanism by which fluid penetrates into the ductile crust, or the general alteration state of the lower part of slow spreading crust. These are first order questions that can only be answered by achieving deep crustal penetration and extensive core recovery with a series of offset holes. Thus, there are a host of petrological, hydrothermal, structural, and geophysical problems that can be investigated by drilling in the gabbroic layer, such as the nature of sub-axial magmatic processes, the architecture, size, and longevity of magma chambers, the composition of magmas that enter these sub-axial systems, the nature of crystal fractionation and the degree to which magmas mix in this environment, the nature of cumulate processes and magmatic evolution as defined by fine-scale studies of cryptic chemical variations through the crust, the nature and extent of deformation throughout the plutonic levels of the crust, the depth and avenues for hydrothermal fluid penetration into plutonic levels, and the general physical properties in the plutonic part of the crust.

A second goal of Leg 153 is the drilling of the master fault zone along which the deep level gabbroic massif has been unroofed. The proposed drill site has been located by *Alvin* and exposes a moderately dipping fault zone as well as gabbroic rocks and greenstones. Both rock types exhibit gneissic to cataclastic textures, developed under amphibolite to greenschist facies conditions. The proposed site is located along *Alvin* dive tract 1014 on a narrow bench between stations 6 and 9 (Karson and Dick, 1983). Studies on fluid inclusions (Kelley and Delaney 1987) from gabbroic rocks sampled in close proximity to these outcrops (*Alvin* dives 1008, 1011 and 1012) suggest a minimum entrapment depth of 2 km below the basement-water interface, giving some estimate of the degree to which the gabbroic massif has been unroofed.

This hole will drill through a major high- to low-temperature detachment shear zone, or at least part of the detachment zone, in the same hole that a long gabbro section can be sampled and thus will address a number of major, related tectonic problems, such as identifying the minimum thickness of a major detachment with respect to the seismic wavelengths to determine if these shear zones are likely candidates for dipping seismic reflectors, the degree of fabric and seismic anisotropy in the shear zone rocks, the P-T-t-d history exhibited by the rocks along the shear zone, the mechanisms responsible for strain localization in the oceanic crust, the role of detachments as fluid conduits, the orientation of major shear zone, the orientation of a major shear zone or zones in the mid to lower crust, the question of symmetric versus asymmetric rifting models, and the questions concerning whether near-surface, low-angle detachments are responsible for plutonic exposures along the rift valley walls or whether the crust is fundamentally different than the prescribed notion of a layer-cake stratigraphy in a magma-starved region such as the MARK area.

In recent years, ODP has drilled two relatively deep holes through oceanic lithosphere (Site 504B in the fast-spreading Pacific lithosphere drilled through 1000 m of effusive lavas and into the dike complex; and Site 735B in the slow-spreading Southwest Indian lithosphere provided valuable information on the magmatic and tectonic structure of the lower, gabbroic, oceanic crust). A comparable data set for upper mantle rocks is absent. A deep hole in the upper mantle at an active oceanic ridge will better define the chemical nature and evolution of the mantle beneath a ridge (degree and homogeneity of melting and the degree of serpentinization), the geometry of magmatic structures (magma extraction, percolation, and intrusion), the deformation structures related to asthenospheric flow, and the degree of mantle incorporation into the ridge axis lithosphere. Fresh samples are essential to determine the architecture of the deformation fabrics, the petrological and geochemical compositions of the mantle, and their evolution with depth. The deepest samples recovered at Site 670 suggest that peridotites may become less serpentinized with depth. The recovery of very fresh mantle rocks may be achieved by drilling a deep hole, reducing the geochemical and textural uncertainties inherent in sampling of highly-serpentinized rocks recovered from surface exposures. Finally, such a hole will provide a data base for the evaluation of ophiolites as actual samples of ridge-generated lithosphere.

Drilling into exposed peridotites in a slow-spreading environment will address a number of specific issues, many of which remain poorly constrained. The modalities of the uplift of upper mantle rocks in the axial region should be a function of the rheological properties of the thickened (low magma budget) axial lithosphere. Leg 153 will examine if such properties allow for strain concentration and the development of detachment faults, thus determining whether axial lithospheric stretching occurs in a symmetrical, or asymmetrical fashion. The order of magnitude of deviatoric stresses and strain rates in the stretched axial region will also be examined and, in addition, the relative importance of the ductile- and brittle-stain domains which should vary as a function both of the rocks rheology at the imposed strain rates, and of the temperature distribution in the axial lithosphere. Leg 153 will attempt to clarify the mechanisms by which water penetrates into the mantle (faults?), whether the uprising mantle is serpentinized at great depths, and if serpentinite diapirism and swelling play a significant role in the uplift. The proposed deep hole would also allow for borehole seismic experiments, stress measurements, and possible, long-term *in situ* observations, such as the variation of seismicity and stress with time.

The structure and composition of the magmatic crust created in low-magma-budget conditions is also poorly constrained. It is presumed to be intensely disrupted by faulting, but may also be formed by discontinuous magmatic intrusions. Studies of peridotite and gabbro samples from the MARK area (Mével *et al.*, 1991; Tartarotti *et al.*, in prep.), and from the 15°N area of the Mid-Atlantic Ridge (Cannat *et al.*, 1992) suggest that there may be gabbro pockets intrusive into the uplifted mantle peridotites. Such a setting, similar to that of some Western Alps ophiolites (Lagabrielle and Cannat, 1990), differs significantly from the layered magmatic crust model, and could be tested by a deep hole drilled into an axial valley peridotite outcrop.

The influence of serpentinization on the budget of lithosphere/seawater interaction is poorly documented. More serpentinite outcrops are discovered on the seafloor of the M.A.R., and peculiar anomalies recorded in the water column are attributed to active serpentinization (Bougault *et al.*, 1991). A direct control on the depth and chemical effect of serpentinization of peridotites obtained by drilling will help constrain the chemical budget of this interaction.

Leg 153 also seeks to identify the source of magnetic anomalies. Serpentinized peridotites form a significant portion of the seafloor in slow-spreading environments and the magnetic properties of these rocks, and their ability to produce magnetic anomaly patterns, becomes an important issue. Finally, the asthenospheric history (petrological, geochemical, and deformational) of the cored peridotites will be compared with peridotites from fast-spreading (Hess Deep, Leg 147), and/or magma-rich ridges.

DRILLING PLAN/STRATEGY

Two drill sites are proposed (Figs. 1 and 2) in the western wall of the rift valley, one through gabbros (MK-1) and the second through peridotites (MK-2). The drillability of peridotites has been firmly established during Leg 109 and the depth of drilling at Site 670 was limited only by a lack of time. Successful drilling of a continuous gabbro section has been demonstrated at Site 735B in the Indian Ocean and would seem feasible with a guide base in the MARK area as well. Peridotites and gabbros have proved to be easily drillable with the standard rotary system and the diamond coring system is therefore not required.

Each hole should be drilled to a depth of 500 to 1000 m and further objectives could be achieved by future reentries. Two hard rock guide basses (HRGBs) are necessary, one for each hole, and adaptation to higher slopes may be necessary for proposed site MK-1.

Three-dimensional orientation is essential and can be done indirectly, by matching the cores with the FMS (formation microscanner) images if the recovery is high enough, or through use of the paleomagnetic measurements. However, this assumes that stable remanent magnetization was acquired during a single magnetic interval and that no subsequent tectonic rotation occurred. A system to orientate the cores in the hole (with a mark) would be highly desirable.

These first two holes will be a test for further drilling. If drilling is successful, the MARK area could become a natural laboratory. The two existing holes adjacent to the axial valley could be used for borehole seismic experiments to constrain the structure of the lithosphere and long term observations, such as the variation of seismicity and stress with time.

The hole in the peridotites could be deepened. It has been suggested that the Moho is shallower in this region (Purdy and Detrick, 1986) and MK-1 may represent a hole that could potentially penetrate through gabbros to the seismic or petrological Moho at relatively shallow depths or, by later offset holes, eventually achieve full penetration of the gabbroic crust and penetrate these important petrological and/or seismic boundaries. If drilling proves successful, the potential exists for a long-term, multi-leg strategy of drilling a series of offset holes (or deepening existing holes) through the gabbros, starting in the proposed hole at MK-1. This series of holes would begin near the contact between gabbro and basaltic/diabasic rocks (MK-1) near the top of the western rift valley wall. The hole would be deepened until further penetration proved prohibitive and drilling would then be offset downslope to about the same stratigraphic level as penetrated in the first hole. This strategy would be repeated downslope with a series of holes designed to test the basic architecture of the crust through spatial and stratigraphic sampling, to sample the detachment at multiple sites during each penetration in order to investigate its structural and alteration history during the unroofing process, and ultimately to penetrate deeper stratigraphic levels, including the mafic/ultramafic transition to achieve a composite, full penetration of the lower crust and uppermost mantle. Based on the considerable relief on the western rift valley wall and the extent of exposure of plutonic rocks (3 km of section) along the detachment surface, this site appears to have considerable potential in achieving this composite section and penetrating the petrological and/or seismic Moho. Fluid inclusion work in a series of holes down the dip face of the proposed detachment shear could prove invaluable in quantitatively evaluating and testing the asymmetrical shear zone model of deep crustal exposure and rifting. The changes in the thickness of the shear zone, and the extent of strain localization at various stratigraphic levels, could also be tested using this strategy. The petrological, chemical, and deformation characters of residual peridotites recovered below the gabbros could be compared with those of the exposed peridotites to shed light on the along axis variation mechanisms.

PROPOSED DRILL SITES

Proposed site MK-1 will be drilled through the master fault in the gabbros to a depth of 500-1000 m (Figs. 1 and 2, Table 1). During the *Alvin* and the *Nautile* dive programs near the ridge/transform intersection in the MARK area, gabbros have been observed on the east-facing slope between 6000 and 2200 mbsl. East-facing, moderately-dipping (25°-45°) fault planes subparallel to surface slopes were observed along the western rift valley wall. These faults exposed gabbroic rocks and greenstones. Gabbroic rocks sampled from these outcrops not only show brittle structures such as slickensides and microcracks, but also show cataclastic and ductile structures suggesting that this slope may represent a master fault system along which footwall gabbroic massif has been unroofed. This is interpreted to occur largely during asymmetrical amagmatic extension. A recent side-scan and photographic survey of the southern wall of the Kane Transform at the MARK inside corner (Karson and Delaney, pers. comm.) has constrained the nature and extent of the gabbroic massif. An attempt will be made to drill this gabbroic massif. Some of these outcrops located during *Alvin* and *Nautile* dives and the particular drill site chosen have the added advantage of being at relatively shallow depths (2300 to 2400 m).

Proposed site MK-2 (Figs. 1 and 2, Table 1) will be drilled in peridotites to a depth of 500-1000 m. The second proposed drill site is located on the northern peridotite outcrop discovered with the *Alvin*. In this area, the summit of the western rift valley wall forms a hill (the "Pink Hill"), which culminates at 2600 m. Recent pillow basalts crop out at the bottom of this hill and in the median valley floor. The base of the slope, at bout 3700 m, is a talus made of serpentinite and basalt fragments. Serpentinized peridotites crop out quite continuously from about 3500 m to about 3200 m. The valley wall is a tectonically active slope, dominated by east-facing, presumably normal, faults. These faults are numerous in the serpentinized peridotites, which form massive outcrops between 3500 m and 3100 m. The actual fault planes are moderately to steeply dipping (40° to 70°). The peridotites are also affected by more pervasively distributed serpentinite slickensides, with a dominant north-south trend and moderate eastward dip (20° to 50°). The contact between the serpentinized peridotites and the pillow basalts, which form the top of the wall, is concealed by talus. This contact may be normal, with the pillows stratigraphically overlying the peridotites. Alternatively, basalts and peridotites may belong to two, tectonically juxtaposed blocks. The first interpretation is favored, based on the existence of a gravity high over the Pink Hill (Bergès, 1989), but even if proven incorrect, the scientific relevance of drilling a hole in the peridotites will not be lessened. This hole should be located along the track of *Nautile* dive 13, on a flat surface near the lower limit of the serpentinized peridotite outcrop.

The emplacement of rocks of deep origin in the wall of the axial valley may be related to lithospheric stretching due to magmatic starving. However, the geological interpretation of the proposed drill sites is strongly dependent on the crustal structure inferred. Two extreme models can be considered, depending on the magma budget. In the first case, lithospheric stretching follows a high-magma-budget period which has produced a magmatic crust of "normal" thickness. Long detachment surfaces expose different levels of a layered oceanic lithosphere. In this case, exposing mantle rocks in the Pink Hill requires considerable extension. In the second case, the magma budget is consistently low. The magmatic crust is therefore heterogeneous, gabbro occurring as small isolated pockets enclosed in peridotites. Exposing mantle rocks in that case requires considerably less extension, since they may already be very close to the surface. An intermediate model could correspond to a low-magma-budget regime following a high-magma-budget period. The reality is probable intermediate, and may be different at the two proposed sites because of the three dimensional character of the lithosphere. The first one, located within a magmatic cell, may be close to case 1; the second, located at the edge, may be closer to case 2.

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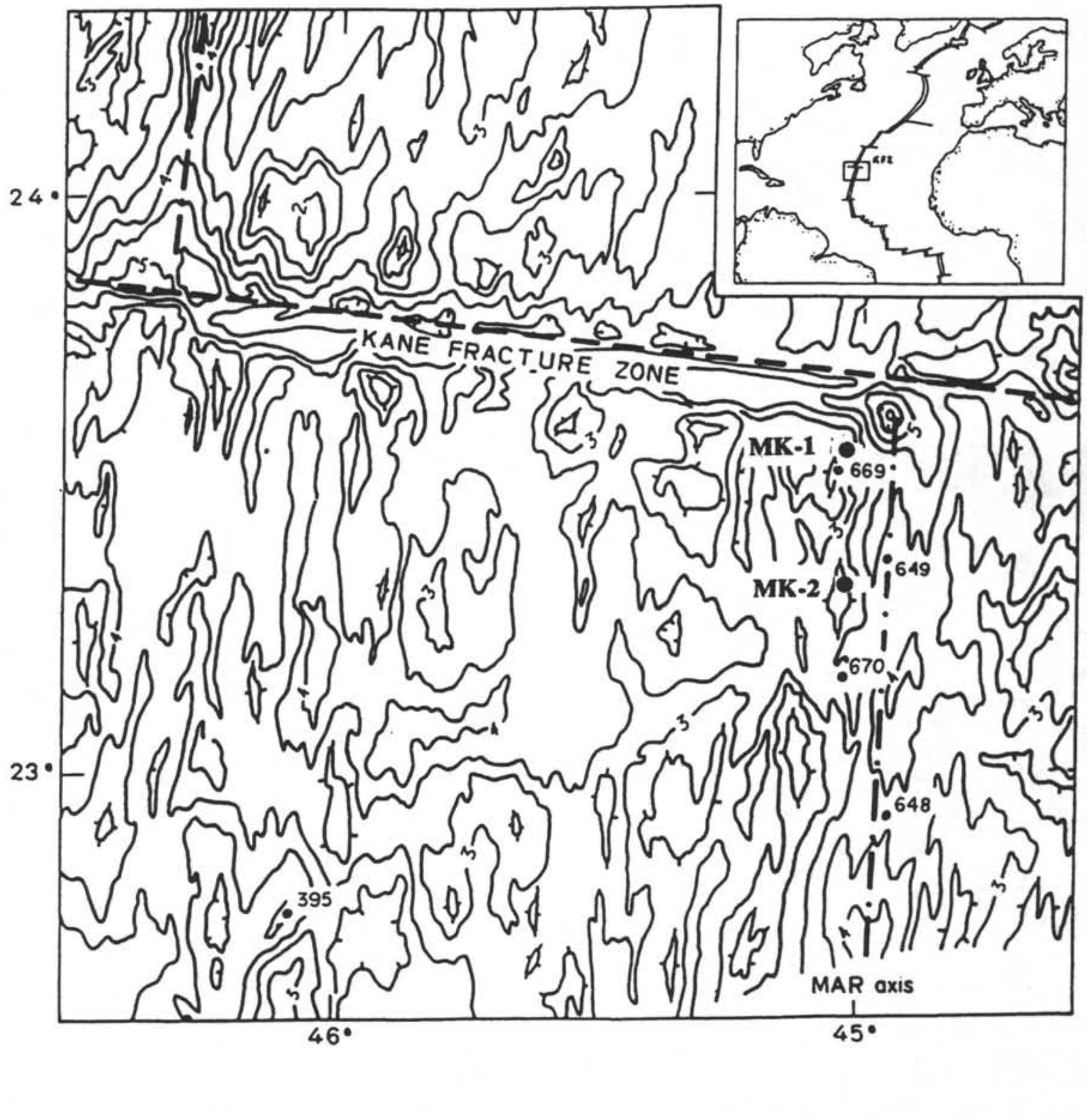

Figure 1. Bathymetric map of the MARK area after Tucholke and Shouten (1988). Solid circles are DSDP and ODP sites. Location of proposed MK-1 and MK-2 sites are shown.

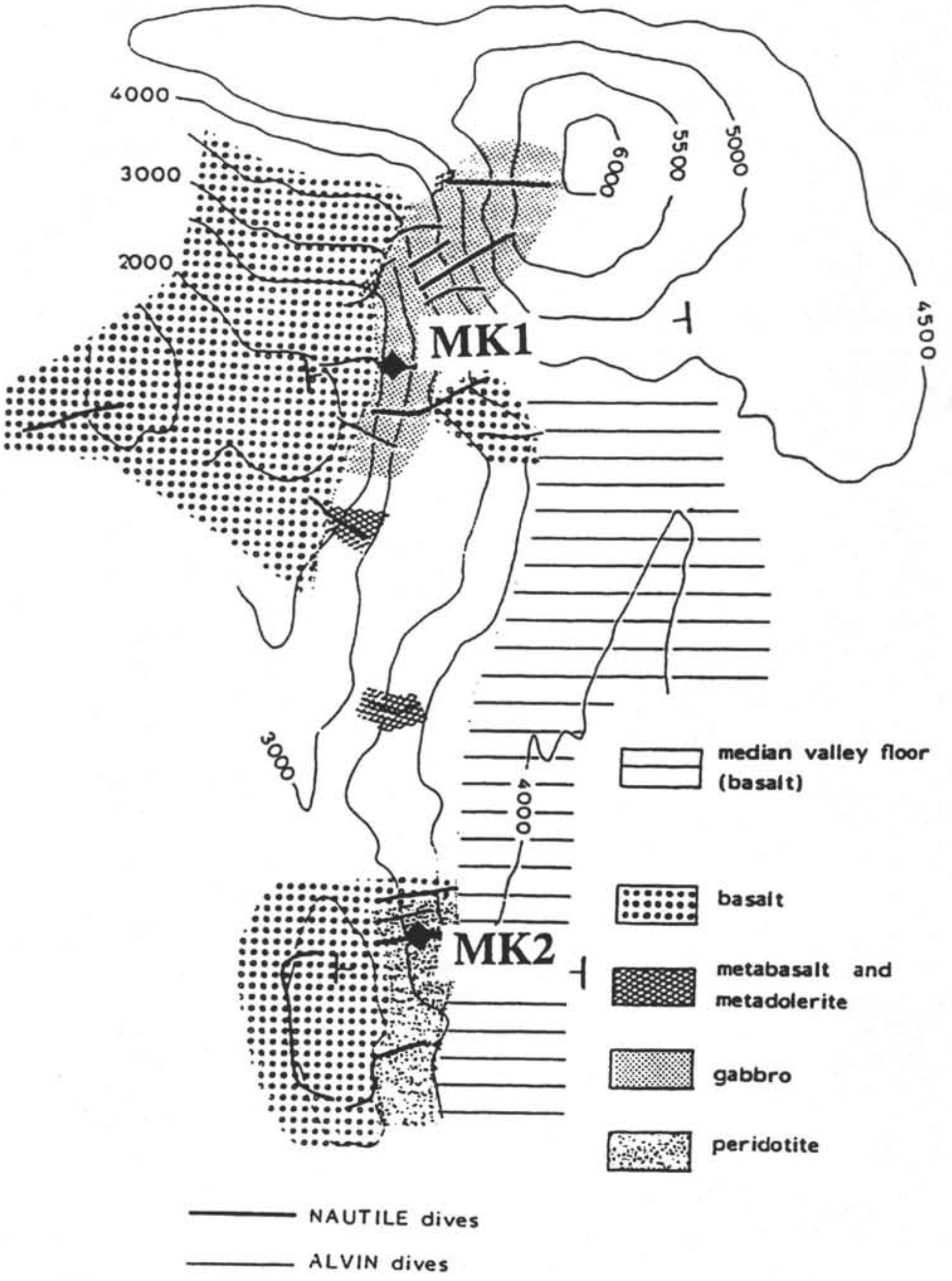

Figure 2. Geological sketch map based on submersible observations of the western rift valley wall in the MARK area (after Mével *et al.*, 1991)

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: MK-1	**PRIORITY:** 1	**POSITION:** 23°34'N, 45°02'W
WATER DEPTH: 2500 m	**SEDIMENT THICKNESS:** 0 m	**TOTAL PENETRATION:** 500-1000 m
SEISMIC COVERAGE:		

Objectives: Long section of oceanic gabbros and master fault at a slow-spreading ridge. To characterize the magmatic, tectonic, and metamorphic evolution of the lower crust and constrain the processes of exposing deep crustal rocks in the rift valley wall.

Drilling Program: RCB coring and reentry.

Logging and Downhole Operations: Standard suite + FMS + BHTV + magnetic logging.

Nature of Rock Anticipated: Gabbros.

SITE: MK-2	**PRIORITY:** 1	**POSITION:** 23°21'N, 45°01'W
WATER DEPTH: 3500 m	**SEDIMENT THICKNESS:** 0 m	**TOTAL PENETRATION:** 500-100 m
SEISMIC COVERAGE:		

Objectives: Long section of oceanic upper mantle at a slow-spreading ridge. To characterize the petrological, structural, and physical properties of the upper mantle and constrain the processes responsible for mantle exposures at slow-spreading ridges.

Drilling Program: RCB coring and reentry.

Logging and Downhole Operations: Standard suite + FMS + BHTV + magnetic logging.

Nature of Rock Anticipated: Peridotites, more or less serpentinized.

LEG 154

NEOGENE HISTORY OF DEEP-WATER CIRCULATION AND CHEMISTRY: CEARA RISE, WEST EQUATORIAL ATLANTIC

Modified From Proposal 388

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ABSTRACT

The Ceara Rise in the western equatorial Atlantic provides an ideal target for constructing a bathymetric transect of Advanced Piston Cores (APC). The rise is well sedimented, with high sedimentation rates and uninterrupted sedimentation for at least the last 10 m.y. Because of the nature of the sediments, it is anticipated that high-quality paleomagnetic records will be obtained. In addition, the Ceara Rise is located in the main flow path of the two principal water masses in the oceans. Mixing between these water masses creates the initial chemical and physical properties for deep water in the eastern basins of the Atlantic and for the Indian and Pacific Oceans. Therefore it is imperative to understand the history of deep-water circulation and chemistry in this region in order to evaluate the changes in deep-water chemistry and carbonate preservation that are observed in other ocean basins.

Leg 154 will consist of a transect of eight APC sites distributed down the eastern flank of Ceara Rise from about 2800 to 4500 m. The average depth spacing of about 250 m is required in order to identify the past depth and shape of the mixing zone between northern- and southern-sources of deep water throughout the Neogene.

Several questions of paleoceanographic significance can be addressed by a depth transect of this type; namely 1) the history of deep-water flow in the Atlantic during the Cenozoic and the relationship between deep-water circulation, chemistry, and the earth's climate; 2) the history of carbonate production and dissolution in the equatorial Atlantic during the Cenozoic and how changes in carbonate production and dissolution have been affected by changes in deep circulation and in the earth's climate; and 3) the Cenozoic history of surface water and climate in the tropics and the variation in $\delta^{13}C$ of nutrient-depleted surface water and oceanic $\Delta\delta^{13}C$.

INTRODUCTION

During the last five years, a coring and drilling strategy has been employed by the Ocean Drilling Program to recover bathymetric transects of Advanced Piston Cores (APCs) in order to reconstruct the Cenozoic history of deep water chemistry, carbonate production and dissolution, and deep water circulation. This strategy has followed a successful research strategy used for the reconstruction of late Quaternary deep water chemistry and sedimentation history (Johnson, 1984; Curry and Lohmann, 1982, 1983, 1985, 1986, 1990; Peterson and Prell, 1985a, 1985b; Jones *et al.*, 1984; Farrell and Prell, 1989, for example) and for pioneering DSDP transects for reconstructing Neogene and Paleogene sedimentation history (e.g., Legs 72 and 74). The research strategy invokes the basic assumption that the principal source of carbonate in the sediments is from surface water production, with little or no down-slope or lateral input. If this assumption is true, then carbonate accumulation in the shallowest sites, if they are always above the lysocline, equals the carbonate productivity of the overlying surface water. If the sites are located close together, and not near any sharp regional gradients in productivity, then the input rate of carbonate in all sites in the bathymetric transect should be equal. Then the difference in carbonate accumulation between shallow and deep sites is a quantitative indicator of the amount of carbonate lost to dissolution. With similar bathymetric transects, gradients in deep water chemistry can be reconstructed. Since water masses vary in three dimensions, the bathymetric distribution of water mass properties contains fundamental information about the geometric relationships and mixing between water masses of different origin. Thus from a single suite of cores located on the slopes of an aseismic rise, two important aspects of the past history of deep water can be determined.

To date, this bathymetric sampling strategy has been used on ODP Leg 108 (eastern equatorial Atlantic), Leg 113 (Maud Rise, sub-Antarctic region), Leg 115 (Madingley Rise, equatorial Indian Ocean), Leg 117 (Owen Ridge, Arabian Sea), and Leg 130 (Ontong Java Plateau, western equatorial Pacific).

An additional bathymetric transect in the western equatorial Atlantic at the Ceara Rise is necessary in order to fully evaluate the Cenozoic history of deep water circulation and chemistry. Deep water circulation in the Atlantic (and to a great extent in the world ocean) is controlled by the production of deep water in the Atlantic and mixing between deep water masses in the western basins of the South Atlantic and southern ocean. The Atlantic contains the source regions for the two major water masses in the deep oceans today, and in the past this ocean probably contained the source area for at least one of the principal water masses. It is the mixing between water masses in the

Southern Atlantic and southern ocean that produces the initial chemical and physical characteristics of the deep water that flows through the Indian Ocean and into the Pacific. Thus no reconstruction of Neogene deep water circulation and chemistry can be complete without a full understanding of the history of deep water circulation in the western Atlantic. On the basis of location, present oceanographic setting, and continuity of high sedimentation rates, the Ceara Rise provides the best target location for reconstructing this paleoceanographic history.

STUDY AREA

Oceanographic Setting

Deep Water

Because of westward intensification of deep water circulation, the western basin of the Atlantic provides the principal conduit for the flow of northern and southern sources of deep water. Today these water masses meet and mix in a broad zone that extends from the South Atlantic to the equatorial regions of the North Atlantic. The mixing zone between northern-source deep water (NADW) and southern-source deep water (AABW) is about 4000 m in the Ceara Rise region. Today this depth marks a large gradient in deep water chemistry that controls the dissolution of calcium carbonate in the western basin. The position of this mixing zone also affects the chemistry of deep water in the eastern Atlantic because it is deep water from the western basins that ventilates the eastern basins. Today deep water in eastern basins originates in the western basins and enters the east through low-latitude fracture zones. Flow across two fracture zones provides most of the deep water in the east: the Romanche fracture zone at the equator (Metcalf *et al.*, 1964) and the Vema fracture zone at about 10° N (M. McCartney, pers. comm.) The sill depths for these fracture zones are close to 4000 m (the depth of the mixing zone), so small changes in the relative intensity of northern- and southern-source deep waters can have a large effect on the initial chemical composition of deep water which enters the eastern basins and on the preservation of calcium carbonate in the eastern Atlantic.

Today the mixing zone between NADW and AABW is mostly below the sill depth of the fracture zones so the deep water entering and filling the eastern Atlantic below 3750 m is a mixture of 80% NADW and 20% AABW. Because it is dominated by NADW, the deep water is warmer, saltier, and less corrosive to carbonate than deep water at the same depths in the western Atlantic. But small changes in the depth of the mixing zone in the western basin would produce large changes in the chemical and physical properties of the deep water in the eastern Atlantic. Oppo and Fairbanks

(1987) and Curry *et al.* (1988) have shown that the large glacial decrease in the carbon isotopic composition of deep water in the eastern Atlantic occurred in part because of geographic displacements of the mixing zone between northern- and southern-source deep water. During the maximum of the last glaciation, decreased production of NADW caused the northward migration of the mixing zone. Consequently a greater proportion of southern-source deep water entered the eastern Atlantic, lowering the CO_3 and increasing the dissolution of calcium carbonate. On the basis of the $\delta^{13}C$ chemistry of benthic foraminifera in the western basin at Ceara Rise, Curry and Lohmann (1990) estimate that the initial ratio of northern- and southern-source deep water in the eastern Atlantic must have been about 1:1 during the glaciation.

Mixing between NADW and AABW today also affects the initial chemical and physical composition of the deep water that enters the Indian and Pacific Oceans. Previous studies have shown that the relative proportion of northern-source deep water decreased during the last glaciation resulting in a lower $\delta^{13}C$ in southern ocean deep water (Oppo and Fairbanks, 1987; Curry *et al.*, 1988). Thus the $\delta^{13}C$ composition of the deep water that entered the Indian and Pacific Oceans was lowered at that time. $\delta^{13}C$ values in the Pacific Ocean were more positive than coeval $\delta^{13}C$ values in the southern ocean, suggesting that ventilation of deep water in the Pacific may have occurred locally (Curry *et al.*, 1988). The gradients between regions and between end-member water masses are key indicators of deep-water flow paths and chemistry. These geographic gradients in $\delta^{13}C$ track the flow of deep water, and in order to evaluate these gradients, it is necessary to understand how the initial compositions of water masses have changed through time. Since this mixing occurs in western basins of the Atlantic and in the southern ocean, again it is necessary to understand the history of circulation and chemistry there in order to fully understand the Neogene history of deep water for the world's oceans.

Raymo *et al.* (1990) successfully used this end-member approach to produce a history of deep-water circulation for the last 2.4 Ma. They compared the isotopic gradients between the northern component of deep water (Site 552), the Pacific component of deep water (Site 677), and an intermediate site (Site 607). By determining the proportion of northern-component deep water at Site 607, they produced a record of northern-component deep-water production. Following the same approach as Raymo *et al.* 1990, the APC sites at Ceara Rise will provide records of deep-water history with greater sensitivity because Ceara Rise is much closer to the present mixing zone between northern and southern sources of deep water. Site 607 is located near Site 552, the northern-component end member, so large decreases in northern component production are needed in order to move the mixing zone so far to the north.

Surface Water

The Ceara Rise is located in the western equatorial Atlantic beneath a surface water pool that exhibits little annual variation in temperature. Surface water temperatures generally exceed 27°C. On glacial-interglacial time scales, CLIMAP (1976) has suggested that surface water cooling in this region was small, less than 2°C. Because it is located on the western side of the Atlantic, it is less affected by annual or glacial-interglacial variations in upwelling; therefore the nutrient concentration of the surface water mixed layer is always near zero (Curry and Crowley, 1987). Thus a surface water $\delta^{13}C$ record from this location should be an ideal representation of the Cenozoic history of nutrient-depleted $\delta^{13}C$ and $\Delta\delta^{13}C$ (e.g., Shackleton and Pisias, 1985; Curry and Crowley, 1987). Because of the low variability in surface water temperature caused by upwelling, this location will also be ideal for reconstructing the history of Cenozoic surface water temperature changes caused by global, rather than local, changes in climate.

Geologic Setting

The Ceara Rise is an aseismic feature that formed at the Mid-Atlantic Ridge about 80 Ma. Along with its conjugate, the Sierra Leone Rise in the eastern equatorial Atlantic, the Ceara Rise reaches a minimum bathymetry of about 2000 m. It is surrounded by sea floor with an average depth of about 4500 m. The Ceara Rise is draped with a thick sequence (>1000 m) of undisturbed lithogenic and biogenic sediments (Supko, Perch-Nielsen, *et al.*, 1977). Deep Sea Drilling Project Site 354 was located on the northern flank of the Ceara Rise at a depth about 4000 m. Although only spot cored, a generalized history of the area was reconstructed from this investigation.

The oldest sediments encountered at this location were Maastrichtian, iron-rich marls, overlain by nannofossil chalks and foraminiferal-nannofossil oozes and marly oozes until about the Pliocene-Pleistocene, where a significant detrital fraction of lithogenic particles becomes a dominant part of the sediments. It is at this time that significant detrital input from the Amazon Cone first affected this region. (Today the Amazon Cone drapes up the northern and western sides of the Ceara Rise and is a significant source of sediments to the eastern margin during glacial intervals.) Overall sedimentation rates are low (<2 cm/k.y.) until the late Miocene when the increase in detrital fraction increases the sedimentation rate to about 6 cm/k.y. At Site 354, the chalk-ooze transition occurs at about 230 m below sea floor.

Based on piston core information, sedimentation rates exhibit large glacial-interglacial changes that result from large variations in the input of detrital components from the Amazon Cone. During the

Holocene (0-12 k.y.) sedimentation rates averaged 1.5-2 cm/k.y., but increase to about 5 cm/k.y. during glacial stage 2 (12-24 k.y.). During the interglacial, sedimentation rates do not exhibit any significant changes with depth in the water column; during the glaciation a small decrease with depth is apparent. This decrease results from the greater dissolution of calcium carbonate in the deeper sites during the glaciation. During the last glaciation, noncarbonate accumulation increased uniformly throughout the water column. In the shallowest cores, calcium carbonate accumulation was the same during the last glaciation and the Holocene, but in the deeper sites, carbonate accumulation decreased. Since the shallow cores have the same accumulation rate of carbonate, and since they were above the lysocline during the last glaciation, the production of carbonate in the surface water probably was the same during stage 2 and the Holocene. The decrease in the deeper sites during stage 2 must have resulted from dissolution and dissolution appeared to be greater at that time. Since the presence of corrosive, southern-source deep water in the western Atlantic today determines the position of the lysocline, the increase in dissolution during the glacial maximum likely occurred from an increase in the amount of southern-source deep water at this location.

There is evidence for higher sedimentation rates in piston cores collected along the northern flanks of Ceara Rise which are caused by greater input of terrigenous sediments. Toward the north, sedimentation rates increase with increasing water depth and overall sedimentation rates are higher in this region than in the south by about 25%. Decreased carbonate concentrations coupled with increased sedimentation rates suggests that greater input of detrital material coming from the Amazon Cone is inflating sedimentation rates along the northern margin of Ceara Rise.

Late Quaternary sedimentation rates in a gravity core depth transect from Ceara Rise average about 4 cm/k.y., but cores to the north average more like 6 cm/k.y. Site 354, which is to the north of the gravity core depth transect, averaged 6 cm/k.y. since the Miocene (Supko, Perch-Nielsen, *et al.*, 1977). At about 230 mbsf, an hiatus or condensed section was encountered within late Miocene sediments. Because this site was spot cored throughout the entire section, it is not possible to determine the true nature of this condensed section. More recent coring results from Legs 115, 117, and 130 identify a dissolution event at this time, followed by an increase in sedimentation that is related to increased productivity. Thus it is possible that sedimentation was continuous throughout the Miocene at Site 354, but with variable sedimentation rates. Below this 230 m, the ooze-chalk transition occurred. On the basis of the sedimentation rate from these investigations and the results from DSDP Site 354, it is likely that an excellent late Neogene depth transect can be obtained from the eastern flank of Ceara Rise. It is clear that sedimentation rates are high over wide areas and depths on the Ceara Rise. It is also clear that this section is suitable for APC coring down to at least the Late Miocene. The history of sedimentation in the region suggests that, if at all, the first hiatus will be encountered below about 230 m. Thus a Neogene depth transect should be mostly uninterrupted by hiatuses.

Today and during the last glaciation, the Carbonate Compensation Depth (CCD) remained below 4500 m. But during the Cenozoic as recently as the Late Miocene, the CCD in this region may have been above 4000 m. Results from recent ODP sites in the eastern Atlantic (Leg 108, Site 665) indicate that the CCD lowered sharply to below 4700 m at about 3.8 Ma (Ruddiman, Sarnthein, Baldauf, *et al.*, 1988). Based on shallower ODP sites from Leg 108, it is clear that the CCD there was probably not shallower than 4500 m since the Late Miocene. The carbonate record for Site 354 suggests that the CCD did not rise above 4000 m during much of the Cenozoic (Supko, Perch-Nielsen, *et al.*, 1977). But McCoy and Zimmerman (1977) show that in much of the nearby South Atlantic, the CCD remained above or near 4000 m throughout most of the Cenozoic, and only recently (5 Ma) fell to below 4500 m. Thus it is likely that the CCD in the equatorial region of the western Atlantic may have been as shallow as 4000 m during parts of the Cenozoic, and that the spot coring of Site 354 missed significant variations in CCD depth.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To establish the history of deep-water flow in the Atlantic since the Miocene and determine the relationship between deep-water circulation, chemistry, and the earth's climate.

2) To determine the history of carbonate production and dissolution in the equatorial Atlantic in the Late Neogene, particularly in respect to changes in deep-water circulation and climate.

3) To investigate the Cenozoic history of surface water and climate in the tropics, particularly the record of nutrient-depleted surface water $\delta^{13}C$ and oceanic $\Delta\delta^{13}C$.

Specific Objectives and Methodology

Figure 1 and Table 1 present a preliminary depth transect for Advanced Piston Core and Extended Core Barrel (XCB) drilling on the eastern flank of Ceara Rise. This transect was chosen to conform with an existing gravity core depth transect (Curry and Lohmann, 1990) because there is a significant amount of sedimentological and geochemical data already available for the late

Quaternary. This transect is considered preliminary, however, because it will be necessary to mount a site survey cruise to document the nature of sedimentation below the late Quaternary. (Previous investigations of late Quaternary sedimentation reveal this to be a region with few turbidites or other evidence of down-slope reworking. However, Leg 108 (Ruddiman, Sarnthein, Baldauf, *et al.*, 1988) revealed that down-slope reworking is an important process even beneath regions with continuous, uninterrupted, Late Quaternary sedimentation.).

The proposed depth transect includes eight sites which are distributed at approximately 250-m-intervals over the full depth range of Ceara Rise. Eight is the necessary number of sites to ensure that the critical gradients in deep water chemistry and carbonate sedimentology are recovered. From the temperature profiles, it is clear that the mixing zone between northern- and southern-source deep waters occurs within a narrow bathymetric interval. Today the thickness of the mixing zone between the water masses is only about 400 m. Thus closely spaced sites will be necessary to adequately resolve past depths and gradients of the mixing zone. Eight sites will provide both accurate identification of the depth at which the mixing occurred in the past as well as an excellent representation of the gradient with depth of the chemical or physical parameters. Fewer than six sites in the transect will produce a bathymetric transect of little value for deep water reconstructions.

Because the CCD is unusually deep at this location today, it is necessary to have the transect span the entire depth range from 2500 m to 4500 m. The shallow-depth sites will ensure that the sedimentary sections are mostly free of dissolution, while the deep sites will ensure that the full range of deep-water chemical composition is sampled as well as provide a history of the highly variable depth of the CCD and lysocline. Again in order to determine the depth of the CCD and lysocline with accuracy, the depth differences between the sites should be small.

In order to ensure a complete, undissolved and undisturbed record of surface water conditions, several shallow sites for coring have been proposed. While it is likely that the Neogene stratigraphic sections at Ceara Rise are uninterrupted by major hiatuses, short-duration interruptions in sedimentation may have occurred. In addition, little evidence of the Paleogene history of erosion in this region exists. But by combining the records from several sites, a complete record of surface conditions may be obtained, if the hiatuses are of limited geographic or bathymetric extent. Since recovery of excellent paleomagnetic records at these sites is expected, correlation between sites should be very accurate.

DRILLING PLAN/STRATEGY

It will be necessary to offset APC core each location to minimize sediment disturbance and loss between APC cores. Thus the minimum number of holes at each site in the depth transect should be at least two. For most of the sites, more than two holes should be cored in order to supply enough material for extensive biostratigraphical, sedimentological, geochemical, and paleomagnetic investigations. In this manner, one of the holes at each site can be dedicated to very high frequency sampling. Thus the overall number of holes for the depth transect will total about 24. Several of the sites will be Extended Core Barrel (XCB) cored through the Paleogene and into the Cretaceous section. One site should be from a shallow depth in order to reconstruct the surface water history for the entire Cenozoic. The other sites should be distributed down the slopes of Ceara Rise in order to produce a preliminary (yet coarse) depth transect for the early Cenozoic.

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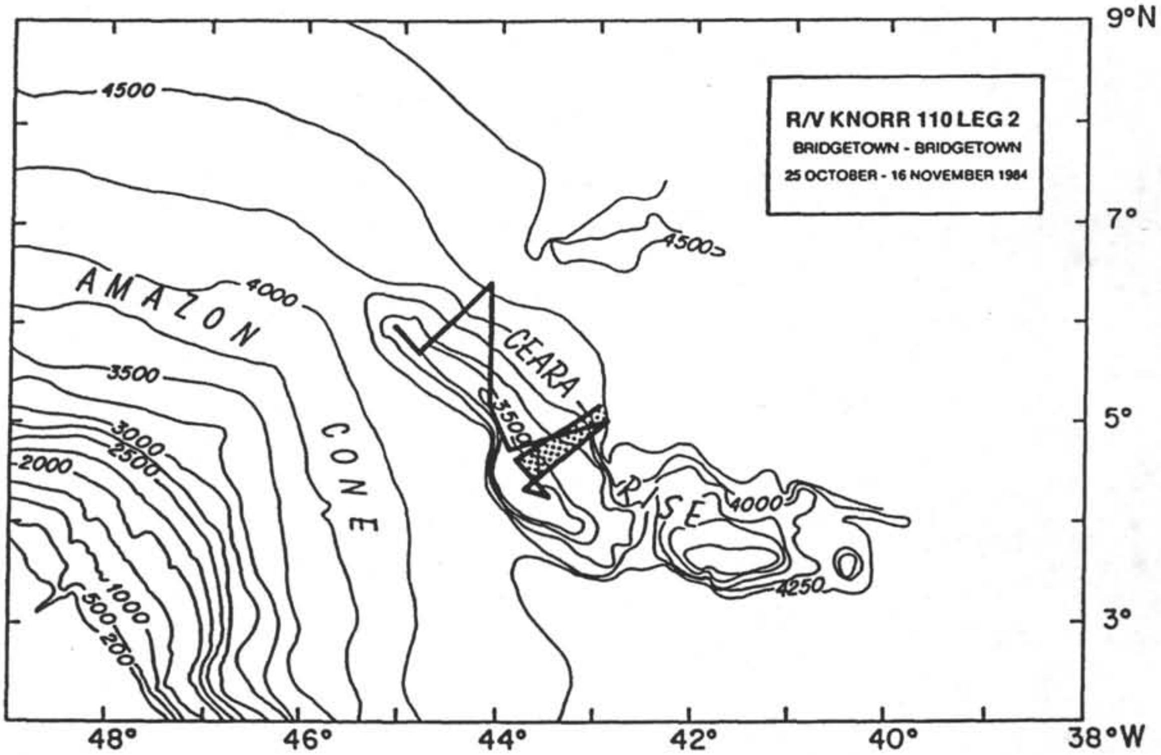

Figure 1. Location of cores recovered during cruise 110 of R/V KNORR. The shaded area marks the best location for Leg 154's APC coring transect.

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: CEA-1 **PRIORITY:** 1 **POSITION:** 4°30'N, 43° 40'W preliminary
WATER DEPTH: 2800 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions and surface water temperature, chemistry, and productivity conditions.

Drilling Program: Offset APC core to refusal. XCB core to refusal.

SITE: CEA-2 **PRIORITY:** 1 **POSITION:** 4°34'N, 43° 32'W preliminary
WATER DEPTH: 3050 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions and surface water temperature, chemistry, and productivity conditions.

Drilling Program: Offset APC core to refusal.

SITE: CEA-3 **PRIORITY:** 2 **POSITION:** 4°38'N, 43° 24'W preliminary
WATER DEPTH: 3300 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions and surface water temperature, chemistry, and productivity conditions.

Drilling Program: Offset APC core to refusal.

SITE: CEA-4 **PRIORITY:** 2 **POSITION:** 4°42'N, 43° 16'W preliminary
WATER DEPTH: 3300 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions

Drilling Program: Offset APC core to refusal. XCB core to refusal.

SITE: CEA-5 **PRIORITY:**1 **POSITION:** 4°46'N, 43° 08'W preliminary
WATER DEPTH: 3800 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions

Drilling Program: Offset APC core to refusal.

SITE: CEA-6 **PRIORITY:**1 **POSITION:** 4°50'N, 43° 00'W preliminary
WATER DEPTH: 4000 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions

Drilling Program: Offset APC core to refusal. XCB core to refusal.

SITE: CEA-7 **PRIORITY:**1 **POSITION:** 4°55'N, 42° 52'W preliminary
WATER DEPTH: 4200 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions

Drilling Program: Offset APC core to refusal.

SITE: CEA-8 **PRIORITY:**1 **POSITION:** 5°00'N, 42° 44'W preliminary
WATER DEPTH: 4450 m preliminary

Objectives: Reconstruction of deep water circulation, chemistry, and carbonate accumulation conditions

Drilling Program: Offset APC core to refusal. XCB core to refusal.

LEG 155

AMAZON DEEP-SEA FAN GROWTH PATTERN: RELATIONSHIP TO EQUATORIAL CLIMATE CHANGE, CONTINENTAL DENUDATION, AND SEA-LEVEL FLUCTUATIONS

Modified From Proposal 405-Rev Submitted By

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ABSTRACT

During low sea-level stands, the Amazon River discharged its sediment load directly into the deep-sea to build the Amazon Fan. The fan has been active since the mid-Miocene and is built of a series of distinctive, stacked and overlapped seismic units that include channel-levee systems of the upper and middle fan, the reflective units of the lower fan, and large, transparent debris flows. Although the structure of such muddy modern fans is often displayed on seismic profiles, the lithologies and ages of the sediments, and their relationships to sea-level change, are poorly defined. To resolve these questions, Leg 155 will sample several of the acoustic units to determine their lithologies, facies, and ages. Since fan sediments are river-derived, analysis of the sediments deposited in the channel levees (e.g., pollen, clay and sand mineralogy, bulk geochemistry, organic matter) should reveal a high-resolution record of equatorial land climate during several glacial-interglacial cycles. The Amazon Fan underlies the western Equatorial Atlantic and careful sampling should produce high-quality planktonic records. Cores recovered from the elevated crests of abandoned levees, especially if shielded from the active levee system, contain high sedimentation-rate records apparently free from downslope flows. These sediments appear to contain a record of surface circulation through the mapping of river-discharge patterns. Temporal changes in river-discharge patterns suggest that surface-circulation patterns change on a time scale of several thousand years. The integrated analysis of fan architecture and growth pattern, land climate, and paleocirculation patterns in the western Equatorial Atlantic will clarify the response of this important equatorial region to glacial-interglacial and other cycles and resolve regional tectonic influences on fan sedimentation such as times of Andean uplift as well as resolve more localized tectonic interactions such as the sedimentological effects of continental margin flexure due to the mass of the fan itself. Leg 155's drilling program addresses a number of the themes discussed at the South Atlantic Workshop in Woods Hole, April 1987 (Damuth *et al.*, 1987).

INTRODUCTION

The Amazon Fan is one of the largest modern submarine fans, and forms a significant proportion of the continental margin off northeastern Brazil. The fan contains much of the material eroded from the continent within the Amazon drainage basin. Large fans such as the Amazon, Mississippi, Indus, and Bengal Fans are formed by the long-term localized input of riverine sediments moderated by glacio-eustatic sea-level fluctuations, climate change, and tectonic activity. These large fans are also significant crustal loads, and can create bulges at or near the coastline which, in turn, affect sedimentation patterns. Although much smaller, often sand-rich modern fans such as Navy Fan (Normark *et al.*, 1979) may appear to be more analogous to ancient fans identified from outcrops, larger fans are an important component of both modern and in-place ancient continental margins. A knowledge of the morphology, structure, and sediment of these large muddy fans is important for understanding processes that control fan growth (including sea level), and also for revealing the record of climate change on land and ocean circulation. Because normal piston cores only sample the upper 10 m of these several-kilometer-thick deposits, understanding of the sedimentary facies associated with the observed seismic and morphological units and the age relationships of these units and the climatic record preserved in their sediments remains poor. Deep, continuous sampling is required to make significant progress towards understanding fan growth and to obtain important and unique climatological records from fan sediments.

Analysis of high-resolution single-channel seismic-reflection profiles and 3.5-kHz profiles (supplemented by GLORIA side-scan sonar, SeaBeam multi-beam bathymetry, and analysis of piston cores) have helped to reveal the structure of this somewhat complex sediment deposit, and have indicated the kind of sampling strategies needed to understand continental margin sedimentation at lateral and temporal scales that are often difficult to approach. These studies suggest that fan growth is in part related to external controls such as sea-level fluctuations and, in part, related to events such as channel avulsions and mass-transport activity that are internal to the fan. Although high-resolution seismic profiles have revealed many aspects of fan architecture, little information is available on the actual sediments that comprise the observed acoustic depositional units or on the relative or absolute ages of those units. A series of sites on the Amazon Fan is proposed to provide critical information on sedimentary facies within different acoustic units, to characterize temporal and spatial variations in the mineralogy, palynology and organic matter (and its early diagenesis), to determine the ages and deposition rates of critical fan units, and to understand the evolution of fan architecture and its relationships to sea-level, climatic, and tectonic events (as well as more localized margin flexure) through the Pleistocene and perhaps back into the mid-Miocene.

STUDY AREA

Fan Morphology and Growth Patterns

The Amazon River has been the major source of terrigenous sediments to the Equatorial Atlantic since Andean uplift in the early Miocene (Castro *et al.*, 1978), and the development of the Amazon Fan was apparently initiated by that event. During the present sea-level high, sediments discharged by the Amazon River (derived in part from the Andes and in part from weathering within the Amazon Basin) are of mixed size grades (silt and clay dominate; Gibbs, 1967), contain organics derived both from within the drainage basin and from upland sources (Hedges *et al.*, 1986; Ertel *et al.*, 1986), and are deposited on the shelf in a large subaqueous delta (Kuehl *et al.*, 1982; Nittrouer *et al.*, 1983, 1986). The high-sea-level stand prevents sediment from crossing the shelf, thus the fan has been inactive during the Holocene (Damuth and Fairbridge, 1970; Damuth and Kumar, 1975). Characteristics of the river load are poorly known for previous glacial sea-level lows when the Amazon River crossed the emerged shelf and discharged directly into deep water and onto the fan (Damuth and Fairbridge, 1970; Damuth and Kumar, 1975; Milliman *et al.*, 1975). The few studies of the bulk chemistry of the uppermost Pleistocene fan sediments (ca. 11,000 y.b.p.) suggest that weathering patterns in the source area at this time were broadly similar to those observed today (Kronberg *et al.*, 1986; Nesbitt *et al.*, 1990).

The Amazon Fan (Fig. 1) extends seaward 700 km to abyssal depths and contains sedimentary/ acoustic sequences that appear to be characteristic of many large and small modern elongate or mud-rich fan systems (Stow *et al.*, 1985). These characteristics include large, leveed, sinuous channels on the upper and middle fan that become smaller and evolve into unleveed channels on the highly-reflective lower fan (Damuth and Kumar, 1975; Damuth and Embley, 1981; Damuth *et al.*, 1983a, b, 1988; Damuth and Flood, 1983/1984, 1985). The unchannelized Demerara Abyssal Plain extends seaward from the base of the fan below a depth of 4800 m. The late glacial sediments of the upper and middle fan are in general muds with occasional thin sand/silt layers, whereas those sediments of the lower fan contain abundant, thicker, sandy turbidites (Damuth and Kumar, 1975; Coumes and Le Fournier, 1979; Moyes *et al.*, 1978).

The Amazon Fan has been the subject of several studies undertaken by L-DGO scientists and students (Manley, 1989), sedimentology and especially sediment geochemistry undertaken by French scientists during expedition ORGON II (summarized in Combaz and Pelet, 1978), and paleontological studies undertaken by Showers on L-DGO core material and in conjunction with a 1991 Meteor cruise (Showers *et al.*, in press, in prep). Some of the existing PETROBRAS seismic data for the shelf and upper fan has recently been summarized by Bruno (1987).

Detailed mapping of the fan with high-resolution seismics (digitally-recorded airgun and watergun), supplemented with long-range side-scan sonar (GLORIA) and SeaBeam multibeam bathymetry, has shown a complex pattern of submarine channels and large debris flows (Damuth *et al.*, 1983a, b; Damuth and Flood, 1983/1984, 1985; Flood and Damuth, 1987; Damuth *et al.*, 1988; Manley and Flood, 1988; Flood *et al.*, 1991). Channels are common from the base of the submarine canyon to about 4000 m water depth. These channels are remarkably sinuous with length scales and sinuousities similar to those of terrestrial rivers, suggesting that the channels have been formed through a continuing interaction between turbidity flow and sediment deposition. Although numerous channel segments are recognized on the fan, only one channel is now connected to the Amazon Submarine Canyon (termed Channel 1 or Amazon Channel); all other channels have been disconnected from their upstream source. Channel 1 is the most recently active channel and it has been studied in detail from the canyon to 4273 m water depth on the lower fan where the channel is too small to be resolved on SeaBeam bathymetry (i.e., <200 m wide).

The sinuous fan channels, including Channel 1, are perched on top of lens-shaped, aggradational overbank deposits to form channel-levee systems in the upper and middle fan. On both the upper and middle fan, channel axes are marked by near-vertical, high-amplitude reflections (HAR). Drilling of the youngest channel floor on the Mississippi Fan has demonstrated that these high-amplitude reflections are associated with sands and gravels in the channel axis (Stelting *et al.*, 1985b). The HAR pattern commonly appears to extend deep within the channel-levee system, and its presence and distribution within the levee has been used to map the evolution and the meandering of the channel-levee system (e.g., Stelting *et al.*, 1985a; Kastens and Shor, 1986). However, seismic modeling studies suggest that the precise pattern of HARs within the levees may result, in part, from the plan geometry of the highly-reflective channel floor and, thus, do not always indicate the distribution of more deeply buried sand within the levee (Flood, 1987).

As the downfan limit of the middle fan is approached, semi-transparent levee deposits and transparent debris-flow deposits begin to interfinger with units composed of multiple, strong, parallel seismic reflections. As the lower fan is reached, levee deposits and debris flows pinch out to give rise to a sequence of highly-reflective, nearly parallel horizons that extend at least to the lower fan. Channels on the lower fan are generally less than 20 m deep and have small, reflective levees.

The large number of abandoned channel segments on the fan appear to have been created through the process of avulsion (Damuth *et al.*, 1983b). Avulsion occurs when turbidity currents breach an existing channel wall. Subsequent downslope flows abandon the track of the old channel downstream of the gap to create a new channel segment. With time, overbank deposits from the newly created channel fill the adjacent older channel near the point of avulsion, but the topographic expression of the older channel can remain preserved for a relatively long time. Because avulsion has occurred many times on the fan, there are numerous local topographic highs associated with abandoned channel sections at mid-depths on the fan.

Detailed topographic analysis of the fan suggests that the sinuous channels appear to approach graded profiles because channel sinuosity varies downfan apparently to keep the along-channel gradient uniformly decreasing downfan (Flood and Damuth, 1987). Graded profiles exist on the fan apparently because of the passive margin setting and the large sediment influx. If the channels are at grade, localized changes in channel depth, such as caused by an avulsion, will cause the channel to cut down rapidly upstream of the avulsion and to aggrade rapidly downstream of the avulsion (Flood *et al.*, 1991; Pirmez, in prep.). Such rapid deposition may create the flat-lying, high-amplitude, lobe-like reflection packets (HARPs) that underlie a channel-levee system in the middle fan and that extend downfan to form part of the lower fan. This interpretation suggests that portions of the seismically identified lower fan are formed concurrently with channel-levee systems. Also, coarse sediments may be transported through the long, leveed channels by repeated cycles of avulsion and downcutting, thus providing a mechanism for transporting coarse material to the deeper, sandy parts of the fan.

Analysis of closely-spaced watergun profiles in the vicinity of Channel 1 show that individual lens-shaped channel-levee systems overlap and coalesce to build levee complexes that also stack and overlap, but that are bounded by large debris-flow deposits. This alternation of acoustic facies appears to form a cyclic pattern but, because both channel-levee systems and debris flows can be active at the same time (for example, one of the major near-surface debris flows can be traced to a diapir field), this cyclicity may not necessarily develop as a result of external controls such as sea-level change. However, while channels of the Upper Levee Complex (above debris flow? Unit R) can be traced to the modern canyon, those of the buried Middle Levee Complex lead to a buried canyon. This suggests that at least portions of these complexes might have formed during different sea-level low-stands.

Several approaches have been undertaken to estimate the age of distinctive seismic facies observed on Amazon Fan to determine the possible relationships between fan activity and sea-level fluctuations. These estimates provide a wide range of possible ages that each have important implications for sea-level controls on fan development. Damuth *et al.* (1983b) estimated, based on sedimentation rates thought typical of surficial Amazon Fan sediments, that the 6 to 10 major levees exposed on the fan surface could all have been deposited within the last 2 to 8 m.y. or about 200,000 to perhaps 1.3 m.y. per system. Pirmez (in prep.) has extrapolated sedimentation rates observed in channel-axis piston cores on Channel 1 to the base of that channel-levee system and estimates that only the channel-levee systems closely associated with Channel 1 were deposited during the last glacial low stand, suggesting that each major levee results from a single low-stand. Manley and Flood (1988) note that nearly all of the exposed channel-levee systems can be traced to the present-day Amazon Canyon while a more deeply buried channel-levee system seems to be related to a buried canyon system. Thus all of the exposed levees (actually, the Upper Levee Complex) may have been deposited during the last glacial period. Such a high fan-growth rate may require that nearly **all** of the sediments discharged by the Amazon River during the low-stand be deposited on the fan. Only through deep sampling can the precise relationship between fan growth and sea-level fluctuations be determined.

Piston-core transects were collected across channel and levee deposits at several depths downfan in conjunction with SeaBeam surveys. Dating of middle-fan turbidites associated with the most recently active Channel 1 yielded a maximum age of about 13,000 years (C^{14} dating of coarse organic debris; Flood *et al*, 1991), suggesting that active levee building continued into the post-glacial sea-level rise of the early Holocene. Analysis of cores from along Channel 1 suggest that the locus of deposition migrated landward during the early interglacial period. At about 9,500 y.b.p., sea level became high enough to prohibit significant river-derived sediment from reaching the fan.

Many of the cores collected from the Amazon Fan contain relatively high organic carbon levels, as is typical for muddy fan sediments. Early sediment diagenesis occurs on the fan as gas in 10-m piston cores occasionally causes 10-cm gas cracks developing after the cores were retrieved. This was especially true for cores collected near a recent bifurcation point along Channel 1 at about

3600 m water depth. Perhaps sediments accumulate rapidly immediately following channel avulsion, allowing high-quality organics to become incorporated into fan sediments. At least one authigenic carbonate nodule has been recovered from the Amazon Fan with a C^{13} value of $-52^{o}/_{oo}$, consistent with a biogenic methane source (Showers, in prep). The nature of organics and of their early diagenesis in different fan environments needs to be studied to understand their sources, the role of fan processes in preserving organic matter, and the paleoclimatic information of the organic material itself.

While these bathymetric, subbottom, seismic, and limited core data provide a picture of the distributary channel system and of the fan-growth pattern, a more realistic and detailed understanding of the vertical succession of sediment facies, sediment composition, and relative and absolute ages, and thus a fuller understanding of actual fan growth patterns and processes and their relationships to sea-level fluctuations, will require direct sampling of sediment sequences.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To establish an absolute chronostratigraphic framework to define the relationship, if any, between the development of fan deposits, sea-level fluctuations, and uplift of the Andes.

2) To determine the sediment lithologies and sedimentary processes associated with distinctive acoustic facies and the relationship, if any, between these facies and sea-level fluctuations.

3) To determine rates for the accumulation of the fan and its discrete facies and rates of continental denudation and temporal variations in the volume of transported sediment as a function of sea-level, land climate, and Andean tectonics.

4) To determine the nature of depositional processes creating meandering distributary channel systems which have been discovered on a number of modern fans (Bowen *et al.*, 1984).

5) To characterize the sediment facies distributions within a large, mud-rich fan system in order to compare them to turbidite facies associations derived from smaller, sandy ancient fans (Mutti and Ricci Lucci, 1972).

6) To understand climate change within the Amazon drainage basin as recorded in Amazon Fan sediments and to compare this record with oceanic glacial/interglacial climate cycles world-wide.

7) To characterize the nature, origin, and early diagenesis of organic carbon present in different fan sedimentary units.

8) To determine the nature and timing of surficial circulation patterns within the western equatorial Atlantic and their relationships to climatic signals observed in South America and elsewhere (Broecker *et al.*, 1990).

9) To gain an independent record of Andean tectonics through the identification and geochemical analyses of intervals of increased sediment flux to the fan independent of sea level fluctuations.

10) To integrate information from Amazon shelf studies (e.g., AmasSEDS) and eustatic sea-level curves (e.g., Chappell and Shackleton, 1986; Fairbanks, 1989) with fan sedimentation, land climate, and equatorial circulation patterns to determine Amazon-region changes within natural time scales such as the glacial/interglacial period.

Specific Objectives and Methodology

The Vail/Exxon Conceptual Sea-Level Model For Deep-Water Systems Tracks

The past decade has witnessed the refinement, popularization, and sometimes wide-spread application of the conceptual sea-level model based on seismic stratigraphy that was advanced by P.R. Vail and colleagues during the late 70's (see AAPG Memoir 26 and SEPM Memoir 42). One facet of this conceptual model predicts that various components of deep-water depositional systems, especially deep-sea fans and associated submarine canyons, form at specific times of any single sea-level cycle. In other words, the relative rise and fall of sea level controls development of fan subenvironments in a predictable manner (Mitchum, 1984; Mutti, 1985; Posamentier *et al.*, 1988; Posamentier and Vail, 1988). For example, the current Vail conceptual model predicts that the sand-rich lower fan (lobe) sub-environment forms during initial relative fall and downward acceleration of sea level in response to the incision and erosion of the continental shelf and upper slope by the submarine feeder canyon and its associated fluvial valley. The resultant mound-shaped, unchannelized deposit downlaps onto the previous sequence boundary and is termed the "basin-floor fan" (Van Wagoner *et al.*, 1988). As sea-level fall slows and reaches maximum fall, erosion decreases and a more muddy middle-to-upper fan sub-environment composed of channel-levee systems called the "slope fan" is deposited over the "basin-floor fan." Vail (pers. comm.) and Mitchum (1985) consider the "basin-floor fan" to be equivalent to the sandy lower fan sub-environment (depositional lobes) identified on modern fans and the "slope fan" to be equivalent to the muddy channel-levee systems of the middle-to-upper fan sub-environment on modern fans.

Although this Vail/Exxon fan model based on seismic observations is being increasingly utilized, very little hard data (e.g., cores) have been put forward and the validity of this fan model remains questionable. In fact, stratigraphic relationships observed in cores which penetrate the last glacial-interglacial sea-level cycle on the Amazon Fan and some other modern fans (e.g., Mississippi, Indus) indicate that the sandy lower-fan sub-environment (basin-floor fan of Exxon model) and the muddy middle-to-upper fan sub-environment (slope fan of Exxon model) actually form contemporaneously throughout the sea-level cycle (Damuth and Kumar, 1975; Damuth *et al.*, 1988; Kolla and Macurda, 1988; Flood *et al*, 1991). Critical to identifying the basin-floor fan in a setting such as the Amazon Fan is the identification of sequence boundaries (times of relative sea-level fall) because basin-floor fans lie on the sequence boundary. This kind of information is completely missing on the Amazon Fan and in other large fan systems making it very difficult to clearly identify a basin-floor fan in these systems.

Unfortunately, piston coring of the Amazon and other fans, as well as recent drilling of the Mississippi Fan during DSDP Leg 96 (Bouma, Coleman, *et al.*, 1986) have failed to penetrate sediments older than the last glacial (Wisconsin) and therefore do not even completely record one complete 4th order (100,000 year) sea-level cycle. Leg 155 will penetrate several, overlapping stacked channel-levee systems and levee complexes that may (based on sedimentation rates obtained in piston cores) represent several 4th order (100,000 year) sea-level cycles and perhaps one or more 3rd order (1-3 m.y.) cycles, thereby testing the validity of the Vail/Exxon model for deep-water systems tracts by allowing the following questions to be addressed.

> (1) What is the timing of formation of submarine fan sub-environments in relation to sea-level cycles? Does a single channel-levee system form in response to a single sea-level cycle (3rd or 4th order) or is there no relationship between channel-levee formation and sea-level fluctuation, i.e., channel-levee systems form as a result of channel avulsion processes unrelated to sea-level change? What relationships are there between debris-flows and sea-level change?

(2) Do Vail/Exxon sequence boundaries and maximum flooding surfaces exist in the submarine fans and are they truly recognizable on seismic records? If so, what is the relationship of channel-levee systems to sequence boundaries and flooding surfaces? Do the high-amplitude reflections that commonly mark the upper surfaces of channel-levee systems actually represent condensed sections/maximum flooding surfaces and are the erosional surfaces at the bases of channel-levee systems sequence boundaries as suggested by Weimer (1989) for Mississippi Fan? Or do these surfaces merely represent local erosion, growth and shifting through avulsion of individual channel-levee systems unrelated to sea-level changes?

(3) What is the temporal relationship of lower-fan deposits (depositional lobes) to middle and upper-fan deposits (channel-levee systems)? Is the lower fan (basin-floor fan of Exxon model) a separate older feature than the middle fan (slope fan of Exxon model), as put forward by the model (Mitchum, 1985; Van Wagoner *et al.*, 1988), or are channel-levee systems and lower-fan lobe contemporaneous as the data from modern fans suggest (e.g., Damuth and Kumar, 1975; Damuth *et al.*, 1988; Kolla and Macurda, 1988; Flood *et al*, 1991).

Sediment Chronology

There are three primary time periods of interest, each relying on a series of techniques and datums. First, the climatic and sedimentary history of the last major sea-level lowering from about 40,000 y.b.p. to the present must be characterized (Chappell and Shackleton, 1986). The prime tools for this time interval include AMS (and perhaps bulk) C^{14} (half life 5700 years) dating of all appropriate sediment components, including foraminiferal tests, pollen and seeds, coarse woody debris, dispersed organic matter, and other organic fractions that can be separated. Each kind of sedimentary environment sampled (e.g., channel floor, proximal levees, distal levees, condensed sections) will preferentially contain a different mix of sediment components (e.g., foraminiferal tests in condensed intervals, wood fragments in channels and proximal levees), and results will need to be correlated between sites using other techniques such as seismic profiles and perhaps mineralogy, physical properties, and magnetics. Initial assessment of the value of AMS and bulk-C^{14} dating, along with small-volume O^{18} data, in this high-sedimentation-rate environment (Showers and Bevis, 1988; Showers *et al.*, in press; Flood *et al.*, 1991), is encouraging. Since each sediment component will experience a different time delay between the inclusion of C^{14} and burial in the sediments, the resulting profiles may contain additional information about organic carbon storage and cycling.

Other dating opportunities in this interval include standard biostratigraphy zonations (especially *Globorotallia menardii* and *Pulleniatina obliquiloculata*) and perhaps less standard paleomagnetic techniques such as secular variation where sedimentation rates are high. O^{18} curves may clarify sediment stratigraphy in this range, but the O^{18} record here contains spikes due to the Amazon River and changes in ocean circulation patterns. Thus the value of this approach for dating can not be assessed until the O^{18} profiles are available. Showers at NCSU can develop O^{18} curves from very small samples such as those available from high-sedimentation-rate environments on the fan. Showers has recently been funded to acquire a "Kiel device" to allow the rapid analysis of O^{18} on small-volume samples, and it is anticipated that a large number of O^{18} analyses will be acquired from these cores even in intervals where sedimentation rates are high.

U-series dating, especially using Th^{230} (half life 7.52 x 10^4 years) along with Pa^{231} (half life 3.43 x 10^4 years), have been used in other areas to provide age estimates in this time interval, but due to the large lateral and temporal changes in sediment flux to the fan very precise dates are not expected here. However, understanding the flux of these elements to the sediment within relatively well dated fan sedimentary environments is interesting in its own right, and will probably feed back to a better stratigraphy (M. Bacon, WHOI, pers. comm., 1992). New high-sensitivity analytical techniques are now becoming available for the analysis of relatively old samples in high-sedimentation-rate environments (M. Bacon, WHOI, pers. comm., 1992).

Using this kind of integrated approach, it should be possible to recognize sediment ages corresponding to the Stage 3 sea level high (~ 30,000-40,000 y.b.p.), sea level fall (~ 20,000-30,000 y.b.p.), the maximum low stand (~ 18,000-20,000 y.b.p.), and the modern sea-level rise (~ 18,000 y.b.p. to present).

Our second time interval of interest is the last one to a few glacial-interglacial cycles (to about 125,000 to 300,000 y.b.p.) where it is necessary to identify the sediments and seismic horizons that correspond to the last, and perhaps prior, sea-level high stands and climatic warm periods. Again, an integrated approach is needed, but it is anticipated that identification of the high-stand interval will rely primarily on planktonic foraminiferal type and abundance (along with carbonate percentage, etc.). O^{18} isotopes will probably prove a useful stratigraphic tool in this time range, but will need to be approached with caution. Th^{230}/Pa^{231} dating techniques will be used to distinguish the Stage 5 interglacial from the one previous. For condensed sections that extend back through several glacial-interglacial climatic cycles, the U-series dating may actually work well.

Standard biostratigraphic zonation techniques, supplemented with magnetostratigraphy and perhaps stable isotopes, will be used to characterize the longer-term development of the continental margin, extending back to Pliocene or perhaps earlier. O^{18} records (with the caveats noted above) and species composition will help to resolve local sea-level stages, but precise dating or correlation of each sea level sequence at high resolution is unnecessary. This stratigraphic resolution will enable dating of the major pulses of sedimentation that may be related to Andean uplift and also clarify the general changes in the nature of fan sedimentation and the climatic records during the passage from a time of large sea-level fluctuations (700,000 y.b.p. to present) to a time of smaller sea-level fluctuations (pre-700,000 y.b.p.).

The Equatorial South Atlantic Continental Climatic Record

Studies of land fauna and Pleistocene geology within the Amazon drainage basin indicate that climate during glacial cycles may have been vastly different from that of today; during glacials, the vast tropical rain forests shrank and all but disappeared, and semi-arid savannahs prevailed (Damuth and Fairbridge, 1970). However, the continental record of these changes remains incomplete and poorly known or dated. In particular, the paleotemperature record derived from continents and oceans for the last glacial maximum (LGM) at 18k is inconsistent. No process that can account for continent-derived large temperature depressions and very little sea surface temperature change at low latitudes has been identified (Rind and Peteet, 1985). Recent evidence from one locality (paleotemperatures based on measurements of atmospheric noble gasses dissolved in groundwater of a Texas aquifer (Stute *et al.*, 1992) supports the existing continental data.

The question of glacial-interglacial temperature difference is a fundamental question of importance for understanding future climate change. Whether or not the ocean was 2° colder than today at low latitudes has major implications for the hydrological cycle (which in turn controls deep water circulation) and for the temperature gradient from high to low latitudes.

Very little continental data is derived from the Amazon region, and none of it from the Amazon Basin extends back to the LGM. Thus our proposed record of glacial-interglacial change from pollen and other indicators in the Amazon Fan should be a very important one, reflecting changes in the Amazon drainage basin.

Studies of Amazon Fan sediments to date show an interesting, although limited, record of land climate and its past fluctuations. Damuth and Fairbridge (1970) reported that arkosic sand grains were deposited throughout the Guyana Basin during the last glacial, suggesting an arid Amazon Basin during glacials. However, preliminary studies by R. Kowsmann (pers. comm., PETROBRAS, 1987) suggest not all Amazon sands are arkosic, thus changes in sand composition may reflect temporal patterns of arid versus humid climate within the source area. Also, Kronberg *et al.* (1986) and Nesbitt *et al.* (1990) note that the uppermost Pleistocene sediments (~ 11,000 to 9,500 y.b.p.) have bulk chemical compositions and rare-earth enrichment patterns slightly less pronounced than those observed on the Amazon shelf or river today. These compositional trends reflect severe weathering within the source area, and possibly temporal changes in weathering pattern.

A number of techniques, including those described above, are available for understanding continental climate from marine sediments. Pollen and spores from land plants are incorporated in marine sediments, and the record of land vegetation can often be reconstructed by pollen studies (Heusser and Shackleton, 1979). An understanding of glacial-interglacial vegetation changes is important in estimating the rapidity and size of future climatic changes (Peteet, 1986). Pollen-derived land temperature records need to be compared with oceanic paleotemperature estimates in order to more fully understand the role of tropical and subtropical regions in climate dynamics. For example, in subtropical regions, land temperatures appear to be colder in glacial periods while correlative ocean temperatures are warmer (Rind and Peteet, 1985). Records of past pollen variation have been obtained from some large lakes in the Amazon rain forest (Absy, 1985), but so far these records extend back only about 7,500 years. The pollen preserved in the Amazon Fan (when properly interpreted in light of fan sedimentation and growth patterns) will provide a longer and more detailed record of land vegetation in the Amazon River drainage basin. The marine pollen record has been studied in piston cores off northern Brazil, including several sites on the Amazon Fan, by Caratini and Tissot (1976) and Caratini *et al.* (1978). These pollen records suggest an overall change in land vegetation for northeastern South America from savannah to mangrove during the transition from the last glacial to full interglacial (Holocene) conditions. However, temporal and spatial resolution are poor, and the patterns reported in distal settings may reflect a change in the source of the pollen (from river-derived to coastal mangrove) rather than a change in land climate. It is anticipated that pollen records preserved within relatively proximal levee sediments will record river-borne material whenever the levees are actively building.

The record of pollen and spores incorporated in the sediment can be dated through the use of AMS C^{14} techniques by isolating the pollen and spores before dating (Brown *et al.*, 1989; Peteet, Goddard, pers. comm., 1991). The resulting age dates the time when the plant was alive (a very important date for paleontological studies), not when it was incorporated into the fan sediments (a more important date for determining fan growth). The age of its deposition will be somewhat later than its demise because of reworking that occurs during the transport of material through the river to the fan.

By comparing AMS C^{14} dates on the pollen and spore fraction with those determined by AMS C^{14} dates on planktonic foraminifera and on other organic matter fractions in the same or correlative sediments, the lag between organism demise and burial can be estimated for different sediment ages during the last 40,000 years, thus providing an indicator of the role of temporary storage within the basin for different climatic and sea-level stages. Such a record will assist in evaluating the degree to which the faunal and other land climate records are degraded by mixing.
Sediment geochemistry, both inorganic and organic, and mineralogy will also provide critical data on continental climate. The suite of clay minerals transported by the Amazon river at any given time should be indicative of terrestrial weathering patterns within the drainage basin and thus of prevailing climate. Chemical weathering leads to an enrichment of kaolinite and gibbsite. Mechanical weathering, predominant during glacials in the Andes, could enhance the abundance of chlorite if weathering is not severe. Weathering under savannah conditions will probably lead to a relative decrease of illite with respect to kaolinite and gibbsite. It is anticipated that fan sediments will show clay mineral fluctuations that reflect temporal fluctuations of glacial/interglacial climate within the source area, including Andean glaciation and changing vegetation patterns (rain forest to semi-arid savannah) along the river pathway. Modern-day clay mineral distribution patterns in the western Equatorial Atlantic do not show a pronounced tropical weathering signature (Biscaye, 1965), presumably because the Amazon River sediments are trapped on the shelf and carried northward by coastal currents. Fluctuations in clay mineral types and abundances will provide an important record of land climate within the Amazon drainage basin.

As noted above, geochemical approaches to sedimentation can provide important evidence about the source (provenance) of sediments and their geochemical history (Table 1; McLennan *et al.*, 1990; submitted). These kinds of measurements can be used to characterize source areas (e.g., old shield rocks vs younger uplifted rocks based on Nd-isotopic composition and mean sediment source ages from whole-rock dating) and the intensity of weathering or diagenesis (e.g., major element chemistry, trace element isotopic character, rare-earth element patterns). These kinds of results, which supplement standard petrographic analysis, can be determined on bulk sediment samples (preferably of the same lithologic character) as well as on particular components such as zircon grains (if available), feldspars, and, in favorable circumstances, quartz populations. Through such analysis it should be possible to determine temporal changes in source rock areas (e.g., shield vs younger mountains) as well as variations in the intensity of weathering on the craton. The manner in which these indicators co-vary should clarify the relative contributions of tectonic uplift and sea-level falls on sediment supply to the Amazon Fan as well as changes in South American equatorial climate. These powerful geochemical approaches have been developed from studies of ancient rocks on land, and a systematic evaluation of the approach in a well-constrained modern setting such as the Amazon Fan would be of tremendous value.

The geochemistry of organic matter on the Amazon Fan can also contribute to the understanding of equatorial climate as well as the organic carbon cycle. Submarine fans can be large reservoirs of organic carbon as a result of high accumulation rates and the close association with land and coastal carbon sources. Questions that can be addressed through organic geochemistry include the source or sources of the carbon, especially the distinction between modern material and material recycled from the continent and the characterization of terrestrial source material. Organic geochemistry can also provide information on organic carbon maturation, migration and degradation, and the changes in these processes with sedimentation history and sediment province. Studies can provide independent evidence of ocean temperature through the analysis of plankton-derived components such as alkenones (Prahl *et al.*, 1988; McCaffrey *et al.*, 1990). Such independent evidence for ocean temperature is needed to correctly quantify equatorial climate dynamics.

Organic chemistry techniques are continually becoming more refined, allowing more quantitative results to be obtained now than was possible even a few years ago such as during DSDP Leg 96 drilling on the Mississippi Fan (Kennicutt *et al.*, 1985; Whelan, 1986). The specific contributions that organic carbon studies can make towards Amazon Fan drilling (and vice-versa) will be discussed by Jean Whelan at the Gordon Conference on Organic Geochemistry this August.

By coring through a sequence of successively older levee deposits, a nearly continuous, high-resolution section of fine-grained sediments will be obtained for analysis of temporal changes in pollen, sediment mineralogy, sediment geochemistry, and organic carbon. From this record, it will be possible to construct an important record of land climate that extends from at least the last interglacial period through the last glacial period to the present Holocene interglacial, and perhaps back to Pliocene or perhaps Miocene times.

Equatorial Oceanic Dynamics and Paleocirculation Patterns

In addition to containing an important record of land climate during glacial/interglacial climatic stages and transitions, the Amazon Fan also underlies the western tropical Atlantic water masses.

These water masses and their circulation are particularly important in terms of ocean dynamics and inter-ocean heat transfer. Oceanic currents in this area include the westward-flowing South Equatorial Current (SEC), the north-westward-flowing North Brazil Coastal Current (NBCC; Metcalf and Stalcup, 1967; Richardson and Walsh, 1986), and the eastward-flowing North Equatorial Countercurrent (NECC). The NBCC is the only know cross-equatorial heat transport in the global circulation pattern, and thus an important link in the present-day climatic regime. From December to June, the NBCC may extend into the Guyana Current and link with the Caribbean Current when wind stress variation causes increased transport in the NBCC (Picaut *et al.*, 1985; Philander and Pacanowski, 1986). However, the NBCC turns eastward (retroflects back) into the NECC between July and November. Lenses of low-salinity surface water occasionally become detached and can move seaward, perhaps also as a result of weakening of trade winds, NECC eddies, or variations in Amazon River discharge (Nittrouer and DeMaster, 1986). During low sea-level stands, the river will discharge directly into relatively deep water, and mixing of the river plume into the coastal water may occur more slowly than at present allowing more extensive fresh-water lenses to form.

Planktonic foraminifera are found in sediments of the Amazon Fan despite the relatively high accumulation rates. These high accumulation rates expand the planktonic record making high-resolution time series possible, and small-volume analytical techniques (Showers and Palczuk, submitted) have allowed isotopic stratigraphies from these rapidly deposited hemipelagic sediments (confirmed by AMS C^{14} dates on small quantities of foraminifera) to be constructed for the first time. The stratigraphy of V31-133, for example, based on the O^{18} curve (including spikes discussed below) and 5 AMS C^{14} dates, suggests accumulation rates as high as 168 cm/k.y. in the late glacial period from 14,300-16,000 y.b.p. with somewhat lower rates in the overlying sediments. Brunner and Ledbetter (1985) note that the presence of fine-grained downslope flows capable of influencing the planktonic foraminiferal record can be detected through the analysis of grain size characteristics. Examination of V31-133 suggests no grain size anomalies within this zone.

The absence of downslope flows in this region is also expected because the site is located on a topographic high that marks an abandoned channel, and thus was not along the pathway of downslope flows once the channel was abandoned.

No foraminifera were recovered from the higher sedimentation rate unit below about 700 cm in V31-133 where somewhat coarser sediments may be related to an adjacent channel-levee system, but this may be due in part to post-coring dissolution of foraminifera in these organic-rich sediments after the core was opened. Showers (in prep.) recovered a core in early 1991 from near the site of V31-133 from the METEOR. The core was opened on board ship and sampled before the black authigenic iron sulfide staining was oxidized. Preliminary analysis suggests that these new samples have significantly higher foram abundances than did V31-133, especially in the deeper sediment layers where no forams had been recovered in V31-133. Thus good material is expected even in some areas where analysis of historic cores has been difficult. However, for time intervals where accumulation is too fast to preserve any forams, sampling will be carried out on seismically correlated sediment deposits that accumulated at a lower rate elsewhere on the fan while this particular channel was active, thus allowing the high-resolution stratigraphic record to be continued back in time.

Showers and Bevis (1988) and Showers *et al.* (in press) note that O^{18} stratigraphies show a number of well-developed negative O^{18} deviations during the late glacial/early interglacial that appear to be correlated and are tentatively interpreted as Amazon River paleo-discharge events. The apparent occurrence of paleo-discharge events (O^{18} spikes) on the eastern portion of the fan but not on the western portion (which lies north of the Amazon River mouth) during certain time intervals suggests that the spikes may be due to reduced activity of the NBCC. Such isotopic events would also mark periods of reduced cross-equatorial oceanic heat and salt transport, important components of the global circulation pattern. If this is the case, then circulation patterns of the glacial western tropical Atlantic could at times have been very different from the modern day circulation regime. Precise dating of the times of these isotopic events and their distribution patterns will allow a better assessment of the relationships between these spikes and other events in global circulation. It will then be possible to identify any leads or lags, and the likely role of Equatorial Atlantic dynamics in global circulation. For example, because the strength of the NBCC is in part due to increased wind stress variation, an equatorial climate regime that resulted in smaller wind stress variation could reduce the strength of the NBCC and thus, perhaps, on cross-equatorial heat flux. Thus the western Equatorial Atlantic could act as a "pressure point" with small changes in regional dynamics having a major effect on ocean circulation. To date, good O^{18} records do not exist prior to about 16,000 y.b.p. because of high sedimentation rates on the fan. Therefore, drilling is needed to collect a more complete suite of core material suitable for isotopic analysis, extending farther back in time and including more areas of the margin to more fully understand possible changes in ocean mixing and current patterns in this critical portion of the oceans.

Andean Tectonics

One of the goals of drilling on Amazon Fan and the adjacent Ceara Rise is a more precise determination of the timing of mountain building in the Central Andean cordillera. Mountain building and the maintenance of high topography are essentially synchronous, that is, high mountains cannot be long maintained without active tectonic forcing (e.g., Turcotte and Schubert, 1982; Kono *et al.*, 1989).

Dating the record of Andean uplift should increase the understanding of the linkages between mountain uplift, crustal stress patterns, plate convergence rates, and magmatism (see for example the prior Andean studies by Pilger, 1984; Sebrier *et al.*, 1988; McKee and Noble, 1989; Nobel *et al.*, 1990; Sebrier and Soler, 1992) and indicate the major impact of the uplift of the Andes upon global climate. Previous tectonic studies have generally been hampered by a poor knowledge of the history of uplift. Most work in this field utilizes radiometric age dating of continental volcanic or sedimentary rocks, studies of paleotopographic surfaces and erosional incisions, and cosmogenic dating of exposed surfaces. There is also one published seismic study (Kolla *et al.*, 1984) which attributes timing of increased inputs of terrigenous sediment on the Magdalena Fan in the Colombian Basin to uplift events in the northern Andes.

Previous climatic studies have considered the importance of uplift of broad plateaus and high cordillera in the Northern Hemisphere upon global climate change (e.g., Ruddiman, 1990). The Andes have been largely neglected in these global circulation models despite the fact that they are the world's longest mountain range. Partly, this neglect is due to uncertainty regarding the timing of their uplift, and partly to suppositions that global climate change was forced by formation rates of North Atlantic deep water.

Sebrier *et al.* (1988) have concluded, on the basis of geomorphological studies in the central Andes, that uplift is a result of compressive tectonic events and that the uplift occurs during or just subsequent to the compressive pulses. Compressive pulses have been dated at ca. 42 Ma, ca 26-28 Ma, ca. 15-17 Ma, ca. 10 Ma, ca. 7 Ma, and ca. 2 Ma. Uplift events in the central Andes have been attributed to Middle Miocene, Late Miocene and Pleistocene (Sebrier *et al.*, 1988). The latter also concluded that the central Andes must have already risen to about 2000 m above sea level (about one-half of their present elevation) by the Early Miocene.

The tectonic drilling objectives in the distal Amazon Fan and on the Ceara Rise are: (1) to determine the mechanisms of sedimentation linking the distal fan and the Ceara Rise to the proximal fan and the Amazon River; (2) to recover the entire Neogene section on the distal fan and on the Ceara Rise in order to determine rates of detrital sedimentation in these holes and thereby infer periods of increased Andean uplift and erosion, and (3) to determine the composition of these sediments as a possible means of provenance identification for understanding differential uplift within the Andes. Because of the extreme thicknesses of Amazon Fan, a complete hole through the fan, even at the distal end, would not be possible within the framework of the present proposal. Also, a more complete understanding of Andean uplift will require similar sampling programs off the Magdalena and Oronoco Rivers which also drain the Andes. However, a single, relatively deep site on the lower portion of the fan, perhaps near Ceara Rise, is an important first step towards recognizing these objectives, especially as previous DSDP holes in this region were not continuously cored.

The Effects of Fan Load on Continental Margin Sedimentation

The Amazon Fan, with horizontal dimensions of about 500 km and a maximum thickness of about 5-8 km (most of which was deposited since the Middle Miocene), presents a significant crustal load on the north Brazil continental margin (Pirmez and Driscoll, in prep.). The primary depocenter associated with post-Middle Miocene deposition is located at the upper continental slope, immediately downslope of the present day shelf edge and to the west of Amazon Canyon with secondary depocenters with localized sediment thicknesses up to 4.2 km observed offshore on Amazon Fan. As described above, the Amazon Fan continues to be the site of rapid sediment accumulation during glacial periods, with the last pulse of sedimentation ending about 13,000 y.b.p. Indeed Manley and Flood (1988) suggest that up to 4 x 10^{13} tonnes of sediment may have been deposited on the offshore portions of Amazon Fan from about 40,000 to 13,000 y.b.p. Sedimentation on the North Brazilian margin continues today through the accumulation of Amazon River sediments in a subaqueous delta (Nittrouer *et al.*, 1991).

The rapid deposition of Amazon Fan sediments on the margin constitutes a significant load on the lithosphere, causing a downward deflection. The load is supported regionally because the lithosphere acts as a rigid plate (Walcott, 1970, 1972; Watts, 1978; Karner and Watts, 1982). Cochran (1973) compiled a regional free-air gravity anomaly of the Amazon Fan and adjacent regions, and, using simple lithosphere models, determined that the lithosphere under Amazon Fan had a flexural rigidity (D) between 1 and 5 x 10^{23} N.m., which results in an effective elastic thickness (Te) for the lithosphere of between 25 and 43 km. His best fit model resulted in a Te of 32 km. Pirmez and Driscoll (in prep.) estimate that the total crustal deflection associated with sediment accumulation in the last 10.5 Ma is about 4 km. While the region near the load will be depressed, regions far away from the load may experience uplift (the flexural bulge). In addition, because the lithosphere flexes in a nearly elastic fashion, the deformation associated with this loading continues as long as the load is in place.

Pirmez and Driscoll (in prep.) have determined, using a simple two-dimensional model for the lithosphere and assuming point loads (Turcotte and Schubert, 1982), that the flexural bulge from this load should be about 170 m high and about 240 km from the depocenter, or nearly along the coastline directly north of the Amazon River mouth. This portion of the continental margin apparently shows evidence of both long-term and short-term uplift, including Pre-Cambrian basement outcropping 15 km from the coastline, a thin (~ 5-km-wide) strip of alluvial Tertiary deposits, and a thin (~ 10-km-wide) strip of more recent sediment at the coastline. Apparently uplift has not left much accommodation space for Neogene and Quaternary sediments to accumulate.

In addition to these overall indicators of coastal uplift, there also appears to be evidence, compiled by Nittrouer *et al.* (1991) and Dias *et al.*, (1990), that is consistent with very recent vertical movement in this region, including diversion of coastal rivers, ponding of lakes, present-day erosion of sediments deposited only 500-1000 y.b.p., and a region of no accumulation on the shelf where the bulge is predicted. Pirmez and Driscoll (in prep.) suggest that these recent vertical movements are in part due to the lateral shifting of the flexural bulge in response to shifting depocenters on the margin offshore during the last sea-level low-stand and onshore during the present high-stand. The lateral and vertical movement associated with the flexural bulge combine with glacial eustacy to create the relative sea level curve for this portion of the margin. Because the mantle is viscous, the response to loading or unloading (relaxation) occurs over a period of time (Cathles, 1977; Peltier, 1980). Relaxation times determined for large loads such as the Northern Hemisphere ice-sheets (wavelengths on the order of a few thousand kilometers) are of the order of a few thousand years (Turcotte and Schubert, 1982). Smaller loads, of a few hundred kilometers in size such as channel-levee complexes will involve considerably longer relaxation times.

In order to evaluate how visco-elasticity and temporal response of the lithosphere by loading by fan sediments will interact with coastal (and potentially fan) dynamics at time scales on the order of 10^3 to 10^4 years, additional information about margin sedimentation is needed. In particular, it is necessary to 1) determine the ages and rates of deposition of fan sediments in different portions of the fan, 2) calculate, using three-dimensional models with realistic mantle viscosities, how shifts in fan depocenters and the size of channel-levee systems and complexes will affect the lithosphere, and 3) determine in detail the characteristics, paleoenvironments and ages of the sediments being eroded near the coast and within the shallow offshore unconformity to better constrain the history of subsidence/uplift in the different regions (this last work is presently underway under the direction of C. Nittrouer, MSRC/SUNY, as part of AmasSEDS). Drilling on the Amazon Fan, integrated with the regional seismic grid and growing knowledge of coastal and continental shelf sedimentation, will clarify the temporal changes in sedimentation that occur due to subsidence and flexure. This tectonic feedback mechanism will affect coastal, and perhaps fan, sedimentation processes, and, in certain circumstances, might even affect the delivery of sediment to the margin itself, thus potentially altering the stratigraphic response of the margin to sea level change.

DRILLING PLAN/STRATEGY

Channel-levee sequences are one of the basic sedimentary units of large, muddy fans. In particular, the middle fan is built of a large number of these sequences deposited one on top of another, punctuated by large-scale debris flows. A series of APC/XCB sites (15 to 20) which penetrate a number of these stacked middle-fan levee sequences (water depth about 3.5 km) should provide a complete stratigraphic sequence for the last major cycle of fan deposition (the Upper Levee Complex of Manley and Flood, 1988) which may span one or more glacial sea-level lowerings. These proposed APC/XCB sites will be located on the levees of well-imaged channel-levee systems whose relative ages can be deduced from seismic profiles (Damuth *et al*, 1983b; Manley and Flood, 1988). The record will be considerably expanded (probably with a better pollen and mineralogy record) where the levees are cored near active channels, and somewhat compressed (probably with a better planktonic stratigraphy) where the thinner portions of active levees are sampled and, especially, on the tops of abandoned levees. To obtain a complete stratigraphy from both proximal and distal levee environments, sections from more than one channel-levee system will have to be combined. Sites will also be positioned along levee systems in order to determine variations in sedimentation and timing of deposition down-fan. Sampling sites should also include channel-floor deposits and the highly reflective, flat-lying HARP units that underlie channel-levee systems in order to characterize the turbidite facies and sequences within these units and their relationships with other acoustic units. At least one or two core sites should be deep enough (400 to 600 m subbottom) to reach Unit R (the debris flow deposit?) that underlies the Upper Levee Complex and to reach channel-levee system preserved in the buried Middle and Lower Levee Complexes. These deeper holes are necessary in order to determine the upper age limit of these older levee complexes, as well as to determine the sedimentological nature of the transparent and highly reflective acoustic zones between levee complexes. One deeper hole should also be drilled on the lower fan to help understand fluctuations in Andean uplift.

PROPOSED DRILL SITES

Twenty proposed drill sites (Table 1, Fig. 2) have been identified on the Amazon Fan. Eleven holes are primarily APC/XCB holes with total depths of 100-207 m. Five holes have total depths of 226-369 m, and may require APC/XCB to refusal followed by RCB. Two holes have a total depth of 568 m and will most likely require RCB following APC/XCB to refusal. The uppermost portions of all holes will be double-cored to ensure a complete section. While most of the holes will be in relatively fine-grained sediments, some holes will encounter unconsolidated sands that will need the VPC (vibro-percussive corer) to recover. Holes greater than about 150 m most likely will be logged.

Proposed site AF-1 is located in deep water on the middle or lower fan and will sample the oldest fan sediments. At present, this is a somewhat generic site on the middle fan that penetrates through a relatively thin sequence of channel-levee distal levees and debris flows, and reaches the sediments of the Lower Levee Complex. This kind of site will provide a longer-term record of changes in sediment input due to Andean uplift.

Proposed sites AF-2 and AF-3 are in relatively deep water and most likely will sample the oldest fan sediments. Specific deep objectives for proposed site AF-2 are the proximal levee of Amazon Channel, the high-amplitude reflectors that underlie this channel-levee system, the debris-flow unit (Unit R), the Red system (related to an older submarine canyon), and the Green and Gold systems (separated from the Red system elsewhere on the fan by a debris-flow unit). Sampling the Gold system near the top of the levee will recover a sequence dateable by paleontological techniques. Proposed site AF-3 will also sample the top of the debris-flow 50 km downslope where it is beginning to thin. AF-2 and AF-3 penetrate and sample the pronounced reflective layers that may be sheet sands associated with channel avulsion. These holes will reveal the character of the sediments that make up these layers and their likely depositional processes. AF-2 and AF-3 also will sample levee sediments of the recently active channel and the contact between the Channel 1 levee and underlying levees. The Brown system (sampled in AF-13 less than 2 miles from AF-3) is initiated between the sites of AF-2 and AF-3 and sampling will identify how the levee system upslope of the avulsion responds to this recent avulsion event.

Proposed sites AF-4 and AF-5 are located towards the western portion of the fan where much of the surface morphology is covered by one or more large debris flows. AF-4 samples the proximal portions of the Purple system and the transition to the present Channel 1. AF-5 samples the western debris flow to determine the number of flows represented and the source of the material and will also sample an undated but relatively shallow system (2B). AF-4 and AF-5 both sample through these uppermost system and into more deeply buried systems that have not been dated. Because of the patchy distribution of levees on the fan, these undated but relatively shallow systems may record important time intervals.

Proposed site AF-6 is located on the levee of Channel 1 near the site where the channel diverged from the path of the Aqua system. The levee at this proposed site shows several distinctive layers that will be sampled. These layers may have been formed as part of the response of the channel-levee system to downstream avulsions and resulting changes in base level or they may represent pelagic intervals deposited during sea-level high-stands. The hole will end in sediments that predate levee deposition in this area.

Proposed sites AF-12 and AF-15 are shallow holes that complement AF-6 and sample sediments closely associated with the levee of Channel 1 and the systems that immediately precede it. AF-12 penetrates through relatively acoustically-transparent sediments near the upper fan channel into more uniformly layered sediments below. The recent change in sediments from acoustically-laminated to transparent may signify a change in the kinds of flows that pass through the system, possibly related to sea-level rise. Morphological evidence suggests that the change from laminated to nearly transparent sedimentation correlates to a change from a relatively sinuous to a relatively straight channel. The timing of this change (possibly from C^{14} dating) and the sediment lithologies and facies need to be determined. AF-15 penetrates into the fill of an abandoned channel meander still attached to Channel 1 in order to determine the sedimentary facies in this environment and the age at which the channel fill started. The meander may have been abandoned as a result of avulsion and downcutting associated with the abandonment of the Brown system. Proposed sites AF-6, AF-12 and AF-15 are in areas of recent rapid deposition, and may be good sites to study early sediment and organic matter diagenesis.

Proposed sites AF-7, AF-8, AF-9, AF-10, and AF-11 all sample proximal levee sediments (along with intervening condensed sections) for the older channel-levee systems within the Upper Levee Complex. AF-7, the shallowest of these holes, is located on the eastern portion of the fan and samples the proximal levee sediments of the Blue and Yellow systems. Systems 6A, B, and C are the oldest channels now exposed on the fan. AF-8 samples the proximal levees of the Blue system and system 6C, but at a deeper water depth and only on levee flanks, and thus perhaps with a less well-preserved planktonic record. AF-9 samples the proximal sediments of the Yellow system, distal levee sediments of system 6A, and also penetrates into the top of a very large, unnamed levee that may be quite old and mark a time of pronounced sediment input, perhaps related to increased

Andean uplift. A good paleontological record should be available from the time following the abandonment of this channel-levee system. AF-10 samples the proximal levees of system 5 on the far eastern part of the fan, and penetrates through this system to the underlying levee sediments. AF-11, a relatively deep hole, samples the pelagic sediments overlying system 6A and levee sediments of systems 6A, 6B, and 6C, ending in the sediments that onlap the large, old channel system. Because of its large total depth, AF-11 is given a priority 2.

Proposed sites AF-2 through AF-12 and AF-15 form an important suite of holes designed to recover proximal levee sediments from each of the channel-levee systems in the Upper Levee Complex that marks the upper 100-200 m of the fan. Such a series of holes will provide a nearly continuous record of the material brought to the ocean by the Amazon River and discharged onto the fan. Such material will contain a valuable record of river discharge and land climate moderated by the effects of sea-level change. Pelagic sections containing interglacial fauna should be recovered from high sea-level stands and these sections will identify the sediments and fan units deposited during a glacial-interglacial cycle.

These holes will also sample several key sedimentary environments to provide important evidence of the sedimentary facies, the structures associated with the evolution of these environments, and the potential relationships between the evolution of these environments and sea level. Several holes provide important information on the sediments associated with recent channel avulsions both upstream and downstream of the avulsion site. Leg 155 will also sample a near-surface debris flow on the western portion of the fan and a deeply-buried debris flow in the central portion of the fan. Through comparing these surficial and deep units, it will be possible to determine the extent to which the near-surface debris flows can be used as an analog for seismically-described units within the fan. The condensed intervals between the levee systems may provide important planktonic material for age-dating, especially where the depositional sites are shielded from the active levee system by intervening abandoned levees. This record will be important for determining where sea-level high-stands, marked by distinctive faunal, organic matter and sedimentary characteristics, fall with respect to the different acoustic units.

Proposed sites AF-13, AF-14, AF-16, AF-17, AF-18, AF-19, and AF-20 all are shallow holes designed to sample the primarily pelagic material that is deposited on topographically-isolated abandoned levees. These holes should provide a continuous record of planktonic material, free of downslope transport because of their elevated locations (based on analysis of existing cores from this environment), for the time intervals following the channel abandonment. While these records are limited in extent by the age of the underlying levee, the records can be extended both horizontally and vertically through the inclusion of material recovered during the condensed intervals from other sites, especially where those other sites are on the flanks of abandoned levees. These holes will provide material from the western (AF-18 and AF-19 at about 3500 m; AF-18 is priority 3 because these sediments should also be sampled by AF-10) and central portions (AF-13 at 3800 m and AF-14 at 3500 m; priority 2 because of the relatively young age expected for the underlying levee) of the fan and from the central portion of the fan (AF-16 and AF-17 at 2800 m). AF-20, on the crest of a relatively old levee on the western edge of the fan, has been added to provide a long, high-sedimentation rate record to complement the record of AF-10 and AF-11 on the eastern portion of the fan, thus providing a better record of surface circulation changes. The priority 2 holes noted above are in general quite close to priority 1 sites, and could possibly be done with little additional time by not fully recovering the drill string between sites.

ADDITIONAL CONSIDERATIONS

Safety

The Amazon continental shelf is a site of exploration for PETROBRAS, the Brazilian national oil company which has sole rights for exploration and exploitation of hydrocarbons in Brazil. While some oil and gas has been found on the Amazon shelf by PETROBRAS, it has not been found in producible quantities. The shelf in this area is underlain primarily by carbonates and sandstones deposited prior to the initiation of fan sedimentation. PETROBRAS has collected multi-channel data on the shelf and on the slope to a depth of 3000 m. Some of this data has been released in the past for a study of diapiric activity on the margin and additional short sections may be available should drilling be likely. The diapirs on the slope appear to be cored by shale, not by salt. A piston core recovered from the top of a diapir at about 1500-m water depth contains organisms indicative of a cold seep.

Bottom simulating reflectors (BSRs) have been identified in water depths less than 2000 m on the upper fan and slope (Manley and Flood, 1989), suggesting the presence of gas hydrates at depth. However, no BSRs have been identified in the areas targeted here for drilling. Piston coring has recovered gassy sediments from near a proposed drilling site. These gassy sediments were probably biogenically-produced methane, perhaps in distributed hydrate form. One carbonate nodule has been analyzed in a piston core and a C-13 analysis of -52$^{\circ}/_{\circ\circ}$ is consistent with a biogenic methane source.

Territorial Considerations

The 200-mile Brazilian territorial limit crosses through the fan at about 2000 m water depth from northwest to southeast. All of the proposed sites (with the exception of proposed site AF-20 and perhaps proposed site AF-5) fall within international waters.

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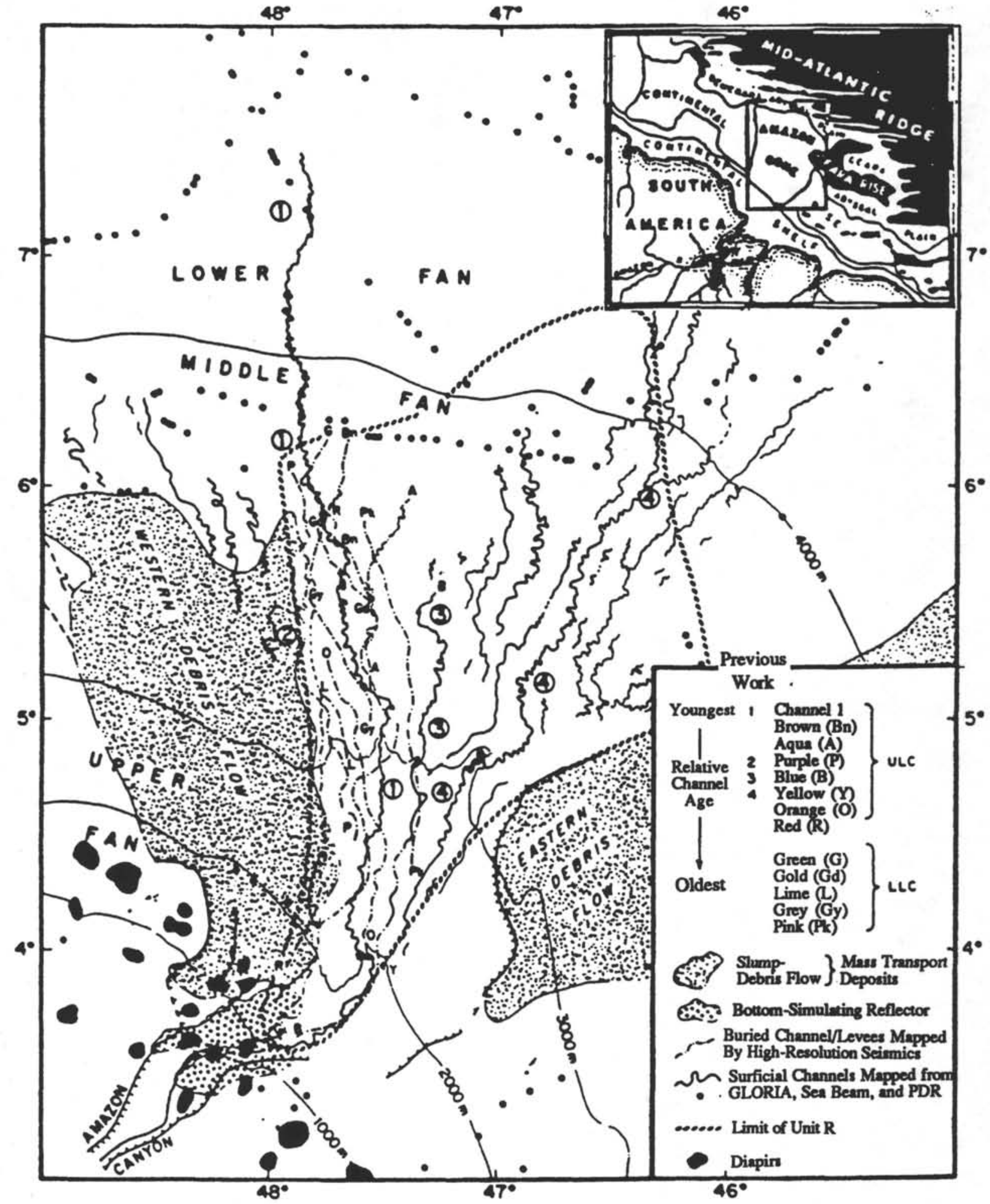

Figure 1. Morphological map of the Amazon fan showing locations of surficial channels, levees, canyons, and debris flows. Channels are ranked in terms of age following Damuth et al., 1983b (numbers) and Manley and Flood, 1988 (colors). Buried channels can be resolved into an Upper Levee Complex, a Middle Levee Complex and a Lower Levee Complex.

(From Manley and Flood, 1988)

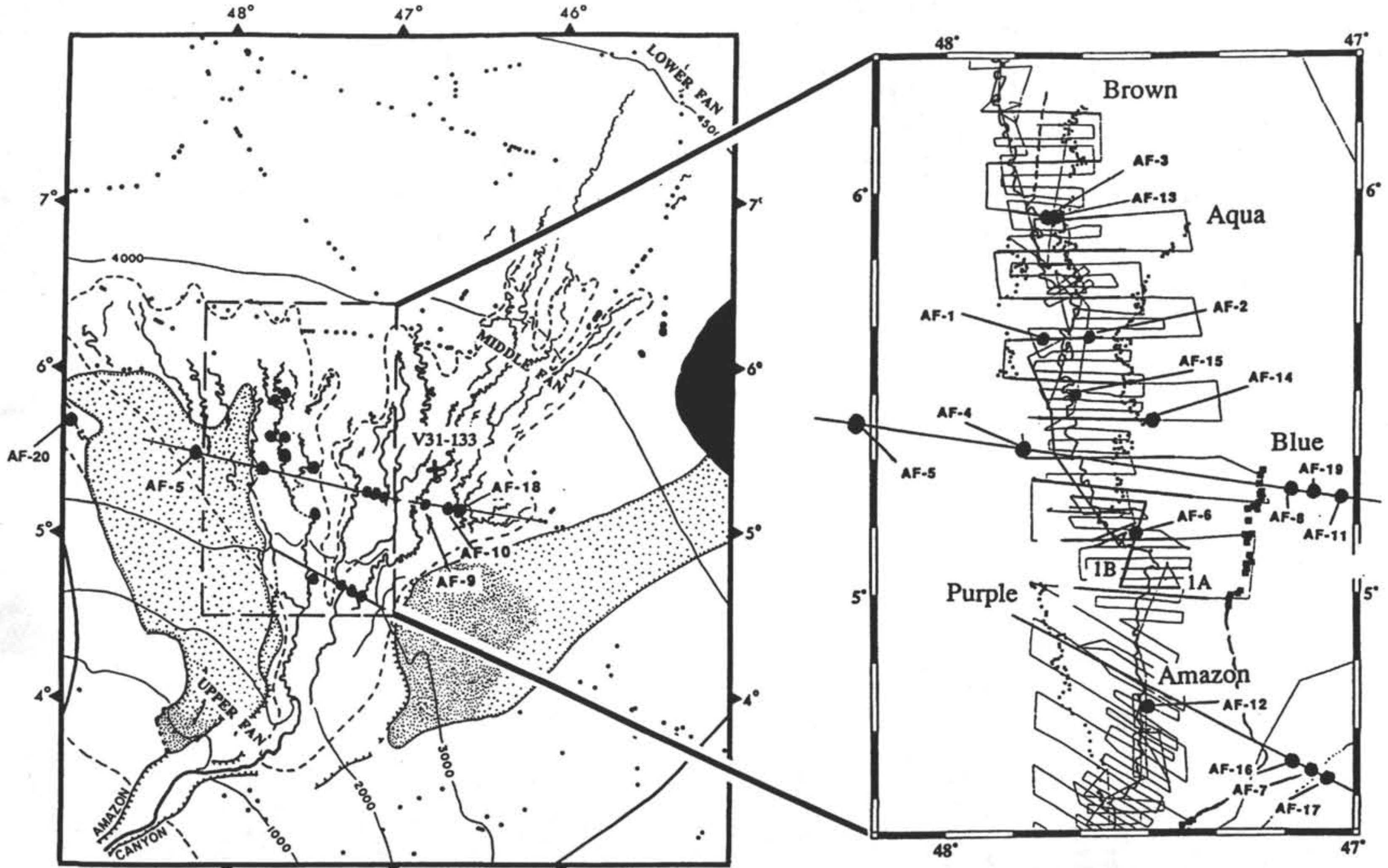

Figure 2. Map of the Amazon fan showing the locations of proposed drill sites (large dots) with respect to surface morphology and bathymetry. Color names are given to many of the exposed, abandoned channel-levee systems.

TABLE 1

PROPOSED SITE INFORMATION and DRILLING STRATEGY

SITE: AF-1	**PRIORITY:** 1	**POSITION:** 5°37.6'N, 47°45.1'W
WATER DEPTH: 3570 m	**SEDIMENT PENETRATION:** 568 m	**SUBB. TIME** (s): 0.60
SEDIMENT THICKNESS: 4000 m		

Objectives: A generic deep water site to study the longer-term evolution of sediment supply to Amazon Fan.

Drilling Program: APC, VPC, XCB and RCB coring. All holes double APC to 100 m, XCB to 400 m, then RCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-2	**PRIORITY:** 1	**POSITION:** 5°38.0'N, 47°36.4'W
WATER DEPTH: 3600 m	**SEDIMENT PENETRATION:** 369 m	**SUBB. TIME** (s): 0.40
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample levees in Upper Levee complex, underlying flat-lying reflectors, debris flow (?), and deeply-buried channel-levee systems.

Drilling Program: APC, VPC, XCB, and RCB coring. All holes double APC to 100 m, XCB to 400 m, then RCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-3	**PRIORITY:** 1	**POSITION:** 5°56.1'N, 47°45.3'W
WATER DEPTH: 3685 m	**SEDIMENT PENETRATION:** 226 m	**SUBB. TIME** (s): 0.25
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample overbank sediments of Brown and Ch. 1 systems, sample flat-lying reflectors, sample upper portion of debris flow (?).

Drilling Program: APC, VPC, and XCB coring. All holes double APC to 100 m, then XCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-4	**PRIORITY:** 1	**POSITION:** 5°21.4'N, 47°49.1'W
WATER DEPTH: 3450 m	**SEDIMENT PENETRATION:** 115 m	**SUBB. TIME** (s): 0.13
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample overbank sediments of Brown and Channel 1 systems, sample flat-lying reflectors, sample upper portion of debris flow (?).

Drilling Program: APC, VPC (?), and XCB coring. All holes double APC to 100 m, then XCB.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-5	**PRIORITY:** 1	**POSITION:** 5°22.5'N, 48°01.5'W
WATER DEPTH: 3390 m	**SEDIMENT PENETRATION:** 344 m	**SUBB. TIME** (s): 0.38
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample debris flow overlying buried channel-levee system, sample buried system and associated condensed sections, sample more deeply buried levee and associated sediments.

Drilling Program: APC, VPC (?), XCB, and RCB (?) coring. All holes double APC to 100 m, XCB to 400 m, then RCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-6	**PRIORITY:** 1	**POSITION:** 5°08.6'N, 47°31.4'W
WATER DEPTH: 3180 m	**SEDIMENT PENETRATION:** 301 m	**SUBB. TIME** (s): 0.33
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample overbank (levee) sediments of Channel 1. Sample for early diagenetic gases.

Drilling Program: APC, VPC (?), XCB and PCS (?) coring. All holes double APC to 100 m, then XCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-7	**PRIORITY:** 1	**POSITION:** 4°37.3'N, 47°15.2'W
WATER DEPTH: 2845 m	**SEDIMENT PENETRATION:** 320 m	**SUBB. TIME** (s): 0.35
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample overbank (levee) sediments of the Blue and Yellow levees.

Drilling Program: APC, VPC (?), XCB, and RCB (?) coring. All holes double APC to 100 m, XCB to 400m, then RCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-8 **PRIORITY:** 2 **POSITION:** 5°14.4'N, 47°09.3'W
WATER DEPTH: 3520 m **SEDIMENT PENETRATION:** 226 m **SUBB. TIME** (s): 0.25
SEDIMENT THICKNESS: 4000 m

Objectives: Sample overbank sediments of Channel 6C and the Blue system. Sample the base of the Channel 6C system and underlying sediments.

Drilling Program: APC, VPC (?), and XCB coring. All holes double APC to 100 m, then XCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-9 **PRIORITY:** 1 **POSITION:** 5°10.4'N, 46°38.3'W
WATER DEPTH: 3500 m **SEDIMENT PENETRATION:** 226 m **SUBB. TIME** (s): 0.25
SEDIMENT THICKNESS: 4000 m

Objectives: Sample sediments in overbank deposit of the Yellow system, Channel 6A, and the underlying large levee. Sample condensed sections between overbank deposits.

Drilling Program: APC, VPC (?), XCB, and RCB (?) coring. All holes double APC to 100 m, then XCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-10 **PRIORITY:** 1 **POSITION:** 5°08.6'N, 46°38.3'W
WATER DEPTH: 3500 m **SEDIMENT PENETRATION:** 207 m **SUBB. TIME** (s): 0.23
SEDIMENT THICKNESS: 4000 m

Objectives: Sample levee (overbank) deposits associated with system 5 and underlying levee system.

Drilling Program: APC, VPC (?), and XCB coring. All holes double APC to 100 m, then XCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-11 **PRIORITY:** 2 **POSITION:** 5°12.8'N, 47°02.0'W
WATER DEPTH: 3384 m **SEDIMENT PENETRATION:** 568 m **SUBB. TIME** (s): 0.60
SEDIMENT THICKNESS: 4000 m

Objectives: Sample levee (overbank) deposits associated with system 5 and underlying levee system.

Drilling Program: APC, VPC (?), and XCB coring. All holes double APC to 100 m, XCB to 400 , then RCB.

Logging and Downhole Operations: Logging to include quad combo tool and geochemical combinations.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-12 **PRIORITY:** 1 **POSITION:** 4°44.0'N, 47°30.0'W
WATER DEPTH: 2790 m **SEDIMENT PENETRATION:** 100 m **SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m

Objectives: Sample two most recent acoustic facies associated with the recently active Channel 1. Sample for early diagenetic gasses.

Drilling Program: APC and PCS (?) coring. All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clay with occasional sand layers.

SITE: AF-13 **PRIORITY:** 2 **POSITION:** 5°56.1'N, 47°44.6'W
WATER DEPTH: 3710 m **SEDIMENT PENETRATION:** 100 m **SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m

Objectives: Sample sediments overlying the inactive Brown system to provide a potential planktonic record at 3780 m.

Drilling Program: All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clay with very rare sand layers.

SITE: AF-14 **PRIORITY:** 2 **POSITION:** 5°25.4'N, 47°29.5'W
WATER DEPTH: 3475 m **SEDIMENT PENETRATION:** 100 m **SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m

Objectives: Sample sediments overlying the Aqua system to recover a planktonic record at 3475 m.

Drilling Program: All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clay with rare sand layers.

SITE: AF-15 **PRIORITY:** 1 **POSITION:** 5°29.1'N, 47°40.8'W
WATER DEPTH: 3415 m **SEDIMENT PENETRATION:** 100 m **SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m

Objectives: Sample sediments accumulating in cut-off channel meander to determine sedimentological characteristics and relationship of meander to downstream avulsions. Sample sediment organics and early diagenetic gasses.

Drilling Program: APC, VPC, XCB, and PCS (?) coring. All holes double APC to 100 m, then XCB.

Nature of Rock Anticipated: Sands with interbedded silts and clays.

SITE: AF-16	**PRIORITY:** 1	**POSITION:** 4°39.6'N, 47°18.8'W
WATER DEPTH: 2810 m	**SEDIMENT PENETRATION:** 100 m	**SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample sediments overlying the Blue system at a water depth of 2780 m.

Drilling Program: All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clays with rare sand layers.

SITE: AF-17	**PRIORITY:** 1	**POSITION:** 4°35.2'N, 47°11.4'W
WATER DEPTH: 2780 m	**SEDIMENT PENETRATION:** 100 m	**SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample sediments overlying the Yellow system at a water depth of 2780 m.

Drilling Program: All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clays with very rare sand layers.

SITE: AF-18	**PRIORITY:** 3	**POSITION:** 5°08.4'N, 46°36.2'W
WATER DEPTH: 3475 m	**SEDIMENT PENETRATION:** 100 m	**SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample sediments overlying the system 6C at a water depth of 3475 m.

Drilling Program: All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clays with very rare sand layers.

SITE: AF-19	**PRIORITY:** 1	**POSITION:** 5°13.5'N, 47°06.1'W
WATER DEPTH: 3450 m	**SEDIMENT PENETRATION:** 100 m	**SUBB. TIME** (s): 0.11
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample sediments overlying the system 5 on the eastern portion of the fan at a water depth of 3450 m.

Drilling Program: All holes double APC to 100 m.

Nature of Rock Anticipated: Silty clays with very rare sand layers.

SITE: AF-20	**PRIORITY:** 1	**POSITION:** 5°42.5'N, 49°04.3'W
WATER DEPTH: 3364 m	**SEDIMENT PENETRATION:** 198 m	**SUBB. TIME** (s): 0.22
SEDIMENT THICKNESS: 4000 m		

Objectives: Sample sediments overlying a levee of the Middle Levee Complex on the far western side of the fan for a good pelagic record.

Drilling Program: APC and XCB coring. All holes double APC to 100 m, then XCB.

Nature of Rock Anticipated: Silty clays with very rare sand layers.

LEG 156

RATES, EFFECTS, AND EPISODICITY OF STRUCTURAL AND FLUID PROCESSES, NORTHERN BARBADOS RIDGE ACCRETIONARY PRISM

Modified From Proposal 414-Rev

Tom Shipley: Co-Chief **Yujiro Ogawa:Co-Chief**

To Be Named: Staff Scientist

ABSTRACT

Fluids in the Earth's crust are a critical element in its geochemical evolution and geophysical structure, being responsible for a multitude of chemical/rock interactions and catalyzing deformation in both the brittle and ductile regimes. Fluid systems at both convergent and divergent plate boundaries fundamentally modify the resulting geology, and influence the composition of sea water. The hydrogeologic system of the Northern Barbados Ridge contrasts with the more diffuse fluid expulsion regions initially associated with coarser sediment-dominated margins. Thermogenic methane in the décollement zone, but not elsewhere in the accretionary prism above, indicates that the décollement zone is a conduit for preferential transport of deeply sourced fluids.

Leg 156 is scheduled to drill a number of instrumented holes penetrating the décollement zone and spanning the deformation front of the Northern Barbados Ridge along a predicted fluid flow line. These proposed sites will define the interrelationship of the dynamics of deeply sourced fluids, tectonic features, and geochemical signatures in the décollement zone. Monitoring by instrumentation packages atop borehole seals should provide a continuous, long-term record of fluid pressure, temperature, and perhaps resistivity, and the option of fluid sampling and permeability determinations during revisitation of the sites with a submersible. The episodicity of the fluid flow will be investigated, particularly in regard to its relationship to various observed geologic, geochemical, and geophysical features of the holes. The proposed sites are specifically located to span and monitor the movement of a seismic amplitude anomaly in the décollement zone, which potentially represents a pulse of migrating fluid.

INTRODUCTION

Understanding a number of geological processes such as the earthquake cycle, petroleum migration, and ore deposition, all require evaluation of fluid flow in complex geologic environments.

Crustal fluid processes can be evaluated through the penetration, instrumentation, and analysis of divergent and convergent plate boundaries. At active divergent plate boundaries, thermal gradients drive vigorous hydrothermal systems (Klein, 1991) that are strongly influenced by extensional tectonics. At passive margins, reflux of terrestrial groundwater significantly modifies the submarine geology (Paull and Neumann, 1987). At subduction zones, convergent tectonic phenomena provide both the driving force for fluid flow and the control of paths of fluid expulsion (Langseth and Moore, 1990). Fluid systems at both plate boundaries fundamentally modify the resulting geology, and influence the composition of sea water. In these active environments, sampling, together with measurement and evaluation of the active processes, can contribute to a better understanding of ancient sequences of the continents. Measurements of ambient conditions can be conducted during drilling and physical and chemical conditions may be monitored over a number of years, therefore address questions of episodicity inherent in many geologic processes.

Fluid flow profoundly influences the development of accretionary prisms and ultimately the mountain belts they form. In accretionary prisms, the partitioning of accreted, underthrust and subducted sediments (Shipley *et al.*, 1990), the regional temperature regimes (Foucher *et al.*, 1990), the nature of diagenetic/metamorphic processes (Sample, 1990), the redistribution of hydrocarbons (Vrolijk *et al.*, 1990), and even the surface biology (Suess *et al.*, 1985; Le Pichon *et al.*, 1987) are dependent to some degree on large-scale fluid flow, fluid pressures and permeability, and the episodicity of these phenomena. The evaluation of the rates, magnitude and episodicity of fluid flow by ODP penetrations links these hydrogeologic processes to the observed geologic features. For example, the volume of fluid flow and ambient fluid chemistry and temperature can be related to the distribution of faults, small-scale structural features, permeable stratigraphic layers, and to the degree of cementation, veining, and mineralogical alteration. Such observations at drillable depths in accretionary prisms provide a basis for interpretations of similar phenomena at crustal depths inaccessible by drilling.

STUDY AREA

The key result of previous Barbados drilling was definition of fluid flow by the pore water geochemical (Gieskes *et al.*, 1990) and temperature (Fisher and Hounslow, 1990) anomalies, and their correlation to specific familiar structural features (Behrmann *et al.*, 1988). Following the Barbados drilling (Leg 110), pore water geochemical anomalies have been utilized at a number of convergent margins as primary evidence of fluid flow (Suess, von Huene *et al.*, 1988; Kastner *et al.*, 1991; Taira, Hill, Firth *et al.*, 1991). The low intergranular permeability of the mud-dominated sedimentary sequence initially focuses fluid flow along faults in the accretionary prism and along the décollement zone (Gieskes *et al.*, 1990). The hydrogeologic system of the Northern Barbados Ridge thus specifically contrasts with the more diffuse fluid expulsion regions initially associated with coarser sediment-dominated margins, such as the Nankai Trough (Taira, Hill, Firth *et al.*, 1991). Thermogenic methane in the décollement zone, but not elsewhere in the accretionary prism above, indicates that the décollement zone is a conduit for preferential transport of deeply sourced fluids (Vrolijk *et al.*, 1990). Because of the development of the décollement zone at an initially shallow depth in the sedimentary column and the low taper of the accretionary prism, the décollement zone is readily accessible by drilling.

Previous Barbados (and Nankai) drilling was successful in recovery of core that yielded much information on structural geology and pore water geochemistry. Neither leg was effective in collecting information on the ambient conditions under which the recovered structures developed. Efforts to log and emplace downhole instruments were largely unsuccessful. The exception was collection of downhole temperature measurements; the Barbados temperature data apparently require that the fluid flow be episodic (Fisher and Hounslow, 1990). Overall, the Barbados (and Nankai) results indicate that the frontier in prism drilling is not in recovering core but in measurements of the operative physical and chemical processes.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To investigate fluid pressure in and around the décollement zone.

2) To assess the permeability of prism sediments and the associated fault zones.

3) To determine if fluid flow is continuous or episodic.

4) To establish the space/time variations in fluid composition and compare this composition with that of veins and authigenic mineral phases.

5) To determine if amplitude anomalies or 'bright spots' along faults are actually pulses of migrating fluid (i.e. 'dilatational strain waves').

Specific Objectives and Methodology

Leg 156 constitutes a drilling and experimental program to evaluate the effects, rates, and episodicity of fluid flow in the accretionary prism environment. The program will focus on a study of deeply sourced fluids in the décollement zone of the Barbados Ridge Complex and include efforts to measure fluid flow through the accretionary prism and sediments underthrust beneath the décollement zone. Proposed efforts efficiently utilize the geologic and hydrogeologic framework developed by previous drilling of the Northern Barbados Ridge and take advantage of a three-dimensional seismic reflection survey and submersible investigations completed in 1992.

Fluid Pressure In And Around The Décollement Zone

No reliable fluid pressure measurements exist for the frontal area of accretionary prisms though several attempts at measurement (inadvertent or otherwise) have been made (Biju-Duval, Moore *et al.*, 1984; von Huene 1985). Fluid pressure is the driving force for fluid flow, and must be known to create any reasonable model of fluid expulsion. Fluid pressure must be known in order to evaluate structural models of prism tectonics.

Permeabilities of Prism Sediments And Associated Fault Zones

Although measurements on recovered core samples provide estimates of matrix permeability (e.g. Taylor and Leonard, 1990), *in situ* measurements are essential to determine permeability at the scale of the flow system. Some models suggest that fault zones may be 3-5 orders of magnitude more permeable than the matrix (Screaton *et al.*, 1990). Obviously, information on permeability will dramatically influence the understanding of the dynamics of fluid flow.

Continuous or Episodic Flow?

Although groundwater systems driven by semi-constant water tables tend to flow continuously, structural and seismologic intuition suggests that tectonohydrologic systems are episodic. The nature of the earthquake cycle (Kanamori, 1986) and related fluid flow (Sibson, 1981), and the ubiquitous crack-seal textures of deformed rocks (e.g. Ramsay, 1980) supports this view. Accordingly, the temporal and spatial variability of fluid flow along a convergent plate boundary, the décollement zone, must be determined.

The Space/Time Variation In Fluid Composition And Its Comparison With Veins And Authigenic Mineral Phases

The variability of fluid composition in space and time will provide information on potential fluid sources and allow modeling of solute fluxes.

Amplitude Anomalies Or 'Bright Spots' Along Faults

High amplitude, reversed-polarity reflections in seismic reflection data from the Northern Barbados Ridge (Bangs and Westbrook, 1991) have been modeled as dilatant zones. Similar reversals in the Oregon accretionary prism which correlate with surface vents (Moore *et al.*, 1991) have also been interpreted as dilatant zones. Seismic data from the new 3-D survey in the Leg 110 area shows a large negative polarity amplitude anomaly along the décollement zone. Proposed sites are located to penetrate this amplitude anomaly, monitor its fluid pressure, and ultimately measure its migration.

DRILLING PLAN/STRATEGY

Borehole seals (CORKS) will be positioned to intercept a predicted flow line along the décollement zone and its immediate seaward extension. The décollement zone is the focus of the measurements because previous geochemical studies have defined it as the major conduit for deeply sourced fluids (Gieskes *et al.*, 1990; Vrolijk *et al.*, 1990). Packer measurements then would yield data on fluid pressure and permeability in the décollement zone, and perhaps above and below, depending on the casing strategy. Thus the flow of fluid along the zone could be measured at the time of drilling. The borehole seal would allow monitoring over a time period of up to two years after drilling, ideally providing a record of the physical and chemical signatures of fluid flow.

Defining the Flow Line and Related Site Locations

Hydraulic head at the base of the prism probably varies directly with the thickness of overlying prism (S. Dreiss, Chi Wang, pers. comm.). Thus locating the three proposed drill sites along a line perpendicular to the prism isopachs should be along the direction of maximum change in head or a flow line. Currently the proposed sites are picked along a preliminary version of one of the lines from the 3-D seismic reflection survey.

The high heat flow in the Northern Barbados Ridge drilling area can be interpreted as either due to episodic flow or to lateral (along strike) influx of fluids (e.g. Foucher *et al.*, 1990). Even if there were a large scale component of lateral flow, basic hydrogeology argues strongly that the local flow would be controlled by the local variation in prism thickness; hence locating three holes along a line perpendicular to prism isochrons (~ isopachs) is a valid strategy to approximate a single local flow line.

Drilling and Coring Strategy

Each hole will be drilled with the primary goal of casing it to the décollement zone. Each hole will be drilled beyond the décollement as permitted by hole stability, to obtain lithologic and geochemical information on the deeper parts of the section. Depending on the time available, and the casing program, logging and downhole measurements will be carried out incrementally with pore pressure measurements being conducted on the approach and penetration through the décollement. Because proposed sites NBR-1 and -2 are essentially reoccupation of DSDP Sites 672 and 671, respectively, only the deeper parts of these new sites need be cored. The faster total drilling time of uncored holes generally results in greater hole stability, and better opportunities for logging and downhole measurements. The décollement zone and adjacent sediments will be repeatedly cored to accumulate the maximum amount of material for both the detailed geochemical studies and the structural studies necessary to correlate fabrics with fluid history.

Logging, Downhole Measurements, and Borehole Sealing

Each hole will be explored with a full suite of logs. Use of the side-entry sub plus liberal amounts of KCL-based mud may allow successful logging. Neither was available during Leg 110. Additionally, it may be possible to image the hole interior with the formation microscanner tool. After open-hole logging, the emplacement of casing to the décollement would allow for pore pressure measurements using the ODP packer system that has been successfully used in hard rocks. The first priority would be to measure fluid pressure and permeability in the décollement zone. Hence the emplaced casing could be perforated only in this interval. If the casing was run in intervals, pore pressure and permeability measurements could also be made incrementally, during emplacement, at the end of each casing string.

Borehole seals will be emplaced on each of the three holes; each hole being cased and perforated to specifically communicate with the décollement or its seaward equivalent. During the drilling cruise, a packer will measure pore pressure and permeability in each hole, and therefore define flow rates between holes. The borehole seals include an instrumentation package that records temperature from a string of thermistors, and fluid pressure for up to two years. The seal also includes a tube that extends to an arbitrary depth in the borehole, allowing sampling of fluids at a later date. Because the borehole-seal data-logging package has several free recording channels, a resistivity measuring device will be added at the terminus of the sampling tube. Thus the salinity of the borehole fluids can be monitored continuously. The salinity could vary significantly, because the fluids defining the "low chloride anomalies" are substantially less saline than seawater. Various ionic species and dissolved organics may also be monitored.

A zero-offset VSP (vertical seismic profile) will be shot in each of the cased holes to tie the drilled section to the 3-D seismic survey. At least one hole will have an offset VSP shot to help define lateral velocity (and therefore porosity) variations and the amount and direction of velocity anisotropy.

PROPOSED SITES

Leg 156 proposes to drill five sites (Fig. 1, Table 1).

Proposed site NBR-1 is located at Leg 110 Site 672. This hole would quantify the amount of fluid flowing seaward through the incoming sedimentary sequence. Coring would only be required in the lower of 300 m of the hole, but permeability and fluid pressure measurements would be essential at the depth of the propagating décollement and, if possible, within the subjacent permeable sand layer. Fluid sampling would be essential throughout. The hole would have to be cased to about 200 m.

Proposed site NBR-2 is located at Leg 110 Site 671. This hole is designed to repenetrate the décollement to the permeable sand layer in the underthrust sequence and, if possible, continue to the oceanic crust. The hole is located just at the eastern (leading?) edge of a larger reversed polarity reflection (fluid pulse or dilational strain wave) and could potentially record its migration. Accordingly, first priority will be given to casing to the décollement to about 500 m depth for packing and long-term monitoring. Additionally, a profile of physical, hydrogeologic, and geochemical conditions including temperature, fluid chemistry, fluid pressure, permeability, and fluid-flow rate, may be developed. Since the geology is well established from Site 671 to 700 m sub-bottom, coring would only be required for the basal 250 m of the hole, and in selected zones of great geochemical and structural interest, such as the décollement zone.

Proposed site NBR-3 is located 6.4 km west of the deformation front and about 700 m above the décollement. This site is designed to provide a sampling of conditions in the center of the high-amplitude, negative-polarity reflection along the décollement surface. Although the first priority of this hole will be casing to, and experiments in, the décollement zone, continuing penetration into the underthrust sequence will be attempted. Principal goals will be definition of the structural evolution of the décollement as well as conducting a series of geophysical, geochemical, and hydrogeological tests along the décollement zone to establish gradients in temperature, chemical anomalies, and fluid pressure relative to the penetrations at proposed sites NBR-1 and NBR-2. These gradients, when combined with permeability measurements, will provide a regional measure of flow rate, and establish a basis for reasonable estimates of heat and chemical fluxes along the décollement.

Proposed site NBR-4, located between proposed site NBR-2 and the toe of the accretionary prism, will monitor the seaward flux of fluid along the décollement. The hole would penetrate the décollement and into the underthrust sedimentary section. The hole will be cased to the décollement with the installation of a borehole seal. The proposed experimental and logging program will be similar to proposed site NBR-2.

Proposed site NBR-5 will penetrate the décollement zone in a region of low reflectivity at the western (trailing?) edge of the high-amplitude reversed-polarity reflection. The depth of the décollement is 850 m. If possible, casing will be emplace to this depth with the installation of a borehole seal for long-term monitoring of the fluid flow in this deepest of décollement-zone penetrations. The experimental and logging program will be similar to proposed site NBR-3.

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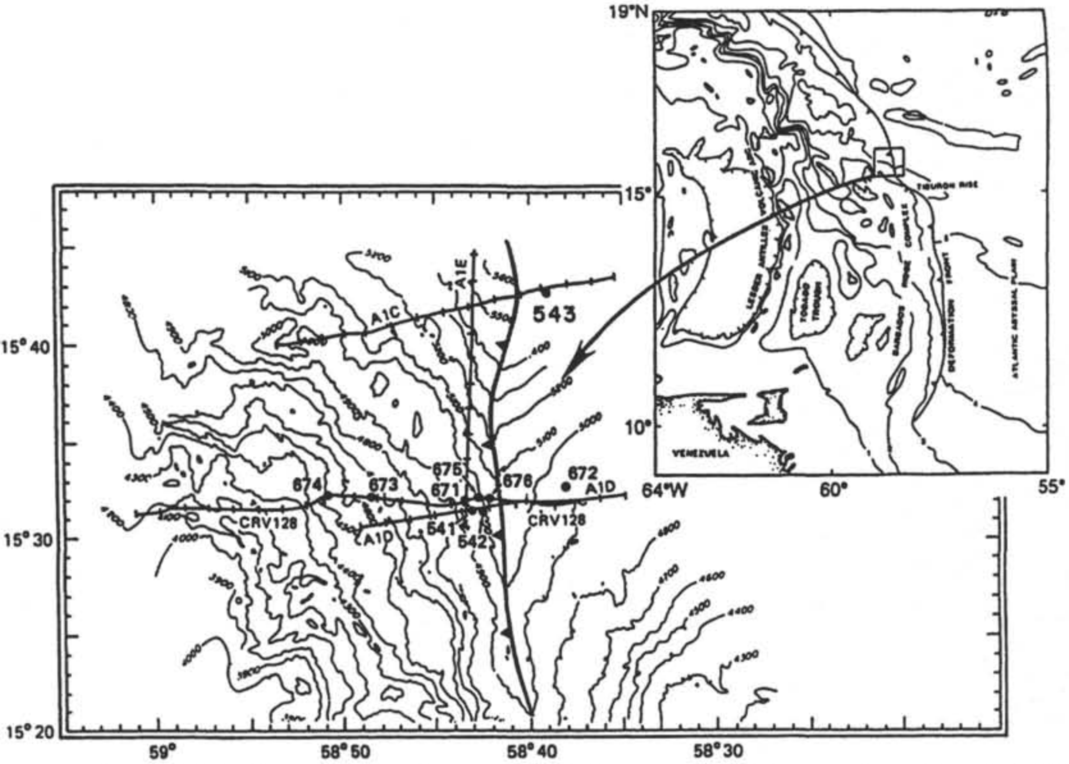

Figure 1a. Top Right: General location map of Lesser Antilles margin. Bottom Left: Location of ODP Leg 110 Sites 671 through 676 on a SeaBeam bathymetric map with location of MCS profiles and DSDP sites (contour interval of 100 m).

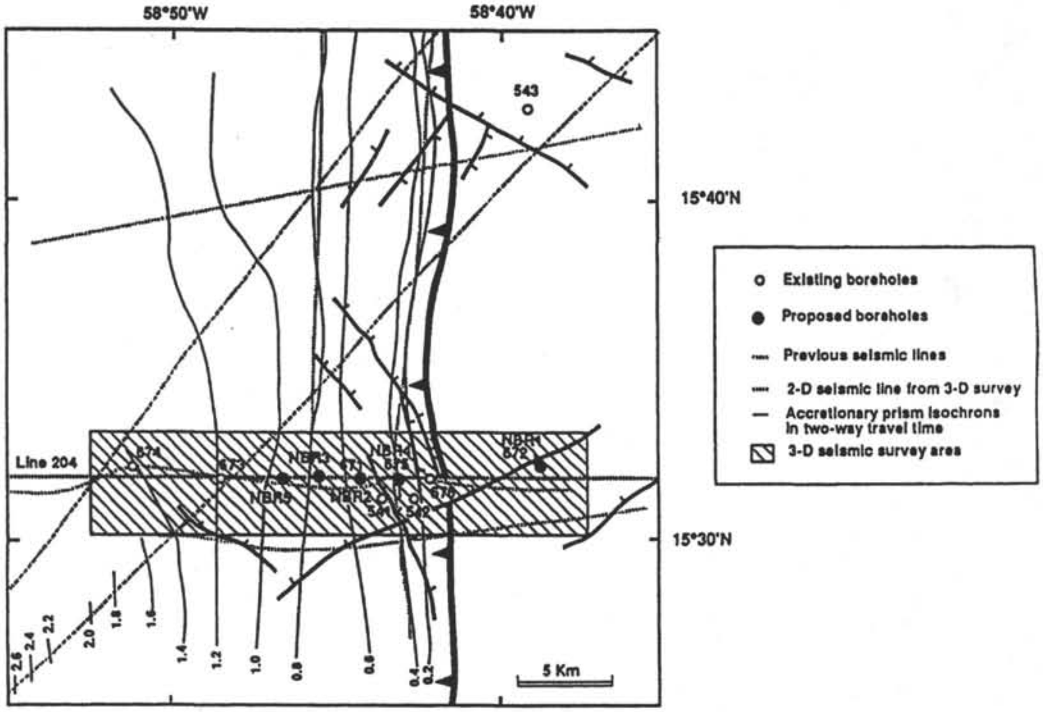

Figure 1b. Detailed location map of DSDP Leg 78A and ODP Leg 110 sites showing thickness of accretionary prism. The isochrons of the accretionary prism roughly parallel the deformation front, suggesting fluid flow would be predominantly up-dip. Units are in seconds, two-way travel time. Location of Leg 156 proposed sites is shown.

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: NBR-1 **PRIORITY:** 1 **POSITION:** 15°32.4'N, 58°38.5'W
WATER DEPTH: 5477 m **SEDIMENT THICKNESS:** 750 m **TOTAL PENETRATION:** 800 m
SEISMIC COVERAGE: 3D seismic survey Line 204 (UT Austin, Univ. Hawaii, UC Santa Cruz)

Objectives: To establish an oceanic reference, quantifying the amount of fluid flowing seaward through the incoming sedimentary sequence, drilling to complete ODP Site 672 to basement. Borehole seal would be installed to monitor fluid in the propagating décollement.

Drilling Program: APC, XCB, and RCB coring and reentry.

Logging and Downhole Operations: Logs, borehole seal, FMS, WSTP, and packer.

Nature of Rock Anticipated: Hemipelagic, pelagic, and minor terrigenous.

SITE: NBR-2 **PRIORITY:** 1 **POSITION:** 15°31.7'N, 58°44.5'W
WATER DEPTH: 4890 m **SEDIMENT THICKNESS:** 900 m **TOTAL PENETRATION:** 950 m
SEISMIC COVERAGE: 3D seismic survey Line 204 (UT Austin, Univ. Hawaii, UC Santa Cruz)

Objectives: To establish a profile of fluid pressure, permeability, temperature, and physical properties of a hole penetrating through the accretionary prism, décollement zone, and underthrust sediments. Sampling would be conducted as necessary to compliment the existing data from ODP Site 671 at this location. Borehole seal would be installed to monitor fluid in the décollement zone.

Drilling Program: APC, XCB, and RCB coring and reentry.

Logging and Downhole Operations: Logs, borehole seal, FMS, WSTP, and packer.

Nature of Rock Anticipated: Hemipelagic, pelagic, and minor terrigenous.

SITE: NBR-3 **PRIORITY:** 1 **POSITION:** 15°31.7'N, 58°45.5'W
WATER DEPTH: 4755 m **SEDIMENT THICKNESS:** 1200 m **TOTAL PENETRATION:** 820 m
SEISMIC COVERAGE: 3D seismic survey Line 204 (UT Austin, Univ. Hawaii, UC Santa Cruz)

Objectives: To provide a sampling of hydrogeologic conditions and structural features of a high amplitude, reversed polarity reflection in the décollement zone. To establish a vertical profile of fluid pressure, permeability, temperature, and physical properties, geochemistry and geology through the accretionary prism. Borehole seal would be installed to monitor fluid in the décollement zone.

Drilling Program: APC, XCB, RCB coring and reentry.

Logging and Downhole Operations: Logs, borehole seal, FMS, WSTP, and packer.

Nature of Rock Anticipated: Hemipelagic, pelagic, and minor terrigenous.

SITE: NBR-4 **PRIORITY:** 2 **POSITION:** 15°31.6'N, 58°43.4'W
WATER DEPTH: 4965 m **SEDIMENT THICKNESS:** 900 m **TOTAL PENETRATION:** 570 m
SEISMIC COVERAGE: 3D seismic survey Line 204 (UT Austin, Univ. Hawaii, UC Santa Cruz)

Objectives: To provide control on fluid and structural processes in the décollement zone between NBR-2 and the frontal thrust. Borehole seal would be installed to monitor fluid in the décollement zone.

Drilling Program: APC, XCB, RCB coring and reentry.

Logging and Downhole Operations: Logs, borehole seal, FMS, WSTP, and packer.

Nature of Rock Anticipated: Hemipelagic, pelagic, and minor terrigenous.

SITE: NBR-5 **PRIORITY:** 2 **POSITION:** 15°31.5'N, 58°46.5'W
WATER DEPTH: 4852 m **SEDIMENT THICKNESS:** 1500 m **TOTAL PENETRATION:** 960 m
SEISMIC COVERAGE: 3D seismic survey Line 204 (UT Austin, Univ. Hawaii, UC Santa Cruz)

Objectives: To sample and monitor hydrogeologic and structural conditions at the eastern edge of the high amplitude reflection (fluid pulse?) along the décollement. The site should establish a vertical profile of lithology, structural features, geochemistry, and temperature through the accretionary prism. Borehole seal would be installed to monitor fluid pressure, temperature, and aspects of fluid chemistry.

Drilling Program: APC, XCB, RCB coring and reentry.

Logging and Downhole Operations: Logs, borehole seal, FMS, WSTP, and packer.

Nature of Rock Anticipated: Hemipelagic, pelagic, and minor terrigenous.

LEG 157

DIAMOND CORING SYSTEM:
VEMA FRACTURE ZONE
A BRIEF ENGINEERING AND OPERATIONS PROSPECTUS

Modified From The August 1992 Report to the JOIDES Planning Committee and Material Prepared and Supplied By Dan Reudelhuber, ODP Engineer

To Be Named: Co-Chief Scientist and Staff Scientist

ABSTRACT

The Vema Fracture Zone has been proposed as the next engineering test site for the Diamond Coring System (Phase II), scheduled for Leg 157 in July-August-September 1994. The area is characterized by relatively thin sediments overlying limestone formations, deposited on upthrust blocks of crust. The limestone is anticipated to be on the order of 400-m thick in some areas. Water depths range from a few hundred meters to over 2,000 m.

Only two out of the three previous deployments of the Diamond Coring System can be considered successful. A failure of the secondary heave compensation system during Leg 142 precluded successful coring with the system.

Changes made to the Phase II system during 1992-1993 will be tested at sea for the first time during Leg 157, the most significant of these changes being the modifications made to the secondary heave compensation system. The development, testing, and proving of the secondary heave compensation is critical to the future of the Diamond Coring System, as it is impossible to slimhole core offshore without effectively removing heave motion at the core bit.

A secondary objective of the Leg 157 engineering test will be an assessment of new hardware, in particular the diamond retractable bit which has the potential to significantly improve the operational efficiency of the Diamond Coring System by greatly decreasing the time required for coring bit trips.

INTRODUCTION

Although the Diamond Coring System (DCS) (Fig. 1) has been deployed three times since its inception in 1988, only two deployments can be considered successful.

The DCS-Phase I system was tested in 1989 during Leg 124E. The concept was to core using a narrow kerf diamond core bit rotated at high speeds with light bit weights and precise heave compensation, all in deep water. Based on the test, the concept appeared feasible and the decision was made to design and develop an operational prototype. The Phase II version of the DCS was designed, built, deployed, and tested during a one-year period between August 1989 and August 1990. A 79-m hole was drilled/cored on Leg 132 at the Bonin Ridge with respectable recovery through the fractured zone. Good quality cores of the elusive, highly fractured basalts were finally, successfully recovered. In 1992, the Phase II version was deployed for the second time on Leg 142 (January-March, 1992). A failure of the secondary heave compensation system precluded successful coring with the system. Based on documented visual observations, there were problems associated with computer control of weight on bit. A bent cylinder and erratic load cell readings were, at that time, felt to be major contributors to the system's failure to compensate.

The Vema Fracture Zone has been proposed as the next engineering test site for the DCS, scheduled for Leg 157 in July-August-September 1994. Changes made to the DCS system during 1992-1993 will be tested at sea for the first time during Leg 157. The most significant of these changes has been made to the secondary heave compensation system. A much more robust compensation controller has been designed, and it will be built and tested extensively on land during 1993.

TEST AREA

Formations expected at the Vema Fracture Zone are characterized by relatively thin sediments overlying limestone formations, deposited on upthrust blocks of crust. The limestone is anticipated to be quite thick in some areas, on the order of 400 m. Water depths range from a few hundred meters to over 2,000 m.

In August, 1992, a multichannel seismic reflection survey was conducted at the Vema Fracture Zone with the ship *OGS Explora* (Fig. 2). The preliminary shipboard analysis of the data, as summarized below, was carried out by E. Vera, M. Ligi, and E. Bonatti.

The transverse ridge, located on the southern side of the Vema Fracture Zone, is an east-west elongated feature that reaches exceptionally shallow bathymetry (up to <600 mbsl) about 80 km west of the intersection of the fracture zone with the Mid-Atlantic Ridge (Fig. 2)

Limestones and other rocks dredged from this segment of the ridge indicate that the transverse ridge is an uplifted sliver of oceanic crust capped by shallow-water reef limestones (Bonatti *et al.*, 1983). From the study of paleofacies and ages of these limestones, Bonatti *et al.* (1983) concluded that the crustal block was exposed subaerially in middle Pliocene time (about 3 m.y. ago) and subsequently sank to its present depth at an average rate of 0.3 mm/yr, i.e. at a rate one order of magnitude faster than the predicted thermal contraction subsidence.

Vera, Ligi, and Bonatti have tentatively reached the following conclusions, illustrated in Fig. 3:

1. A ~ 400-m thick layer of material with average 2 km/s velocity caps the summit of the transverse ridge. Based on studies of bottom samples, this layer represents a shallow water carbonate platform that emerged as an island up to about 3 Ma.

2. The carbonate cap lies on a horizontal surface, i.e. the top of an uplifted block of igneous rock. The horizontal boundary suggests erosion at sea level during subsidence.

3. The seismic velocity of the top of the basement is ~ 4 km/s, grading up to ~ 5.4 km/s about 200 m below the top of the basement. A possible interpretation calls for basalt grading down into a dike complex, consistent with the transverse ridge being an uplifted block of oceanic crust that is undergoing subsidence since about 3 Ma.

4. The average ~ 2 km/s velocity of the ~ 400-m-thick limestone cap, and the <2 km/s inferred for the top ~ 100 m suggest that unconsolidated sediments prevail near the top of the section.

ENGINEERING OBJECTIVES

Summary of Objectives

1) To maximize coring time and recovery time with the DCS.

2) To test additional new hardware, such as the DCS retractable bit (DRB) and, if required, a 6-3/4" Drill-In Bottom Hole Assembly (DI-BHA).

OPERATIONS PLAN

Upon arrival at the Vema Fracture Zone, a bottom TV survey will be conducted in order to locate a possible area for HRB emplacement. Since some limited sediment cover is expected, it is likely that a test hole will be drilled to assess near-surface lithology and to help determine setting depths for the DI-BHA.

The ideal location for the HRB would have less than 1-m sediment cover. A HRB will be assembled and run to bottom once a suitable location is chosen. The 10-3/4" DI-BHA will then be deployed in order to set the stage for coring with the DCS.

The DCS will then be picked up and coring will proceed.

Significant changes will have been made to the secondary heave compensation system prior to Leg 157. Specifically, a completely new compensation system controller will be tested and tuned at the initiation of DCS coring. New bit designs will also be tested when the 10-3/4" DI-BHA is drilled in. Two different diamond bit/center bit designs will be available. These are expected to be much more efficient in the limestone formation than the 12-1/2" roller cone bits used on Leg 142 at the East Pacific Rise (EPR). New bits for the 6-3/4" DI-BHA system may also be tested if hole conditions dictate that a second string of casing be set. The 6-3/4" DI-BHA hardware has also been modified to include a loss of pressure indicator for when back-off occurs.

If initial coring is successful with conventional diamond bits, a segmented DRB system may be tested. The DRB allows the 3.96" diamond core bit to be changed without tripping the DCS tubing out of the hole. This retractable bit hardware will ride on the inner core barrel and can be viewed after each core run. Successful deployment of this hardware will potentially save a significant amount of time that would have been used for tripping the DCS tubing in place of coring.

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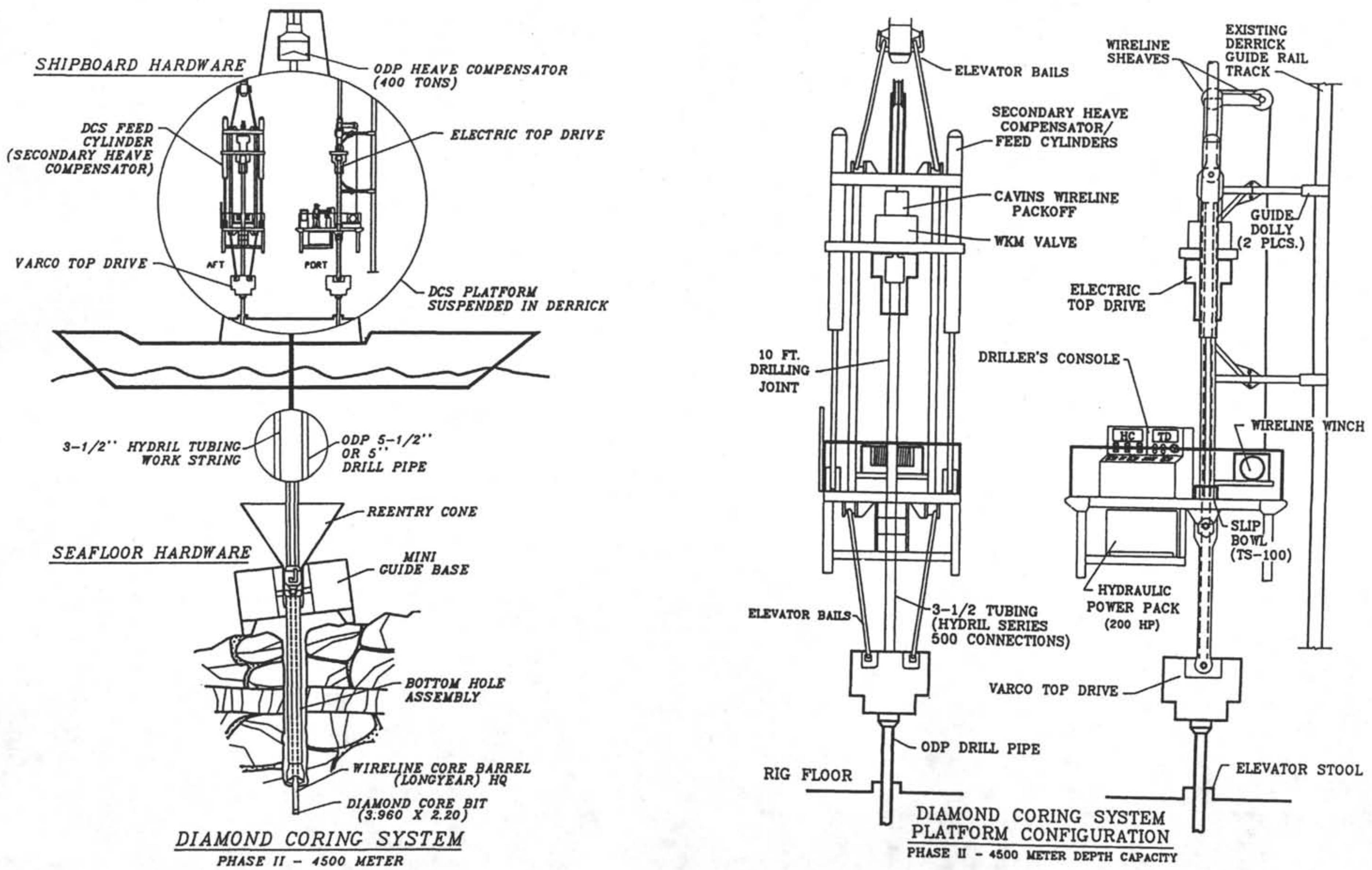

Figure 1. DCS-Phase II configuration during Leg 132 engineering tests.

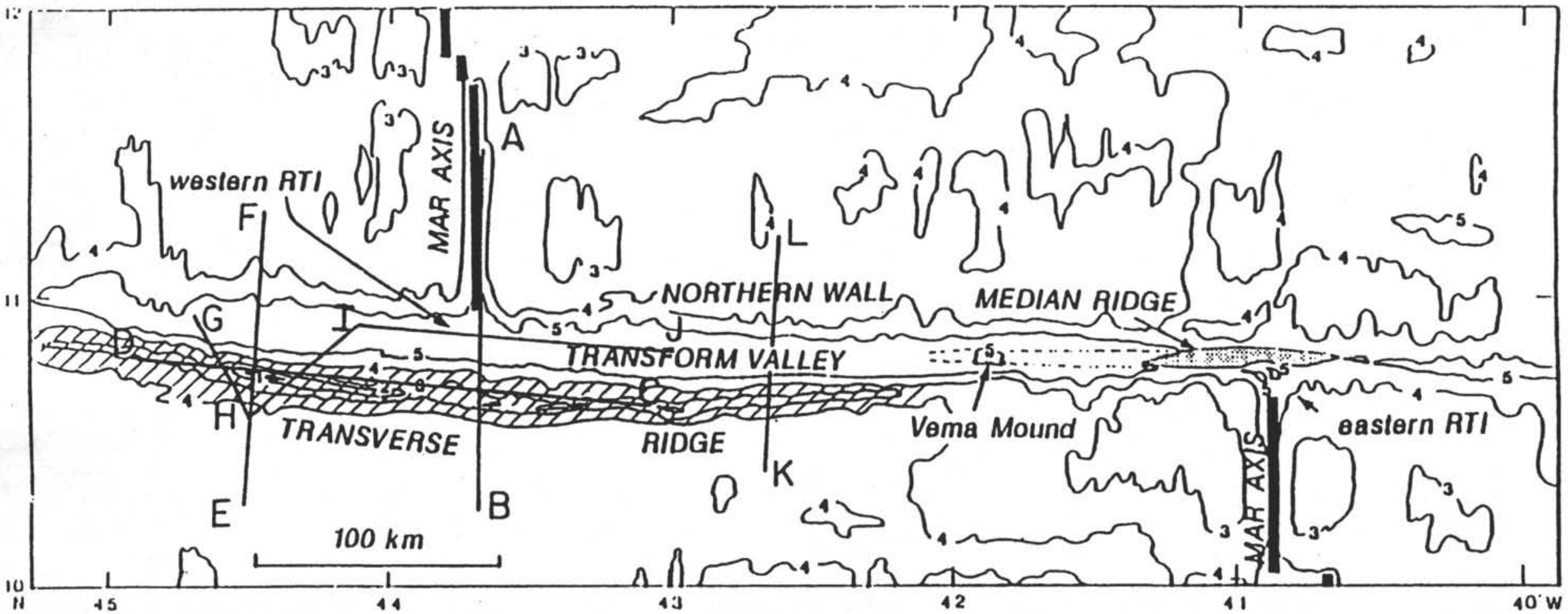

Figure 2. Tracks of the seismic reflection profiles carried out in August 1992 at the Vema Fracture Zone by Vera, Ligi, and Bonatti.

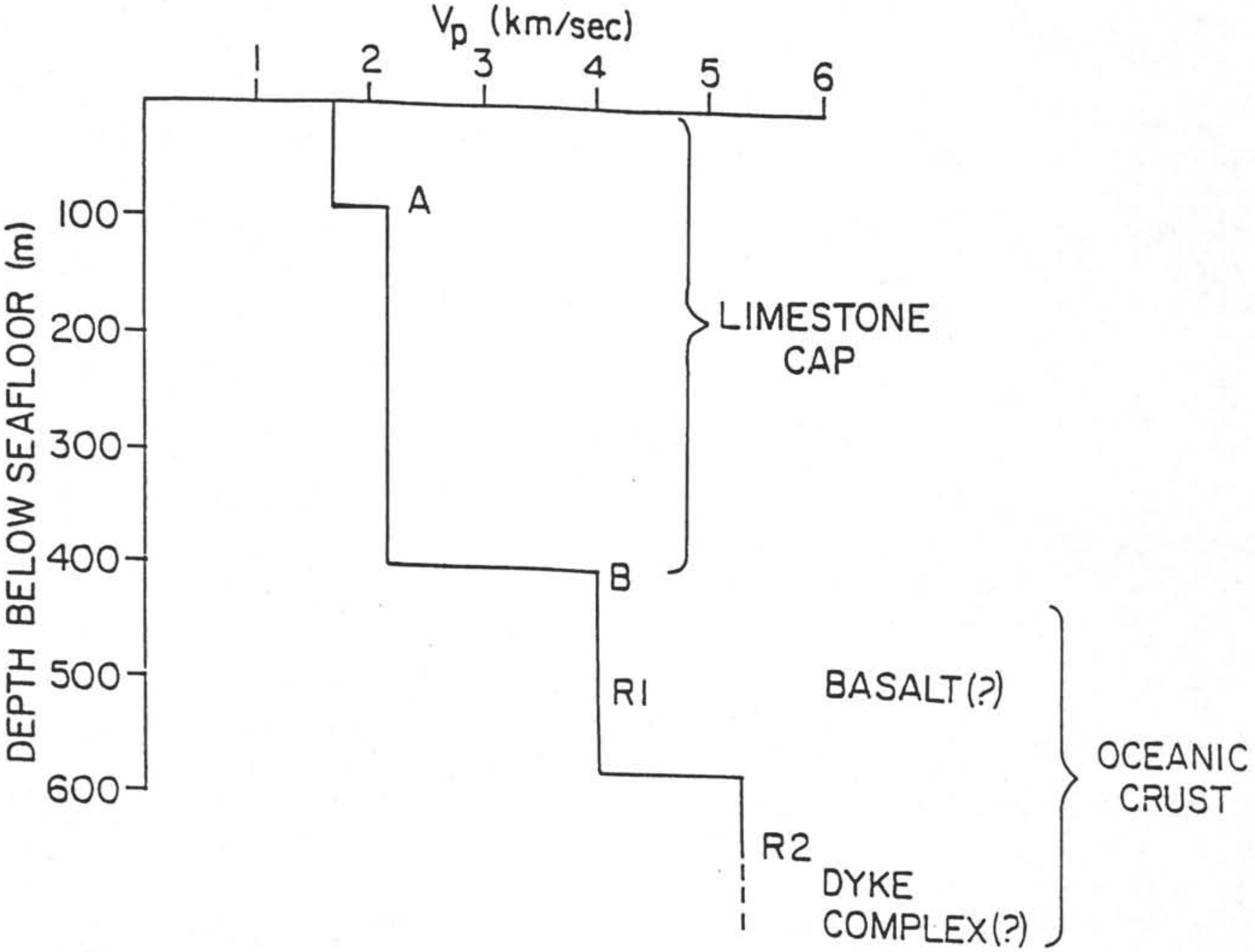

Figure 3. Velocity/depth function for SP 1964 (VEMA-02, August 1992 survey) on the crest of the Vema transverse ridge. Water depth is 595 m and $V_w = 1.475$ km/s.

LEG 158

DRILLING AN ACTIVE HYDROTHERMAL SYSTEM ON A SLOW-SPREADING RIDGE: MAR 26°N (TAG)

Modified From Proposal 361-Rev 2 Submitted By

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Mark D. Hannington, James M. Franklin, Steven D. Scott, Peter M. Herzig,
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To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

The overall scientific objectives of Leg 158 are to investigate the fluid flow, geochemical fluxes and associated alteration and mineralization, and the subsurface nature of an active hydrothermal system on a slow-spreading ridge. The TAG active mound is a large, mature deposit of varying mineralogy with emanating fluids displaying a wide range of temperatures and distinct chemistries. The large size and age argue for a reasonably large and altered crustal root zone suitable for good drill penetration and recovery with conventional drill bits. Studies of this feature will give insight into fluid flow, structure, and "zone-refining" in active hydrothermal systems, and clarify how large deposits, similar in size to those mined on land today, are formed on the modern seafloor.

A transect of three holes, one penetrating into the stockwork zone, is proposed to investigate the nature of fluids, deposits, and altered crust in the near-surface part of the hydrothermal system and in the stockwork and root zone underlying the surface deposit. Although it is anticipated that these objectives can be achieved with the currently available technology in this hostile environment, the nearby inactive MIR mound is proposed as a back-up drilling site. The size and primary sulfide features of the MIR mound are similar to that of TAG, but the MIR mound has undergone extensive recrystallization, being entirely indurated by late-stage fluids that have replaced anhydrite and filled all voids with silica.

Drilling at TAG will directly address the processes occurring during hydrothermal circulation. Understanding these processes, and the implications for energy transfer, geochemical fluxes, and the formation of ore deposits is of fundamental importance to our knowledge of crustal accretion.

INTRODUCTION

Ridge-crest hydrothermal systems play a fundamental role in transferring a large fraction of the heat from the earth's interior to its surface. Through thermally-induced flow of seawater in fractures and fissures in the permeable portion of the crust and upper mantle, much of the mantle-derived thermal energy is dissipated into the lithosphere, hydrosphere, and biosphere along the global mid-ocean ridges. This circulation gives rise to a complex series of physical, chemical, and biological interactions that affect the composition of both seawater and the oceanic crust, and lead to the creation of many types of seafloor ore deposits, and to the existence of unusual biological communities.

Although a considerable amount of surficial sampling has been completed on a number of ridge hydrothermal systems, only drilling an active system on a mid-ocean ridge can clarify 1) the permeability, pressure, and temperature structure within the upflow zone beneath an active hydrothermal system, 2) the nature of the chemical reactions between water and rock in both the upflow zone and the underlying reaction zone, 3) the method of sulfide precipitation and subsequent modification below the seafloor, 4) the structural control on the plumbing system within both the upflow and reaction zones, and 5) the evolution of major black smoker systems.

To date, attempts to answer such questions have relied upon the chemistry of waters from natural systems, samples collected from surface outcrops, experimental and theoretical analyses of basalt/seawater systems, and observations of fossil systems in ophiolites. These sources of evidence make assumptions about the conditions which are present in the sub-seafloor part of an active system, sometimes about which rocks are in equilibrium with which fluids, and sometimes about the nature of the physical structure of an active system. All of these arguments have been carried to their highest level for sediment-free systems, which are predicted to be considerably simpler than sedimented hydrothermal systems. Drilling of a major, sediment-free black smoker system will provide the necessary evidence to discriminate between the many current models.

Hydrothermal systems on unsedimented ridge axes dominate global hydrothermal activity, and hence are an important contributor to global mass and energy fluxes. All previous drilling has been carried out in areas where large deposits have been, or are, developing, such as sedimented-ridge hydrothermal systems. Drilling the interior of a mature, large volcanic-hosted deposit such as the

TAG mound will clarify the processes of recrystallization and "zone-refining", the distribution of minerals, the hydrothermal circulation and plumbing, the nature of the root zone, and the processes occurring during ore formation and deposition.

The TAG area has many features that make it the prime target for drilling an active volcanic-hosted hydrothermal deposit. Firstly, it is a located in a slow-spreading environment, a major characteristic of the global rift system, and the hydrothermal field is situated in the central part of a ridge segment bounded by small non-transform offsets or axial discontinuities, typical of many such segments on slow-spreading ridges. The mound represents a good drill target as the combination of size and maturity argues for a large surface areal target, with a well-developed root zone. The presently active mound is approximately 200 m in diameter and 50 m in height. It is composed of massive sulfides probably well in excess of 5×10^6 tons, being equivalent in size to some of the deposits in the Cyprus, Oman, and other ophiolites. No basalt has been observed outcropping either on the surface of the mound or on the 20-m high talus slopes that bound the mound to the west, north, and east. Furthermore, the deposit is mature. Geochronological studies indicate the mound to be of the order of 40-50,000 years old, and to have undergone intermittent activity, possibly every 5-6,000 years over the last 20,000 years. Duration of an active cycle still has to be resolved but the present day activity is of, at least, 50 years duration based on radiometric dating. The TAG mound exhibits a wide range of polymetallic sulfides with predominantly Fe-Cu-Zn varieties. A recent series of *Alvin* dives indicates the active mound is zoned, both in terms of type of activity and mineralogy, thereby providing the opportunity to study relationships of mineral alteration. There is also evidence of supergene reactions resulting in enrichment in metals such as gold. Exiting hydrothermal solutions range from high (363°C), through medium to low temperatures at the boundaries of the active mound. These fluids are somewhat different from EPR fluids and have been hypothesized as showing interaction with weathered crust (Campbell *et al.*, 1988). This may be a feature of slow-spreading ridges which can be tested by drilling.

The nearby MIR mound is proposed as a back-up drilling target. It is of similar size to the TAG mound, although not active. Primary sulfide features are similar to TAG, but there has been extensive recrystallization and the whole mound has been indurated by late-stage fluids that have replaced anhydrite and filled all voids with silica. Such an indurated feature will also allow conventional drilling.

STUDY AREA

Regional Geologic and Tectonic Setting

The ridge segment along which the TAG hydrothermal field is located, is about 40 km long, trends north-northeasterly, and is bounded by non-transform discontinuities to the south and north at 25°55'N and 26°17'N, respectively (Sempéré, Purdy, and Schouten, 1990; Purdy *et al.*, 1990;

Smith and Cann, 1992). Seafloor spreading has been asymmetric over the last 10 m.y.; half spreading rates are 13 mm/yr to the east and 11 mm/yr to the west (McGregor *et al.*, 1977).

The seafloor morphology of the TAG ridge segment is well defined by SeaBeam bathymetric surveys of the Mid-Atlantic Ridge (MAR) in this area (Rona *et al.*, 1986a; Sempéré *et al.*, 1990; Purdy *et al.*, 1990) The segment has a morphology typical of the 15-18 ridge segments lying between the Kane and Atlantis Fracture Zones (Sempéré *et al.*, 1990; Smith and Cann, 1992). In plan view, the floor of the median valley has an hour-glass shape, narrowing and shallowing towards the center of the segment at about 26°10'N. In cross section, the median valley has an asymmetrical shape, the eastern wall being higher, steeper, and less rough than the western wall (Karson and Rona, 1990; Zonenshain *et al.*, 1989). Using SeaBeam and high-resolution deep-towed side-scan sonar data, Smith and Cann (1990, 1992) and Smith *et al.* (1992) have documented the style of crustal accretion from 24°-30°N. Along this section of the MAR, the floor of the median valley is built of superposed, small-scale seamounts, with the axial volcanic ridges being formed by overlapping individual volcanic edifices (Smith and Cann, 1990, 1992). However, the data are insufficient to resolve the critical geological features needed to establish the distribution of hydrothermal activity and hence its relation to volcanism and tectonism.

Additional data on the geological structure of this segment, primarily concentrated in the vicinity of the hydrothermal field, has been collected from deep-towed camera profiles, piston-coring, water temperature profiling, dredging, and submersible dives (Eberhart *et al.*, 1988; Karson and Rona, 1990; Rona, 1980; Rona *et al.*, 1984, 1986b; Thompson *et al.*, 1988). The western wall of the median valley consists of fault-controlled basaltic scarps and sediment-covered terraces (Eberhart *et al.*, 1988; Zonenshain *et al.*, 1989). Much of the eastern wall is covered with debris-slide deposits partly buried by calcareous ooze; fault scarps range in height from 10 to 20 m but are locally up to 150 m (Karson and Rona, 1990). Outcrops of pillow lavas were also observed on the eastern wall (Zonenshain *et al.*, 1989). Karson and Rona (1990) have suggested that an east-west trending scarp on the eastern wall represents a structural accommodation zone resulting from differential extension and rotation of crustal blocks to the north and south.

Important constraints on the along-axis changes in stress state and seismic velocity structure are provided by a microearthquake survey and seismic refraction experiment carried out on this ridge segment (Kong, 1990; Kong *et al.*, 1992). These studies suggest that most of the micro-earthquake activity occurs at the axial high at the center of the segment; earthquakes are also distributed along-axis and in the eastern rift valley walls. No seismic events were detected in the immediate vicinity of the TAG hydrothermal field. The maximum depth of seismicity shoals toward the center of the segment, and a low velocity zone is observed there as well. The distribution of seismicity, the low velocity zone, and the recent hydrothermal activity suggest recent crustal injection near the axial high.

Magnetic field data from regional surface ship studies (Tivey *et al.*, 1989) indicate that a broad north-northeast-south-southwest-oriented, elongate magnetic low is associated with the TAG hydrothermal field. A more detailed magnetic study of the mound has also been completed during the Alvin diving program , and has defined the mound as a localized low.

Sea surface gravity data indicate that the TAG segment contains a "bull's eye" anomaly (Lin *et al.*, 1990), suggesting that either the crust is anomalously thick or that there is anomalously warm mantle upwelling buoyantly beneath this ridge segment. There may be a relation between the presence of the bull's eye and the presence of the TAG hydrothermal system on this segment.

Geologic and Tectonic Setting of the TAG Hydrothermal Field

Tectonic Setting

Hydrothermal activity in the TAG field is located on a 10-km-long segment of the eastern wall of the MAR. At this location, the east wall forms a broad salient toward the spreading axis and rises from the valley floor, near 4,000-m depth, to a height of 2,000 m through a series of steps formed by fault blocks (Temple *et al.*, 1979).

The TAG hydrothermal field consists of presently active low and high temperature zones, as well as a number of relict deposits. The zone of low temperature activity occurs between 2,400- and 3,100-m depth on the east wall (Rona *et al.*, 1984). The metalliferous deposits of this low temperature zone include widespread surficial metal-rich staining of carbonate ooze, as well as discrete, massive layered deposits of manganese oxide (birnessite), iron oxide (amorphous), and iron silicate (nontronite). The stratiform deposits range from less than 1 m across to about 15 x 20 m. They vary in composition from thick, laminated, crystalline birnessite precipitates, through Fe-rich tubular vents, to deposits of loose, earthy, interlayered birnessite, nontronite, and amorphous Fe-oxides (Thompson *et al.*, 1985). Anomalous temperatures (Rona *et al.*, 1984) and excessive ^{3}He (Jenkins *et al.*, 1980) were recorded in near bottom waters above the low-temperature field. Metal enrichments in the sediments have been recorded both at the surface and at 30-cm depth (Cu and Zn >1,000 ppm, Fe >8%); these enrichments were attributed to past and recent episodes of high-temperature venting in the area (Shearme *et al.*, 1983). The hydrothermal deposits in this low-temperature field exhibit a linear distribution along fault zones, trending sub-parallel to the valley floor, that are inferred to focus hydrothermal discharge (Scott *et al.*, 1974; Rona *et al.*, 1984; Thompson *et al.*, 1985).

The presently active black-smoker system occurs at the juncture between the rift-valley floor and the east wall at a depth of 3,620-3,700 m and at approximately 26°08'N, 44°49'W. The low-temperature field described above lies 3.7 km upslope to the east; the bathymetric axis of the rift valley is 1.5 km to the west. The active high-temperature field lies on oceanic crust at least 100,000 years old, based on the present seafloor-spreading rate. Sediment thickness around the active mound is variable depending on the local morphology. *Alvin* studies show that local basins may have >1 m of ooze, steep slopes are bare, less steep areas have 30-60 cm of sediment.

It is clear that both volcanism and tectonism play an important role in the spatial and temporal distribution of hydrothermal activity in this area, and three hypotheses have been presented addressing their interactions. Based primarily on observations in the low temperature field, Scott *et al.* (1974), Temple *et al.* (1979), and Thompson *et al.* (1985) hypothesized that hydrothermal activity was associated with ridge axis-parallel faults. They suggested these listric faults were the pathways for fluids and that the heat source was probably at the zero-age neovolcanic axis . More recently, based on observations of east-west faults high on the eastern wall in the vicinity of the low temperature field, Karson and Rona (1990) suggested that these transfer faults may intersect the ridge-parallel faults, concentrating hydrothermal activity at the intersections. However, due to lack of data, no direct evidence exists for, or against, the extension of east-west faults in the low-temperature field to the presently active TAG mound.

SeaBeam bathymetry suggests that the active TAG mound is located on the edge of a dome-shaped high. The domes are suggested to be discrete volcanic centers that may act as heat sources for localized hydrothermal activity. Support for this hypothesis comes from a number of observations. Zonenshain *et al.* (1989) noted very recent volcanics, as well as older basalt outcrops, located on the volcanic dome to the southeast of the presently active hydrothermal mound, suggesting intermittent volcanic activity with a very recent eruption. Rocks have been observed and collected from at least two older eruptions at this site, although not of the very recent age observed by the Russians. Some of the other volcanic domes are also known to have relict sulfide mounds associated with them, e.g. the MIR mound, and the Alvin mound; others have relict sulfides photographed on their edges. Samples recovered from the Alvin hydrothermal mound have been dated at 10,000, 50,000, and 100,000 years, suggesting a long and complex history similar to the presently active mound. The MIR mound, discovered in July 1991, is a large

(200 x 50 m) mound with chimney structures >5 m tall that has been described by Rona *et al.* (1992). It probably only recently became inactive because the mound appears bare even though carbonate deposition is of the order of 1.8 cm/103 yrs.

Geologic Setting

The black smokers are located on top of an elliptical-shaped, compound mound consisting of concentric inner and outer portions (Rona *et al.*, 1986b, Figure 2). The outer low-lying mound is composed of carbonate ooze, metalliferous sediment, sulfide blocks, and basalt talus and is about 500 m in diameter. The inner mound is about 200 m in diameter and rises 50 m above the outer mound between depths of 3,640 and 3,690 m. It is composed of massive sulfides, with distinct sample types being distributed from the interior to exterior of the mound. A cluster of chalcopyrite-anhydrite-rich black smoker chimneys emitting fluids up to 363°C caps the mound at about 3640-m depth. This chimney cluster sits on the top of a 10-20- m-high, 40-50-m-diameter cone, the surface of which is covered by a 3-6-cm-thick plate-like layer of massive pyrite and chalcopyrite, with interspersed blocks of corroded massive anhydrite and pyrite. The remainder of the top of the inner mound (at a depth of 3660-3665 m) is composed of both fragile Fe-oxide crusts and blocky to bulbous mixed Zn, Fe, and Cu-Fe sulfides with amorphous silica filling cavities.

A complex of white smokers venting fluids up to 300°C is located in the southeast quadrant of the mound; these "Kremlin"-like spires are composed dominantly of low-Fe sphalerite with minor amounts of chalcopyrite, pyrite, and amorphous silica. Fluids from the white smokers have a very low pH, contain no magnesium, and lesser amounts of iron than the black smoker fluids. They are thought to be derived from the black smoker fluids by conductive cooling and precipitation of sulfides within the mound.

Mass-wasting of the edges of the inner mound results in steep outer slopes to the west, north, and east. Two sample types are exposed: pyrite-rich blocks with trace amounts of late-stage amorphous silica, quartz, and goethite and with outer oxidized layers that include atacamite, and deep-red to orange-brown blocks of amorphous Fe-oxide, goethite, hematite, and silica (as both amorphous silica and quartz). Analogues for these sample types are not found in other known seafloor vent sites, but are present in massive sulfide deposits of Cyprus (Tivey *et al.*, 1992).

The distribution of sample types, their mineralogy, and the distinct compositions exhibited at the black smoker and Kremlin locations, suggest a flow pattern within the mound similar to that shown in Figure 2. Fluid exiting the black smoker complex is extremely focused. Fluid emanating from the Kremlin area has undergone conductive cooling as evidenced both by the presence of amorphous silica and the chemistry of the fluids (Edmond *et al.*, 1990). As the fluid cools and circulates within the mound, pyrite is precipitated. Blocks of this material are exposed during mass-wasting.

Preliminary geochronological studies suggest that the mound is on the order of 40-50,000 years old, and that activity has been intermittent over the past 20,000 years, with a periodicity of 5,000-6,000 years (Lalou *et al.*, 1990). The presence of late-stage quartz in pyritic and iron oxide blocks exposed on the steep slopes of the inner mound are consistent with such episodicity. Present activity commenced about 50 years ago after a hiatus of about 5,000 years (Lalou *et al.*, 1992).

Previous studies of ongoing hydrothermal activity documented by water column studies of Mn and/or particulate anomalies suggest that there are other presently active sites in the TAG area (H. Elderfield and T. Nelsen, pers. comm.). The location of these sites will be addressed in the site survey cruise. Limited photographic coverage (lacking good navigation or correlation with a structural framework) has shown the presence of relict sulfides in other areas of the TAG field, and recent submersible dives by *Alvin* and the Russian *MIR* vessels discovered two other relict sulfide mounds (Eberhart *et al.*, 1988; Rona *et al.*, 1990; Rona *et al.*, 1992). The site survey will collect the data that is needed to place the proposed drilling in the context of the regional time distribution and spatial geometry of hydrothermal activity in the entire field.

Previous magnetic studies (Rona, 1980) and the more recent magnetic data from the 1988 MARNOK cruise (Tivey *et al.*, 1989) reveal that the TAG area is the site of a distinctive anomaly in sea-surface magnetics data. This anomaly indicates an unusually pronounced, point-style magnetization low located in the general vicinity of the TAG mound. Four different hypotheses have been proposed for the cause of the sea-surface magnetic low measured at TAG . Three of these hypotheses propose hydrothermal or thermal demagnetization as the cause, while the fourth proposes structural thinning of the source layer by local normal faulting. A 1990 *Alvin* survey over the TAG mound showed a magnetization low located directly beneath the mound with a possible dip to the south, which has been interpreted as the upflow zone beneath the mound (Tivey *et al.*, 1991; Tivey *et al.*, 1992). The survey also showed that the magnetic low beneath the TAG mound cannot itself produce the observed sea-surface anomaly low. Either there are many more magnetic low source regions caused by hydrothermal demagnetization, as suggested by the presence of relict mounds, or a more regional magnetic low is present due to some thermal effect, as suggested by the recent volcanics and the seismic data. Near-bottom magnetic surveys, to be conducted during the site survey, offer the chance to discriminate between these hypotheses and possibly help in determining the occurrence and distribution of active and relict hydrothermal vent systems in the TAG region as a whole.

Only a few heat flow measurements near the active mound and on the relict mounds have been made (Rona, in prep.). Thermal output from the active mound has been estimated to be about 120 x 106 W using a transistor array and a grid survey at a height of 20 m above the mound (Rona *et al.*, 1991). Measurements at conductive heat stations on the mound ranged between 1.6 and 4.3 W/m^2.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

The overall scientific objectives of drilling at TAG are to investigate fluid flow, geochemical fluxes and associated alteration and mineralization, and the subsurface nature of an active hydrothermal system on a slow-spreading mid-ocean ridge. Understanding the processes operating within a hydrothermal system, and their interrelations, requires answering a number of questions that can be addressed only by drilling. Although studies of fossil hydrothermal deposits preserved in ophiolites have provided valuable insights into their subsurface geometry and composition, the hypothesis that these systems provide a useful analogue for mid-ocean ridge hydrothermal processes still needs to be tested. In addition, a number of critical parameters cannot be determined from extinct systems; for example, variations in permeability and porosity of the host rocks, the composition of the circulating fluid, and the dynamics of the water-rock interface.

Within the near-surface part of the hydrothermal system, Leg 158 will investigate:

1) the temporal and spatial variation in the mineralogy, chemistry, and physical properties of the hydrothermal precipitates;

2) the spatial and temporal variation in the composition of the circulating fluids and the effects of conductive cooling on the composition of these fluids and their relationships to mineralogical variations within the deposits;

3) the method of fluid circulation within the deposit and the spatial characteristics (focused or diffuse) of the flow;

4) the effects of fluid circulation within the mound, e.g. are metals remobilized and concentrated in distinct horizons?; and

5) the physical and chemical effects of epigene and supergene alteration reactions on the deposits, and on the fluxes of elements between the deposits and seawater.

In the stockwork and root zone below the surface deposits, studies aim to clarify:

1) the variation in mineralogical and chemical composition of deposits in this zone;

2) the degree to which fluids have reacted with the adjacent host rocks, the nature of the rock-seawater interactions, and subsequent affects upon the magnetics;

3) the physical and hydrogeological properties of the upper crust in this zone;

4) the chemical composition of the hydrothermal fluid in this zone;

5) the mechanism focusing the fluid flow within this part of the hydrothermal cell; and

6) the amount of heat exchanged in the system and the associated energy fluxes.

DRILLING PLAN/STRATEGY

Complete characterization of the subsurface nature of an active hydrothermal system requires a drilling program of more than one leg, since determining the location and nature of the reaction zone would require drilling a deep hole to the base of the sheeted dikes (i.e. to a depth of about 1.5-2 km). However, this one-leg program will demonstrate that it is possible to successfully drill and attain the scientific objectives in this type of environment.

The size and maturity of the deposit, and its compositional variability in terms of both the mineralogy of the deposits and the circulating fluid makes TAG the only currently known site where questions concerning the near-surface part and stockwork and root zones of the hydrothermal system can be addressed. In addition, capping of one (or more) of the holes will allow their future use for time-series measurements and monitoring fluid composition variability. As future technology develops, particularly the capability to sample high-temperature fluids downhole, these holes could be used for a number of different measurements that will help to clarify temporal variability of hydrothermal systems.

From previous drilling experience, there are a number of arguments which suggest that conventional drilling can accomplish the scientific objectives at TAG. TAG may be situated on crust possibly as old as 100,000 years (calculated from spreading rates) If that is the case, the crust (whether altered through hydrothermal circulation or not) is likely to be weathered, with some of the fractures infilled with minerals of various kinds. Previous experience with drilling weathered and hydrothermally-altered crust (for example, at Hole 504B) has demonstrated that conventional drilling is feasible. Although not as young as TAG, weathering and alteration processes clearly played an important role in achieving penetration through the upper pillow lavas at this site. However, if the TAG hydrothermal mound is associated with a younger volcanic dome, there is a possibility of encountering basalts of a younger age. It is proposed to drill through the basalt directly beneath the TAG hydrothermal mound, a major feature that has been active over at least the last 40-50,000 years. The size of the mound and duration of the activity argue strongly for a highly altered crust, with all veins and fissures completely infilled with secondary minerals. This is also consistent with the magnetic low zone directly beneath the mound. Such altered crust has been successfully drilled at Holes 417A and 418A in the North Atlantic, and at Hole 504B in the Pacific.

The likely thickness of the hydrothermal precipitates at TAG is 50-70 m given the analogous shape and size of the deposits of the Troodos ophiolite. Recent drilling during Leg 139 has provided some evidence that conventional drilling technology can drill through short sections of sulfide deposits, although difficulties are encountered with clearing cuttings for long sections. This suggests that the TAG sulfide deposits should not present a problem in terms of penetration and, if a comprehensive logging program is carried out, the recovery will be sufficient to address the objectives.

Problems were encountered on Leg 106 during attempts to drill into the active sulfide mound in the Snakepit hydrothermal field. The problems consisted of both difficult drilling conditions and extremely poor recovery, and were caused by alternating hard and soft, unconsolidated layers of sulfides. Comparison of these two fields from direct *Alvin* observations and inspection of samples from the two areas indicates distinct differences in their structure. The TAG mound is composed of more massive blocks of sulfide that appear to be more homogeneous in nature. Some of the blocks exposed on the steep talus slopes, which offer a window into the interior of the mound, contain late-stage amorphous silica and quartz. Given the age of the TAG mound (Snakepit is considerably younger), and the evidence for circulating fluids and conductive cooling with precipitation within the mound, the interior of TAG is most likely indurated and recrystallized from its long and complex evolution and will consequently provide a hard and massive target for drilling.

Drilling in stockwork zones has been demonstrated to be possible with the available technology. In Hole 504B, the top of a stockwork zone was encountered in 5.9-m.y. old basalts at a depth of 910 m below the sea floor. Coring in this interval was very successful, with recoveries up to 42%. Good recovery is particularly critical in the stockwork zone if the chemical reactions and their spatial and temporal relationships are to be understood and unravelled.

To meet the objectives of drilling in an active hydrothermal area, a variety of downhole measurements are critical at each site, especially as the recovery might not be high. Important measurements include subbottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress. A full logging program that will include the standard logs and specialty tools will be run at each site, and will be important to the fluid chemistry and flow objectives of the program.

In addition, these drillholes will provide opportunities for time-series experiments at a hydrothermal system. The instrumentation of these holes for temperature measurements and fluid sampling, such as the CORK system, is encouraged to continue after the drilling is completed. As additional technologies become available, other measurements and experiments can be done at this site. The European community is interested in deploying an instrumented station at a hydrothermal site in the Atlantic, so this may prove to be an advantageous site for continued long-term observations and measurements.

PROPOSED DRILL SITES

Leg 158 will complete a transect of three sites across the TAG mound (Figure 1, Table 1).

Proposed site TAG-1 is located near the center of the mound on the shoulder of the central cone in an area that has a slope of less than 10° and is roughly 20-30 m wide. This is the area closest to the black smokers that, from submersible observations, is the most suitable for drilling near the region of high temperature activity. It is designed to penetrate through the entire section of hydrothermal deposits and into the uppermost portion of the highly altered crust. In this region, large black smoker chimneys occur, from which hot (363°C) fluids are emanating. The chemistry of the fluids suggests that they have not mixed with seawater in the subsurface region of the mound, and it is likely that the ascending flow is well-focused beneath the chimneys (Figure 1). This site provides the best opportunity to recover a stratigraphic section of the hydrothermal mound, and to determine the nature of the fluid flow beneath the most active part of the mound.

Proposed site TAG-2 is located off-center to the southeast of TAG-1 in the "Kremlin" area, where warm (250°C) waters are discharging from small (1-2 m) high chimneys composed dominantly of Zn-Fe sulfides. The surface of the mound at this location is relatively flat, less than 5 m of relief over an area of roughly 80 x 80 m, and is suitable for setting a guidebase. Fluids emanating from this region have undergone conductive cooling within the mound (Figure 1); consequently, this site will provide information on the mineralogical and chemical variability within the mound related to these different fluids and physical controls. In addition, any differences in the alteration of the upper crust and the minerals precipitated within veins and fractures within it, will be determined.

Proposed site TAG-3 is located at the edge of the mound, where cool (<100°C) waters are diffusing out of the deposits and older, weathered sulfides are observed on the surface. It is also located over the magnetic low, and thus has a high probability of intersecting the stockwork. Drilling at this site will allow differences in the plumbing system within the mound related to diffuse, rather than focused, flow to be determined. In addition, the extent of the oxidation of the deposits, which is seen on the exposed surfaces of the mound, will be investigated, as well as the composition of the fluids present in this region.

Two of these proposed sites will be shallow (200 m), non-reentry holes and will be designed to penetrate through the hydrothermal deposits and into the top of the altered basaltic crust. The third proposed site (most likely TAG-2) will be a reentry hole that will penetrate into the stockwork zone and will be drilled to at least 500 m on this leg, with the possibility of being deepened further to the reaction zone at a later date. Determination of the exact locations of these sites, and confirmation of which will be the reentry site, will be made from the pending site survey cruises, which include bathymetry, deep-tow magnetics, geothermal and geoelectrical data.

There is the possibility that drilling into this active system may prove difficult, e.g. it may not be well-consolidated, and/or the high temperatures may cause problems (although similar high temperature fluids posed no problems on Leg 139). Consequently, a back-up site should be considered that will allow most of the objectives to be accomplished, except for those addressing fluid composition and flow. The MIR mound is proposed as the back-up site should drilling at TAG prove not to be feasible. Observations from the *MIR* submersibles in 1991 located the MIR mound on the lower part of the east wall of the rift valley about 2 km northeast of the TAG mound. Rona *et al.* (1992) have described the mound as consisting of two concentric zones: an inner zone, about 400 m in diameter, consisting of discontinuous sulfide outcrops with groups of inactive chimneys with intervening metalliferous sediment; and an outer zone of low temperature Fe and

Mn oxide deposits 150-200 m wide. It appears to be associated with a volcanic dome and is consequently in a similar tectonic setting to TAG. It is also about the same size as TAG and has similar primary sulfide features. However, unlike TAG, it is inactive, and the whole mound has been extensively recrystallized (Rona *et al*., 1992), and has been indurated by late-stage fluids that have replaced anhydrite and filled all voids with silica. Such an indurated feature will be considerably easier to drill.

ADDITIONAL CONSIDERATIONS

Safety

The sulfide deposit is volcanogenic-hosted, so hydrocarbons are not expected to pose a problem. The hot circulating solutions and their hydrogen sulfide concentrations have already been demonstrated not to pose a problem with drilling in these system. TAG is significantly deeper than the drilling at Middle Valley on Leg 139, when no problems were encountered. However, precautions for early detection of high levels of hydrogen sulfide will be necessary.

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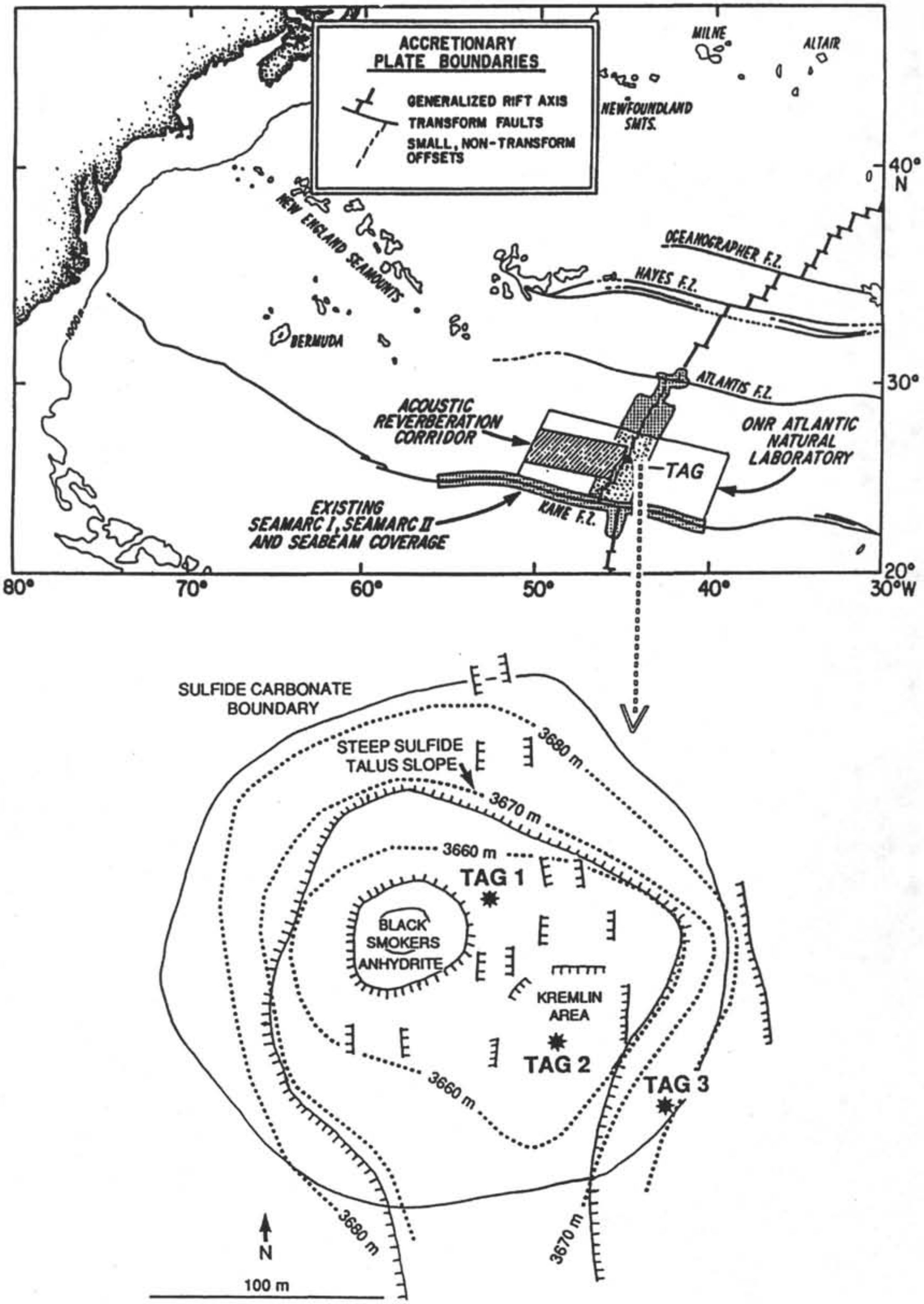

Figure 1. Location of the ONR Atlantic Natural Laboratory on the Mid-Atlantic Ridge (modified from Tucholke *et al.*, 1991) and plan view of the active TAG mound showing the principal boundaries and tectonic features as derived from submersible observations and photography. The locations of the three proposed drill sites are shown.

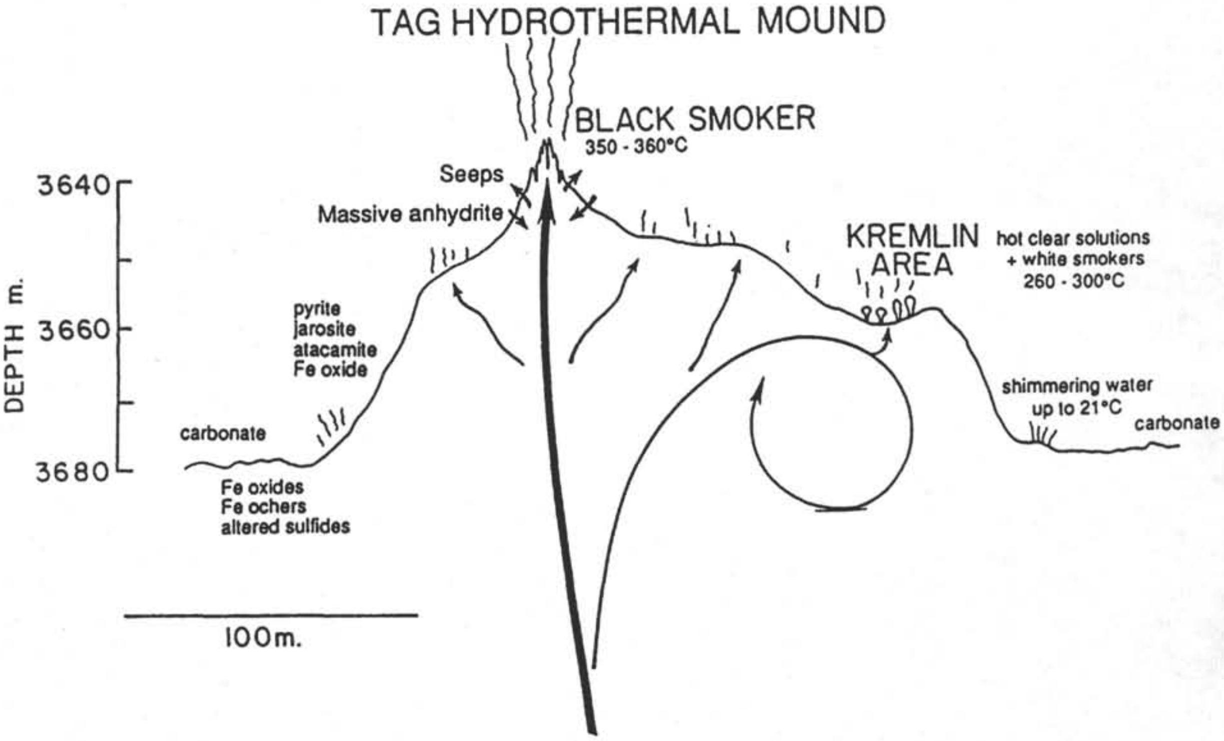

Figure 2. Cross section of the active TAG mound with observations derived from submersible observations. The suggested flow pattern within the mound is derived from the mineralogy of the deposits and the fluid chemistry.

TABLE 1

PROPOSED SITE INFORMATION
and
DRILLING STRATEGY

SITE: TAG-1 **POSITION:** 26°08'N, 44° 49'W
WATER DEPTH: 3660 m **SEDIMENT THICKNESS:** 50-70 m **BASEMENT PENETRATION:** 140 m

Objectives: Sample the entire section of the TAG hydrothermal mound near the black smokers where fluid flow is focused, and into the upper part of the highly altered crust.

Drilling Program: RCB coring.

Logging and Downhole Operations: Standard logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits and hydrothermally altered and veined basalts.

SITE: TAG-2 **POSITION:** 26°08'N, 44° 49'W
WATER DEPTH: 3660 m **SEDIMENT THICKNESS:** 50-70 m **BASEMENT PENETRATION:** 450 m

Objectives: Sample the section of the TAG hydrothermal mound in an area where fluids have undergone conductive cooling within the mound, and extend penetration into the underlying stockwork zone.

Drilling Program: RCB coring and reentry.

Logging and Downhole Operations: Standard logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits, stockwork zone and hydrothermally altered basalts.

SITE: TAG-3 **POSITION:** 26°08'N, 44° 49'W
WATER DEPTH: 3680 m **SEDIMENT THICKNESS:** 20 m **BASEMENT PENETRATION:** 180 m

Objectives: Drill through the older, weathered sulfides where there is diffuse flow and into the stockwork, the existence of which is suggested by the magnetization low.

Drilling Program: RCB coring.

Logging and Downhole Operations: Standard logs and specialty tools to measure sub-bottom formation temperatures, pore pressures and fluid fluxes, formation chemistry, sonic velocity porosity, resistivity, permeability, and stress.

Nature of Rock Anticipated: Massive sulfide deposits, stockwork zone and hydrothermally altered basalts.