SCIENCE PROSPECTUS

FY96 PROGRAM

Prepared from Original Proposals and Working Group Reports

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INTRODUCTION

This FY96 Science Prospectus presents the scheduled scientific operations for ODP Legs 163 through 170. These legs represent scientific cruises commencing September 1995 and continuing through December 1996.

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. For additional information, please contact the Manager of Science Operations at the following address:

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

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

Ocean Drilling Program Cruise Participant Application Form

Name (first, middle, last) ______________________________

Institution (including address) ______________________________

____

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

Permanent Institution Address (if different from above) ______________________________

____

Bitnet or Internet Address ______________________________

Present Position ____________ **Country of Citizenship** ____________

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

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

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

____

Date(s) Available ______________________________

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

____

Expertise (petrologist, sedimentologist, etc.) ______________________________

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

Experience (attach curriculum vitae) ______________________________

____

____

Selected Publications You Have Written Relevant to Requested Cruise ____________

____

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

____

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

____

____

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

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

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

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

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

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

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

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

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

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

Stratigraphy correlators, through cooperation with the Paleontologists, Paleomagnetists, Physical Properties and Logging specialists, and utilizing the site survey and underway seismic data, produce stratigraphic sections for correlation with recovered core.

Paleontologists' chief responsibility is to assign an age to the core-catcher samples as soon as possible after cores are recovered. They may need to examine additional samples to provide as complete a biostratigraphic characterization of the cored section as possible within the time available, including recognition of boundaries and hiatuses. A lead paleontologist must be appointed to write the Synthesis Chapters for the ODP volumes.

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

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

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

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

Structural geologists record structural features of the core and their relationships to other igneous, metamorphic, or sedimentary features. In addition, they integrate and constrain their observations with borehole logging, core magnetic, and micro-structural (petrographic) data to produce local and regional tectonic interpretation. Structural geologists may choose to record their observations using customized versions of ODP Visual Core Description (VCD) forms, independent structural VCD forms, or spread-sheets.

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

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

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

Seismic specialists are responsible for the onboard acquisition, processing, and interpretation of seismic reflection surveys, site surveys, and VSP's and interact with the entire scientific party to relate drilling results to regional geology.

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

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.

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?

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: ______________ ____________________________

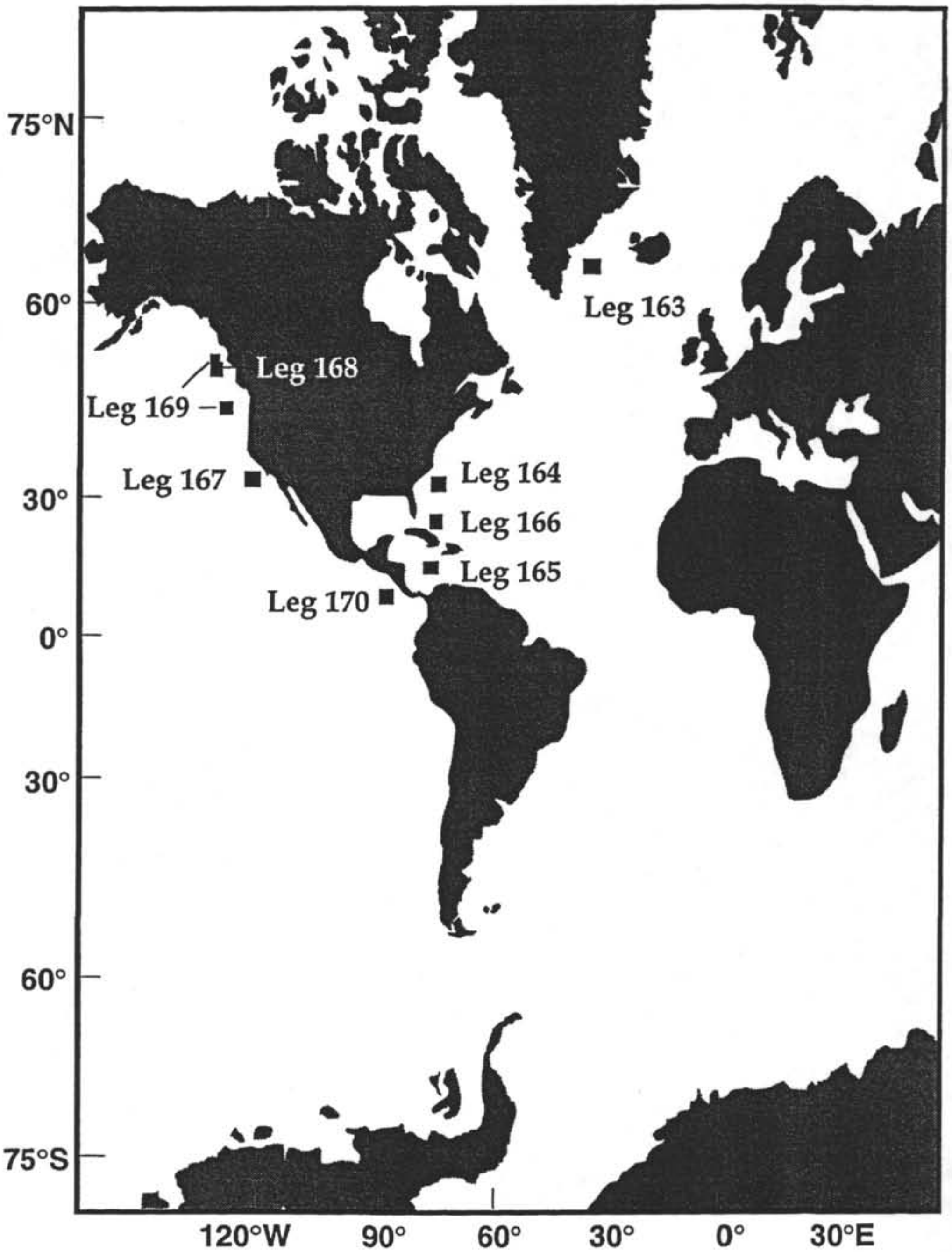
Signatures of Investigators

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

revised 12/90



Location Map of Scheduled Legs 163 through 170

OPERATIONS SCHEDULE

LEG	PORT OF ORIGIN	CRUISE DATES	DAYS AT SEA	DAYS: TRANSIT/SITE (Estimated)
163 SE Greenland	Reykjavik 3 - 6 September 1995	7 September - 26 October 1995	49	7/42
164 Gas Hydrate Sampling	St. John's 26 - 29 October 1995	30 October - 19 December 1995	50	8/42
165* Caribbean Ocean History	Miami 19 - 23 December 1995	24 December '95 - 18 February '96	56	11/45
166* The Bahamas Transect	San Juan 18 - 22 February 1996	23 February - 19 April 1996	56	8/48
167 California Margin	Panama 19 - 23 April 1996	24 April - 19 June 1996	56	17/39
168 Juan de Fuca Hydrothermal Circulation	San Francisco 19 - 23 June 1996	24 June - 19 August 1996	56	4/52
169 Sedimented Ridges II	Victoria 19 - 23 August 1996	24 August - 19 October 1996	56	6/50
170 Costa Rica Accretionary Wedge	San Diego 19 - 23 October 1996	24 October - 19 December 1996	56	11/45
	Panama 19 - 23 December 1996			

* The Caribbean Ocean History and The Bahamas Transect legs may be switched if further study shows that currents in the Santaren Channel are more favorable for the Bahamas Transect during Leg 165.

LEG 163
Southeast Greenland Margin

LEG 163

SOUTHEAST GREENLAND VOLCANIC RIFTED MARGIN (VRM)

Modified from Proposal 460 Submitted By

Hans Christian Larsen, C. Kent Brooks, Keith G. Cox, Paul M. Holm, Trine Dahl-Jensen, Robert A. Duncan, J. Godfrey Fitton, Jeffrey Karson, Lotte M. Larsen, Troels F.D. Nielsen, Andrew D. Saunders, and Michael Storey

To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

VRM's are the dominant type of rifted margin within the Atlantic, if not globally, and studies of these margins contribute toward our understanding of continental breakup, nature of rifting, and formation of large igneous provinces (LIP's) and their relationship to mantle plumes. Leg 163 will drill six sites along two transects off Southeast Greenland as part of an integrated study of geological work on the exposed part of the North Atlantic LIP, deep seismic profiling across the margin, and possible land drilling.

Leg 163's objective is to distinguish between different models for plume emplacement and plume structure and to characterize the weakening, thinning, and rupture of the continental lithosphere during this type of breakup. Leg 152 results suggest that the main part of the anomalous igneous crust along VRM's, the seaward-dipping reflector sequences (SDRS), is created by Icelandic-type oceanic crustal accretion. Recovery of high-Mg picrites shows that excessively high-temperature asthenosphere was present during breakup (i.e., breakup is related to some sort of mantle plume). However, at this distance (> 500 km) from Iceland, the main part of the SDRS seems to have a N-MORB type composition. Leg 163 will provide long stratigraphic sections of the early Paleogene volcanism closer to the hot-spot track to determine if the incompatible-element-depleted nature of Leg 152 and Hatton Bank basalts is a primary feature of the ancestral plume or an offset-dependant feature, suggesting compositional zonation of the plume head. Improved sampling of the highly variable lava compositions in the stratigraphically lowermost part of the SDRS will permit imaging of the first surface expression of the mantle plume. Expanded sampling of the transition from initial continental lithosphere-contaminated volcanism to more pristine oceanic-type volcanism will better characterize the primary magma reservoir. Further investigation of the highly tectonized continental crust and rift sediments below the feather-edge of the SDRS will document the history, nature, width, and environment of a volcanic-margin rift zone and its development into the OCT.

INTRODUCTION

Recovery of highly picritic lavas by Leg 152 show that excessively high temperature asthenosphere plays an important role in continental breakup (Larsen, Saunders, Clift, et al., 1994, in press) and the formation of VRM's, and hence, that mantle plumes somehow are important in this development. Furthermore, by drilling through the volcanic cover and through a basal normal fault into highly deformed pre-rift sediments, Leg 152 showed that ODP drilling can effectively provide crucial data on the deformation of the lithosphere during breakup.

The recently formed Danish Lithosphere Centre (DLC) in international collaboration with researchers from, at present, six US research institutes will perform deep MCS and wide-angle profiling across and along the margin and conduct extensive onshore geological work on the unique exposures of breakup related gabbros, dike swarms, flood basalts, and extensional tectonism. This combination of field geology, geophysics, and offshore drilling will provide an unparalleled, detailed picture of the development of a LIP related to mantle plume activity and continental breakup. To our knowledge, this part of the North Atlantic LIP is globally the only place where the combination of outcrop and subcrop and existing data allow for such a tightly constrained research plan which effectively can move us beyond the exploratory phase for this type of studies.

STUDY AREA[1]

Results of Leg 152

Ocean drilling at the Southeast Greenland margin recovered tectonized pre-rift sediments below continental flood basalts, dacites, picrites and subaerially erupted, MORB-type lavas. These data show that rifting within a narrow zone over a hot asthenosphere was followed by final plate separation and formation of thick oceanic crust at a subaerially exposed spreading ridge; magmatic flux was comparable to that of major mantle plumes. This development and coincident magmatism on the inboard, non-stretched margin suggest that arrival of the plume instigated breakup.

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[1]Text extracted from *Tectonism and Volcanism on the East Greenland Volcanic Rifted Margin: New Constraints on Continental Breakup from ODP Leg 152*: Submitted to *Nature* by H.C. Larsen, A.D. Saunders, P.D. Clift, J.G. Fitton, A. Demant, M.S. Fram, L.M. Larsen, C. Sinton and ODP Leg 152 Scientific Party

Mantle plumes conveniently explain the excessive magmatism at VRM's (White and McKenzie, 1989; Saunders et al., 1992; Campbell and Griffiths, 1990), but their world-wide occurrence and dominance along Atlantic rifted margins (Coffin and Eldholm, 1992; Holbrook and Keleman, 1993) of VRM's implies either that other processes are operating (Mütter, 1993), or that mantle plumes are primary instigators of continental breakup and not only a modification to another primary process. Several large continental flood basalt provinces can be related (White and McKenzie, 1989; Coffin and Eldholm, 1992) to formation of VRM's. However, in terms of magmatic flux and crustal structure, the submerged parts of VRM's are the most anomalous and span the OCT (Eldholm and Grue, 1994; Larsen and Jakobsdóttir, 1988; White et al., 1987).

Breakup of the Southeast Greenland margin apparently took place within a cratonic environment (Larsen, 1990; Larsen, Saunders, Clift, et al., in press). Lack of earlier rift basins contributes to a simple margin structure with the feather-edge of the offshore, huge lava pile, the SDRS onlapping almost directly onto Precambrian crust (Figures 1 and 2). The margin stratigraphy was sampled by drilling six sites (Larsen, Saunders, Clift, et al., in press) along a seismically imaged transect (Figure 2). At the inner site, Site 917, drilling penetrated 874.9 m through the feather-edge of the SDRS and into underlying tectonically-tilted, pre-rift sediments. At the more seaward site, Site 915, drilling recovered a short section of basalts from a stratigraphic position not far above the section drilled at Site 917 (Figures 2 and 3). Below a thick sequence of post-rift sediments (1189 m), Site 918 recovered 122 m of stratigraphically younger basalts from the main SDRS.

Nature of Volcanism

Consistent with the model for the formation of the SDRS (Larsen and Jakobsdóttir, 1988; Pálmason, 1986; Mütter et al., 1982) all of the 110 drilled lavas were subaerially erupted. At all drill sites, the SDRS is overlain by early to middle Eocene shallow-water sediments showing deepening with time (Larsen, Saunders, Clift, et al., in press).

Three lava series can be distinguished (Figure 3); a Lower Series comprising basalts, olivine basalts and picrites, a Middle Series with more evolved basalts and dacitic lavas and tuffs, and an Upper

Series with olivine basalts and picrites. MORB-like lavas occur in the stratigraphically younger Sites 915 and 918.

Several lines of evidence suggest that lavas of the Lower and Middle Series evolved in large, continentally hosted reservoirs; (i) the presence of flows up to 50-m thick and similar to flows from the continental East Greenland Flood Basalts (Larsen et al., 1989) (ii) enrichment of these lavas, presumably by reaction with the continental lithosphere (Saunders et al., 1992; Fitton et al., 1991) in Ba, Sr, Rb, and K relative to the Upper Series and younger lavas (Figures 3 and 4); and (iii) a systematic variation in MgO content with stratigraphic height (Figure 3). The latter suggests that large magma reservoirs sourcing the continental succession were periodically replenished, as shown by peaks in the MgO content, but the overall trend was towards more evolved compositions culminating with the Middle Series.

Evolved magma compositions (MgO < 7%) were not recovered from the Upper Series and younger lavas. In fact, the Upper Series comprises highly magnesian, in part picritic, basalts in which rapid oscillations in MgO content imply short-term storage in smaller reservoirs, accompanied by rapid crystallization and accumulation of olivine (Figure 3). Following transient eruption of picrites, more stable MgO contents around 7-9% characterize the younger lavas, indicating more steady-state conditions within the main SDRS.

Thus, the entire lava sequence can be grouped into two main successions: an older continental succession and a younger oceanic succession (Figure 3). The two successions are separated by a single fluviatile sediment (67 cm recovered) which probably represents the magmatic breakup unconformity, i.e., the change from a magmatic system erupting through continental lithosphere (including large replenishment magma chambers) to one tapping directly from a crystal mush zone at the top of the asthenosphere.

Absence of a large magma chamber could ease the ascent of the dense picritic melts (Stolper and Walker, 1980) during final breakup but subsequent development of an axial magma chamber, beneath the evolving spreading ridge, may have reinstated the density filter retaining high seismic-velocity, olivine-cumulate rocks in the lower crust (underplated material (Holbrook and Keleman, 1993; White et al., 1987; Hinz et al., 1987)). A similar close connection between breakup, the eruption of picrites, and rapid transitions from lithosphere-contaminated to uncontaminated magmas has been suggested for other parts of the North Atlantic (Holm et al., 1993; Gill et al., 1992; Holm, 1988) and in part also from the Basin and Range province (Fitton et al., 1991).

Most Leg 152 basalts seem to originate from normal, or close to normal, depleted asthenosphere. Using the Zr/Nb as a proxy for the degree of depletion, basalts from the oceanic succession fall within the N-MORB and West Greenland fields basalts (Figure 4). Except for a few flows, all Leg 152 basaltic lavas are more depleted (i.e., higher Zr/Nb ratio) than the Scoresby Sund (East Greenland) basalts, and most of them are closely comparable with highly-depleted tholeiites recovered from Hatton Bank (Figure 4).

Rifting, Subsidence, and Uplift

Below the feather-edge of the SDRS and within the underlying fault-block (Figure 2) , drilling encountered a thin, basal quartzose (fluviatile?) sandstone overlying steeply-dipping to subvertical beds of low-metamorphic, finely laminated mud-, silt-, and sandstone (turbidites?); tentative correlation is made with Late Cretaceous-Paleocene pre-basaltic sediments exposed to the north (Nielsen et al., 1981; Soper et al., 1976). However, unlike these, the drilled sediments show strong tectonic disturbance including most likely riftward (seaward) rotation of fault-blocks (up to about 50°). This was followed by considerable uplift, erosion, and formation of a breakup unconformity prior to the main volcanism. Following volcanism, a marked seaward, crustal flexure including several landward-dipping normal faults formed and further increased the dip of the pre-rift sediments (Figure 2). We suggest that buoyant continental lithosphere is present below the landward part of the flexure and that igneous ("oceanic") lithosphere (prone to thermal subsidence) is present below the seaward part of the flexure.

Separation of the tectonic-breakup unconformity and the magmatic-breakup unconformity suggests that initial continental volcanism, aided by tectonic thinning of the lithosphere, was followed by thermal thinning of the lithosphere, leading to complete rupture and establishment of seafloor spreading.

During the Eocene, the post-volcanic sediments of the main SDRS underwent significant subsidence from littoral to deep-shelf conditions (Larsen, Saunders, Clift, et al., in press). A hiatus on the shelf, spanning the late Oligocene to the Quaternary, corresponds with sudden deposition of coarse-grained, terrigenous, high-sedimentation-rate sediments of mid-Oligocene and younger age in the adjacent deep basin; deposition of these followed starved conditions in the late Eocene (Figure 2). These stratigraphic relationships support the notion (Larsen, 1990; Christiansen et al., 1992; Brooks, 1979; Larsen and Marcussen, 1992) that the kilometer-scale, large regional uplift of the inner margin started, or accelerated, approximately 20 m.y. after breakup.

Timing and Magmatic Fluxes

The most seaward (youngest) part of the SDRS is of magnetic chron C24n.3n age, represented by a well-developed seafloor-spreading anomaly (Figure 1; early Eocene, 53.0 Ma (Cande and Kent, 1992)). The main SDRS is associated with a broad magnetic low, possibly representing C24r (Larsen and Jakobsdóttir, 1988; Larsen, 1980). No sediment older than early Eocene were recovered above the SDRS and all lavas, except perhaps four, were exhibited a reverse magnetic polarity (Larsen, Saunders, Clift, et al., in press). suggesting that the main SDRS accreted entirely within magnetic chron C24r during a maximum of only 2.9 m.y. (latest Paleocene to early Eocene (Cande and Kent, 1992)). The East Greenland flood basalts were extruded during the same time interval (Larsen et al., 1989; Nielsen et al., 1981; Soper et al., 1976).

However, preliminary $^{40}Ar/^{39}Ar$ dating suggests that the continental succession may be older than C24r (C. Sinton, unpubl.), and hence, the hiatus between the two main lava successions may be significant and span one, or more, normally-magnetized intervals. Alternatively, the main SDRS could span more than 2.9 m.y. and the low-amplitude positive and semi-linear anomalies within the broad magnetic low (Figure 1) could represent normal magnetic chrons older than C24n.3n. However, levels of remanent magnetization within Leg 152 basalts are high (Larsen, Saunders, Clift, et al., in press), and lack of normally-developed pre-C24n.3n seafloor-spreading anomalies seem to refute this interpretation. We interpret the small positive anomalies within the broad low to represent C24r cryptochrons that have been accentuated by high rates of spreading (Cande and Kent, 1992; Figure 1); this interpretation is consistent with the biostratigraphic data.

A 6-km-thickness of the main SDRS (Larsen, Saunders, Clift, et al., in press) and the 2.9-m.y. duration of their formation implies an average rate of extrusion of 0.28 km^3/k.y./km rift length (half rate) or, if symmetric, 0.56 km^3/k.y; this is about four times larger than estimated for the Iceland and East Greenland flood basalts (Pálmason, 1986; Larsen et al., 1989; Pálmason, 1980). Likewise, the average implied spreading rate is approximately 5 cm/yr (half rate) decreasing over the C24n to C23n interval to 3 cm/yr (Larsen, 1980) and eventually to 1-1.6 cm/yr (Talwani and Eldholm, 1977).

Discussion and Conclusions

An OCT below the feather-edge of the SDRS is consistent with geophysical data (Holbrook and Keleman, 1993; Larsen and Jakobsdóttir, 1988; White et al., 1987; Pálmason, 1986; Mütter et al., 1982), with the observed transition from the "continental succession" to the "oceanic succession", and with the rifting and subsequent crustal flexuring within this zone. Hence, the crust below the main SDRS is entirely igneous, and rapid emplacement of this thick crust (Larsen and Jakobsdóttir, 1988; White et al, 1987; Hinz et al., 1987) implies a very large magmatic flux (Eldholm and Grue, 1994); this, together with the observed initial uplift within the extending rift zone (not to be confused with late, regional margin uplift), the subsequent subaerial eruption of the SDRS, and the transient presence of highly picritic magmas, provides overwhelming evidence for the presence of anomalously hot asthenosphere (>1500°C ?) during breakup and early seafloor spreading. Rapid upward transition from picritic to non-picritic volcanism implies that, during formation of the main SDRS, picritic magmas in general were retained within the lower crust, forming a high seismic velocity layer (White and McKenzie, 1989; Coffin and Eldholm, 1992; Holbrook and Keleman, 1993). While the narrow embryonic rift zone could be interpreted as reflecting steep edges of the flanking cold-lithospheric plates, and hence, could support the model of locally enhanced convection (Mütter et al., 1988), this model provides no explanation for the observed high-temperature magmas. Also, if during formation of the SDRS, asthenospheric material remained in close (thermal boundary layer) contact with the edges of the continental lithosphere, a more gradual transition from continental to oceanic volcanism would be expected.

The presence of a mantle plume during breakup (i.e., the ancestral Iceland Plume) therefore seems the only plausible explanation for our observations. The extensive distribution of an early Tertiary

SDRS along northeast Atlantic margins (White and McKenzie, 1989; Eldholm and Grue, 1994; Larsen and Jakobsdóttir, 1988) and wide occurrence of picrites (Holm et al., 1993; Gill et al., 1992; Holm, 1988; Nielsen et al., 1981) suggests that the thermal anomaly was laterally very wide; the rapid dissipation of its surface expression, except for the Faeroe-Iceland Greenland Ridge (Larsen and Jakobsdóttir, 1988), indicates that outside this area, the thickness of the thermally anomalous mantle layer was limited and only provided a finite heat reservoir.

Presence of lower mantle material within the Iceland plume is reflected in the occurrence of incompatible-element enriched basalts in Iceland along the Reykjanes Ridge and in drill cores from Miocene crust several hundred kilometers south of Iceland (Schilling, 1973; Luyendyk and Cann, 1979). While the absence of incompatible-element enriched basalts from the "oceanic succession" off East Greenland and from the Hatton Bank drill cores (Figure 4) is consistent with the Neogene extent of this anomaly (Figure 1), it would seem that, compared to the Neogene, the much-expanded thermal anomaly during breakup was not associated with a similar expanded presence of incompatible-element enriched material.

The coincidence of volcanism within actively-rifting, as well as non-rifting, parts of the East Greenland margin, and the initially high rates of magmatic flux and plate separation may suggest that the arrival of the plume played a significant role in instigating breakup. However, the large lateral extent of the thermal anomaly compared to an apparently laterally-limited compositional anomaly may indicate that the plume has had time to significantly incubate below the lithosphere prior to rifting (White and McKenzie, 1989; Storey et al., 1991; Lawver and Müller, 1994).
In either case, the late timing of the kilometer-scale large uplift of the inner margin has two implications; (i) margin uplift cannot be explained by plume impact or underplating;
(ii) gravitational spreading from a highly-uplifted rift zone cannot explain the early rifting and apparently high initial spreading rates. Alternatively, we can speculate that the plume developed plate drag which instigated extension; with regard to the margin uplift, we propose flexural uplift (Beek et al., 1994), possibly accentuated by ridge-push when a topographically significant mid-ocean ridge developed (Larsen and Marcussen, 1992).

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To recover long stratigraphic section(s) of the early Paleogene volcanism close to the hot-spot track.

2) To constrain the pre-volcanic rifting history, timing, nature, and width and the environment of the rift zone.

3) To augment Leg 152 sampling of the very earliest volcanism.

4) To augment Leg 152 sampling of the transition from transient picritic volcanism into N-MORB type volcanism within the SDRS.

Specific Objectives and Methodology

The overall goal of our proposed research (including Leg 163 and other studies) is to understand 1) the origin, state, and emplacement of hot asthenospheric material below the margin during breakup, 2) the resultant deformation of the lithosphere, and 3) the interaction between asthenosphere and lithosphere (Figure 5). More specifically, we aim to collect data that can distinguish between different models for plume emplacement and plume structure (cf., Campbell and Griffiths, 1990; Duncan and Richards, 1991; Hill, 1991; White and McKenzie, 1989; Lawver and Müller, 1994), and can characterize the weakening, thinning, and rupture of the continental lithosphere during this type of breakup.

Though most likely derived from a hot mantle plume, the Paleogene Leg 152 picrites and MORB basalts within the main SDRS are all depleted in incompatible elements (Figure 4), unlike the Neogene Iceland plume magmas. Leg 163 will investigate this key issue by expanded stratigraphic sampling, but first and foremost by drilling Paleogene lava sections closer to the assumed plume centre, allowing us to examine whether this is a primary feature of the ancestral plume, or whether it is an offset dependant feature suggestive of compositional zonation of the plume head.

In a recent model, Lawver and Müller (1994) propose a third possible explanation for the apparent lack of lower mantle material during breakup of the Southeast Greenland margin. In this model, the plume centre (stem) of the Iceland plume drifted from west through east below mainland Greenland and passed below the East Greenland margin about 15-20 m.y. after breakup (40-35 Ma). Leg 163 will test this model off East Greenland by drilling Paleogene lavas in a position close to the Faeroe-Iceland-Greenland-Ridge (FIGR), and in an area where enriched magmas are known to occur within the Neogene (DSDP Sites 407-409 and the northern Reykjanes Ridge). There model would be supported if enriched material is absent within the Paleogene, and gradually increases in abundance toward the Neogene. However, if a plume component is clearly present at this position close to the FIGR from start of breakup (unlike the Leg 152 basalts), a compositional zonation away from the FIGR (i.e., away from the track of the plume centre) is likely and would indicate that the plume stem was centered below, or close to, the rift zone during breakup.The latter would strongly support the notion that the arrival of the plume instigates breakup. If, on the other hand, a long-lived plume system has drifted east (relative to the overlying lithosphere) and an extensional stress field independent of the plume has caused rifting over the fringes of the approaching plume (cf., Lawver and Müller, 1994), the role of mantle plumes in instigating breakup would seem less direct and more of a (strongly) modifying process to extension and plate separation.

Further investigations also should be directed toward the rifting of the continental crust in order to start understand how the continental crust and lithosphere weakens and extends in this rifting environment. The Leg 152 discovery (Figure 3) of highly-deformed pre-rift sediments below the feather-edge of the SDRS significantly differ from the onshore pre-rift sediments further north along the margin (Nielsen et al., 1981; Larsen and Marcussen, 1992). These onshore sediments are all concordant with, or at the most, slightly oblique to the volcanic cover. Leg 163 will further investigate the distribution and deformation of pre-rift sediments in the Leg 152 drilling area, and will attempt to recover stratigraphic sections documenting rift history and rift environment.

Leg 163 will also attempt sampling of early SDRS volcanism. This sampling was not achieved during Leg 152 as a result of stratigraphic omission due to normal faulting. The very earliest volcanism is likely to show a large diversity, including a possible alkaline sequence which could be indicative of deep, early melting within the plume (proposed site EG66-1). During Leg 152, drill-bit failure caused early termination of Site 915. Leg 163 will attempt to deepen this hole and obtain stratigraphic coverage of the apparently rapid transition within the feather-edge of the SDRS from continentally-hosted magmatism through picritic magmatism to one producing oceanic N-MORB type lavas of apparently uniform composition (Figure 3).

DRILLING PLAN/STRATEGY

All Leg 163 proposed sites are located on the two main transects at approximately 63°N and 66°N (EG63 and EG66 transects, Figure 6; Table 1). We also propose drilling to deepen one Leg 152 site (Site 915) .

Setting and General Aims of the Two Transects

The general setting of the two transects, EG63 and EG66, is shown in Figure 6. The two transects are supposed to cross fairly similarly structured OCT. The structure of this type of OCT is simple, in the sense that only the rift event related to breakup is present, and hence, the structure of the OCT is not a result of multiple, and possibly different, types of rifting.

The main difference between the two transects is the closer proximity to the hot-spot track (FIGR) of the northern transect and the apparently deeper level of crustal exposure within the OCT in the north. The latter may be due to a relatively higher uplift of the area towards the FIGR (Larsen, 1990).

In order to avoid repetitive drilling, we have concentrated the more extensive and systematic drilling of the OCT and investigation of volcanic development with time in the south (proposed sites EG63-5 and EG63-6 and deepening of Site 915). The seismic data and the Leg 152 drilling data provide optimum constraints in this area. Furthermore, the proven presence of pre-rift sediments allow for important characterization of the rift history and environment and provide markers for the amount of tectonic rotation of the crust during rifting.

Proposed drilling in the northern transect is more limited. This transect is a landward extension of DSDP Sites 407-409. At this offset from the FIGR, incompatible-element enriched lavas from sites 407-409 and from the Reykjanes Ridge are known. Drilling at EG66 will concentrate on recovering, from the feather-edge of the SDRS, a single long section of breakup and early spreading lavas presumably showing a clear component of Icelandic plume-type magmas (proposed site EG66-1A). At proposed site EG66-1, penetration to continental basement will be attempted, possibly by an offset hole, in order to correlate with rift structures exposed along the coast (dike swarm and seaward rotation of fault blocks). A second priority target, at proposed site EG66-2, is sampling of the outer approximately 7 m.y.-younger part of the SDRS in order to monitor possible changes with time in the presumed influence of the Iceland plume. If the plume axis passed through this area considerably after breakup, as recently proposed (Lawver and Müller, 1994), this would be expected to manifest itself by a low abundance, or a lack, of plume material during breakup followed by increasing presence with time.

PROPOSED SITES

Proposed sites EG63-5 and EG63-6, Site 915, and proposed sites EG66-1, EG66-1A, and EG66-2 are described below. The priority of drilling proposed site EG66-2 depends on results from proposed site EG66-1A. Based on experience gained during Leg 152 and other hard-rock legs, we do not plan for deployment of a hard-rock guide base, but alternatively have selected sites with at least a thin sediment cover allowing for spud-in.

Proposed site EG63-5

The main objectives of drilling proposed site EG63-5 are

1) to identify the nature of the landward-dipping reflectors; a sheeted dike complex in a basement host rock or pre-rift sediments?
2) to identify the general dip and rotation of dikes/host rock or of the pre-rift sediment and, using rock orientation and geochemistry, to determine if multiple dike generations are present;
3) if a dike complex is present, to attempt correlation with onshore dike complex and with the nearby SDRS;
4) if a dike complex is present, to identify the nature of deformation (dike width and intensity, fault movements along dikes, P/T conditions);

5) if sediments are present, to recover a long section of pre-rift sediments to characterize the early rift history (timing, environment, subsidence, source area, etc.), including diagenetic and metamorphic alteration.

This site is located on the middle shelf in a water depth of 475 m. The shelf is nearly free of post-rift sediment in this location with only a thin (5-10 m-thick) cover of glacio-marine sediments. In general, the pre-Quaternary and pre-volcanic rocks in this area (inner shelf) are continental basement rocks, most likely of granitic to gneissic nature, and of Archean to early Proterozoic age, as seen along the coast (Figures 1 and 2). However, towards the breakup zone and in the OCT below the mid to outer shelf, the basement is deformed through rifting and seaward flexuring below the feather-edge of the SDRS. Results of Leg 152 (Site 917) show that tectonically-deformed, pre-rift metasediments are present seaward of proposed site EG63-5. The likely types of deformation of the continental crust include injection of a sheeted dike complex and seaward rotation of fault blocks by as much as 40°-60°. Leg 152 data shows incipient biotite formation in the pre-rift metasediments, suggesting thermal alteration of the crust. However, only few dikes were observed at Site 917 which is seaward of, and stratigraphically higher, than proposed site EG63-5. Upward-decreasing intensity of dikes is also observed onshore and the potential for recovering an offshore analogue to the coastal dike complex (Nielsen, 1978; Larsen 1978; Myers, 1980; Myers et al., 1993; Brooks and Nielsen, 1982; Larsen et al., 1989) is therefore better at proposed sites EG63-5 and EG63-6.

At proposed site EG63-5, the existence of landward-dipping reflectors (which may represent dikes) was confirmed by recent seismic data from 1993. This data also determined that the strike of the dipping wedge is slightly oblique to the coast and the margin. However, Leg 152 drilling demonstrated the presence of tectonically-tilted pre-rift sediments in the area and hence, they may represent such sediments. This ambiguity in the interpretation of the reflectors can be addressed by the Leg 163 program. If a sheeted dike swarm exists, there are structurally important implications. If sediments are present, the site will provide an excellent potential for recovery of a long section of pre-rift sediments from which the early rift phase can be characterized in terms of timing, subsidence, and environment.

Also, it would be structurally significant to recover landward-dipping pre-rift sediments at this location, only 6 km landward of Site 917. The steeply-dipping to subvertical orientation of the Site 917 pre-rift sediments presumably was acquired through seaward rotation, suggesting a major tectonic discordance between the two closely-spaced sites.This type of structural information would be invaluable for reconstruction of tectonic development and balanced cross sections. Likewise, if similar structures are found offshore within the OCT, a firm tectonic framework can be established for the sheeted dike complex exposed on the coast further north.

If a dike complex is present, the required depth of penetration depends on the thickness and relative abundance of dikes. If conditions are similar to coastal exposures, drilling to bit destruction (100-200 m?) will be adequate.

Proposed site EG63-6

The main objectives of drilling proposed site EG63-6 are

1) to determine the stratigraphy, composition, nature, and true dip of the volcanics above the breakup unconformity;
2) to determine the nature and age of the breakup unconformity;
3) to determine the nature and style of deformation of the continental basement (composition of host rock, dike intensity, tectonic rotation) for comparison with proposed site EG63-5 and Site 917;
4) to establish dike intensity and orientation (if any) within the early SDRS lavas and the geochemical nature of the dikes.

This site is located on the middle shelf in a water depth of 460 m. In this location, the shelf is nearly sediment free with only a 5-10 m thick cover of glacio-marine sediments. The pre-Quaternary rocks are volcanic; most likely basaltic lavas.

The volcanic rocks dip approximately 10° toward the sea and form the very feather-edge of the SDRS. At proposed site EG63-6, the volcanic cover is around 225 to 250 m thick . Thin sediment beds could be present between, and below, the volcanic units resting on top of the tectonic breakup unconformity. At Site 917, only one intra-volcanic sediment horizon was found as well as a thin, fluviatile sandstone bed below the volcanics and above the breakup unconformity and the underlying, steeply-dipping pre-rift sediments (Figures 2 and 3).

The primary objective at proposed site EG63-6 is the recovery of the oldest part of the volcanic section not drilled at Site 917. A large diversity in volcanism can be expected within these earliest lavas. As an example, an initial, alkaline rock sequence may be present and could provide important constraints on the initial deep-melting history.

Site selection has been made in order to stratigraphically complement, but not overlap, Site 917. If warranted, overlap can be achieved by a slight seaward displacement of the drill site. However, the site should not be moved too far down-dip as this could endanger penetration below the breakup unconformity. The latter is also of high priority in order to complete sampling of the continental crust subcropping below the breakup unconformity at proposed sites EG63-5 and EG63-6 and at Site 917. The three sites together span the inner part of the OCT and will provide truly unique constraints on the structure and development of the continental rift zone prior to volcanism and final breakup.

Total thickness from sea-bed to the breakup unconformity is estimated at approximately 250 m. We have planned for 400 m of total penetration in order to adequately sample and log the interval below the unconformity.

Deepening of Site 915

Together with proposed site EG63-6 and Site 917, deepening of Site 915 will provide an almost complete stratigraphic sampling of the lowermost 1.3 km (approximately) of breakup lavas.

The main objective in deepening Site 915 is

1) to expand the stratigraphic coverage within the early, oceanic SDRS succession in an attempt to prove, or disprove, steady state conditions, study the composition of the asthenospheric magma reservoir, and to provide suitable material for age determination.

At Site 915, located in a water depth of 533 m, Leg 152 drilled through Quaternary (84.8 m) and Eocene (102.3 m) sediments before reaching a thin heterolithic conglomerate (2.2 m) and finally volcanic basement at 189.3 mbsf. Basement penetration was limited to 20.1 m because of bit-failure. Only recovered two igneous units were recovered.

Drilling at nearby Site 917 recovered a 779-m-long section of lavas showing the transition from a lower continental succession (Lower and Middle Series) into an upper oceanic succession (Upper Series). At its base, the oceanic succession includes very picritic lavas. Near the top of Site 917, a trend towards N-MORB type lavas with little MgO variation (Figure 3) was observed. The same type of lavas were recovered from Site 915. However, this limited sampling at Site 915 must be expanded to firmly verify if this sharp transition into a stable system producing N-MORB type lavas takes place within this stratigraphically-oldest part of the SDRS.

According to seismic correlation, drilling approximately 250 m into the basement at Site 915 will enable stratigraphic correlation to Site 917 (Upper Series at Site 917). If the transition is sharp, and the low MgO-variation, N-MORB-type basalts are consistently present over a long interval, then this type of monotonous lava composition is likely to occur throughout the entire main SDRS, consistent with the recovery of 122 m of this lava type within the SDRS at the more seaward Site 918.

Moreover, deepening of Site 915 will triple the stratigraphic coverage within the "pristine" non-contaminated oceanic succession, which is the most suitable for detailed geochemical characterization of the composition of the asthenosphere during breakup. Finally, preliminary age determination has indicated that a considerable hiatus may exist between the continental succession and the oceanic succession; it is important to obtain additional material which is more suitable for Ar/Ar dating of the oceanic succession. Because of the thin sediment cover, we propose to wash to basement and drill 250 m into basement as a single-bit hole.

Proposed site EG66-1A

The main objective of drilling at proposed site EG66-1A is

1) to recover a long section of lavas from the early, oceanic SDRS succession to study the composition of the asthenospheric magma reservoir, to prove, or disprove, steady state conditions, and to provide suitable material for age determination.

Proposed site EG66-1A is located in a water depth of 270 m. A thin glacial cover overlies a > 1-km-thick, seaward-dipping (35°-45°) lava succession, representing the very oldest part of the SDRS. The thickness of the glacial cover varies from 10-40 m around the drill site; the thickness at the site is about 10 m.

The main purpose in drilling this site is to retrieve a stratigraphic record of the early part of the Paleogene SDRS at a position close to the FIGR. At this offset from the FIGR, incompatible-element, Icelandic-plume-type lavas are known from the Neogene. The drill site will test whether or not such enriched, plume-related material can be traced back close to the time of breakup in the Paleogene. The implications of such material being clearly present, not present, or only vaguely present are far-reaching with regard to plume emplacement and plume structure.

For this purpose we have selected proposed site EG66-1A about 2 km seaward of the original NARM-DPG planned site EG66-1. This position allows drilling in a stratigraphic position similar to that of Site 915, i.e., approximately 1 km above the base of the SDRS lava succession. By analogy with Site 915, this will allow us to sample a long section of 'oceanic' material without continental contamination. We will aim at 500 m of penetration in order to get a long representative section and possibly also penetrate into a lower continental succession. However, a section of only 150-200 m (likely to be achieved with a single bit) will be acceptable and excessive amounts of time will not be spend to progress beyond that. Also, the possibility for offset drilling two or three shallower, single bit holes exists. We estimate drilling to 500 m.

Proposed site EG66-1

The main objectives of drilling at proposed site EG66-1 are

1) to recover earliest rift volcanism in a position close to the FIGR; the early volcanism is likely to include, in part, highly-alkaline rocks possibly indicating deep, initial melting within the plume;

2) to provide a firm correlation between seismically-observed, offshore crustal flexure zones below the feather-edge of the SDRS and potentially similar structures exposed along the coast which represent major tectonic and magmatic extension of the crust.

Proposed site EG66-1 is located in a water depth of 260 m. Thin (~ 5 m) Holocene sediment overlies an approximately 200-m-thick succession of the oldest lavas which dip approximately 40°-45° seaward. The lavas overly seaward, down-flexured basement. The whole succession is, by analogy with nearby coastal outcrops, likely to have been intruded by a sheeted-dike complex, originally intruded at right angles to the lavas, and then subsequently tilted about 45° seaward. The general tectono-stratigraphic position is similar to proposed site EG63-6 on the southern transect.

Only very limited, erratic outcrops of lavas exist onshore in a setting close to a major gabbro-syenite complex (Myers, 1980; Myers et al., 1993). The onshore lavas concordantly overly thin, shallow-water conglomeratic sandstones or onlap directly onto the basement. They are highly altered, presumably because of the nearby gabbroic intrusion. The onshore lava succession seems very diverse, spanning nepheline-normative, in part basanitic, alkaline basalts to tholeiitic material and shows indications of eruption into (shallow?) water. Such strongly alkaline compositions are unknown from the other, lower parts of the East Greenland flood basalts, and it would be interesting if such an early, alkaline rock suite exists. At Hawaii, alkaline material in the Loihi Seamount is interpreted as representing low-degree melting at large depth, presumably from the approaching plume. However, more systematic stratigraphic sampling of fresh material must be conducted before drawing a similar conclusion for Southeast Greenland. Such sampling can only be done offshore, where a stratigraphically coherent sequence is preserved.

Although alkaline material may also be present at the southern transect EG63, it is more likely to occur at proposed site EG66-1, or at least to be more distinctly developed here, firstly because it is known from nearby onshore, and secondly because the location is expected to be more plume proximal, and hence, melting at great depth is more likely to occur here.

It is important to determine if any such early, alkaline sequence is present along the margin in this position close to the initial line of breakup, and if present, the precise age of this material. Also, if present at both transects, these sequences may be differently developed with, for example, indications of melting at deeper mantle levels in the north than in the south away from the supposed plume centre.

Drilling at this site will also provide a firm control of the structural similarity of this offshore flexure zone with the coastal flexure zone and associated dike swarm. The seismic data indicates the presence of a flexure zone offshore. The key issue here is the presence, or absence, of the sheeted dike complex offshore; the dike complex is a permanent constituent of the coastal flexure zone. It is important to make this comparison onshore and offshore because, unlike onshore, the offshore flexure is located in a tectonically well constrained setting, i.e., the landward part of the OCT below the feather-edge of the SDRS. Thus, if firm correlation can be made, more far reaching conclusions can be drawn from the studies (including land drilling) of the coastal exposures.

Drilling is planned to penetrate 275 m into the volcanic cover and into the underlying basement.

Proposed site EG66-2

The main objective of drilling at proposed site EG66-2 is

1) to recover a Paleogene basement section from approximately 7-m.y.-younger crust than at proposed sites EG66-1 and -1A to monitor possible increased presence of lower-mantle, plume-derived material.

This site, located in 1660 m of water, is situated near the seaward end of the SDRS on crust of approximately anomaly 22 age (51-52 Ma), i.e., about 7-9 m.y. younger than the initial breakup volcanism (approximately 60-58 Ma). SDR's are developed to great depth in this position (7-8 km). The large thickness of the extrusive part of the oceanic crust shows that a strong thermal anomaly was present during its formation. The main objective is to recover, at least, a 200-m-long section of the SDRS to monitor, through comparisons with the landward site EG66-1A and the seaward DSDP Sites 407-409, possible changes in the presence of lower-mantle, plume-derived material from the Paleogene and into the Neogene. In case a clear plume signal is present at proposed site EG66-1A, the priority of proposed site EG66-2 is lowered considerably. Shipboard XRF analysis will be performed to enable a decision to made during the leg.

A suite of alternate sites exist on 50-35-Ma-old crust seaward of the SDRS crust. According to Lawver et Müller (1994), the plume stem did not pass through this area before approximately 40 Ma, and hence, a more seaward, younger site may be preferable (40-45 Ma?) to monitor increasing plume influence in terms of lower mantle material. These alternate sites have less sediment cover than proposed site EG66-2. In an effort to keep other variables as constant as possible, we have positioned proposed site EG66-2 in the youngest possible position where there is still evidence of a strong thermal anomaly which is comparable to the time of breakup (i.e., thick SDRS).

At proposed site EG66-2, the SDRS is covered by a 520-m-thick sequence of Paleogene shelf sediments and Neogene slope sediments. The proposed site is close to a generic site proposed for Arctic Gateway drilling and considerable paleoceanographic and paleoclimatic information may be derived from the Neogene sediments (Larsen et al., 1994).

SAFETY CONSIDERATIONS

The proposed drilling is located in an area with a very narrow weather window due to presence of polar pack ice. The optimum weather window is mid August to mid October. A Danish ice-class 1A navy vessel, equipped with an excellent radar system, will support *JOIDES Resolution* in areas where ice poses a potential problem; this strategy was successfully employed during Leg 152 which was afforded assistance from the Finnish ice-breaker *Fennica*.

REFERENCES

Beek, P. van der, Cloetingh, S., and Andriessen, P., 1994. Mechanisms of extensional basin formation and vertical motions at rift flanks: constraints from tectonic modelling and fission-track thermochronology. *Earth Planet. Sci. Letters*, 121:417-433.

Brooks, C.K., 1979. Geomorphological observations at Kangerdlugssuaq, East Greenland. *Greenland Geoscience.*, 1:1-21.

Brooks, C.K., and Nielsen, T.F.D., 1982. The E. Greenland continental margin: a transition between oceanic and continental magmatism. *J. Geol. Soc. London*, 139:265-275.

Campbell, I.H., and Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. *Earth Planet Sci. Letters*, 99:79-93.

Campbell, I.H., and Griffiths, R.W., 1991. Megaplumes and giant radiating dykes swarms. *In* Fawcett, J.J., *Abstr. Progr. Geol. Ass. Can., Mineral. Ass. Can., Can. Geophys. Union Joint Annu. Mtg.*, 16:19 (Abstract).

Cande, S.C., and Kent, D.V.J., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *J. Geophys. Res.*, 97: 13,917-13,951.

Christiansen, F.G., Larsen, H.-C., Marcussen, C., Hansen, K., Krabble, H., Larsen, L.M., Piasecki, S., Stemmerik, L., and Watt, W.S., 1992. Uplift study of the Jameson Land basin, East Greenland *Norsk. Geologisk Tidsskrift*, 72:291-294.

Coffin, M.F., and Eldholm, O., 1992. Volcanism and continental break-up: a global compilation of large igneous provinces. *In* Storey, B.C., Alabaster, T., and Pankhurst, R.J. (eds.) *Magmatism and the causes of continental breakup.* Spec. Publ. - Geol. Soc. London, 68: 17-30.

Duncan, R.A., and Richards, M.A., 1990. Early Cretaceous global flood basalt volcanism. *Eos*, 71 (43):1668.

Duncan, R.A., and Richards, M.A., 1991. Hot spots, mantle plumes, flood basalts, and true polar wander. *Rev. Geophys.*, 29:31-50.

Eldholm, O., and Grue, K., 1994. North Atlantic volcanic margins: Dimensions and production rates. *J. Geophys. Res.*, 99:2955-2968.

Fitton, J.G., James, D., and Leeman, W.P., 1991. Basic magmatism associated with late Cenozoic extension in the Western United States; compositional variations in space and time. *J. Geophys. Res.*, 96:13693-13711.

Gill, R.C.O., Pedersen, A.K., and Larsen, J.G.,1992. Tertiary picrites in West Greenland; melting at the periphery of a plume? *In* Storey, B.C., Alabaster, T., and Pankhurst. R.J. (eds) *Magmatism and the causes of continental breakup.* Spec. Publ. - Geol. Soc. London, 68:335-348.

Hill, R.I., 1991. Starting plumes and continental break-up. *Earth Planet. Sci. Letters*, 104:398-416.

Hinz, K., Mütter, J.C., and Zehnder, C.M., 1987. Symmetric conjugation of continent-ocean boundary structures along the Norwegian and East Greenland margins. *Mar. Pet. Geol.*, 4:166-187.

Holbrook, W.S., and Kelemen, P.B., 1993. Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature*, 364:433-436.

Holm, P.M., Gill, R.C.O., Pedersen, A.K., Larsen, J.G., Hald, N., Nielsen, T.F.D., and Thirlwall, M.F., 1993. The Tertiary picrites of West Greenland; contributions from "Icelandic" and other sources. *Earth Planet. Sci. Letters*, 115:227-244.

Holm, P.M., 1988. Nd, Sr, and Pb isotope geochemistry of the Lower Lavas, E. Greenland Tertiary igneous province. *In* Morton, A.C., and Parson, L.M. (eds.) *Early Tertiary volcanism and the opening of the North Atlantic.* Spec. Publ. - Geol. Soc. London, 39:181-195.

Joron, J.L., Bougault, H., Maury, R.C., Bohn, M., and Desprairies, A., 1984. Strongly depleted tholeiites from the Rockall Plateau margin, North Atlantic; geochemistry and mineralogy. *In* Roberts, D.G., and Schnitker, D., et al., *Init. Repts. DSDP*, 81: Washington (U.S. Govt. Printing Office), 783-794.

Larsen, H.C., 1978. Offshore continuation of East Greenland dike swarm and North Atlantic Ocean formation. *Nature*, 274:220-223.

Larsen, H.C., 1980. Geological perspectives of the East Greenland continental margin. *Bull. Geol. Soc. Den.*, 29:77-101.

Larsen, H.C, 1990. The East Greenland Shelf. *In* Grantz, A., Johnson, L., and Sweeney, J. F. (eds.) *The Arctic Ocean region: The Geology of North America.* Geol. Soc. Am., 185-210.

Larsen, H.C., and Jakobsdóttir, S., 1988. Distribution, crustal properties, and significance of seawards-dipping sub-basement reflectors off E. Greenland. *In* Morton, A.C., and Parson, L.M. (eds.) *Early Tertiary volcanism and the opening of the North Atlantic.* Spec. Publ. - Geol. Soc. London, 39:95-114.

Larsen, H.C., and Marcussen, C., 1992. Sill Intrusion, flood basalt emplacement and deep crustal structure of the Scoresby Sund region, East Greenland. *In* Storey, B.C., Alabaster, T., and Pankhurst, R.J. (eds.) *Magmatism and the causes of continental breakup.* Spec. Publ. - Geol. Soc. London, 68:365-386.

Larsen, H.C., Saunders, A.D., Clift, P., and ODP Leg 152 Scientific Party, in press. *Proc. ODP, Init. Repts.*, 152: College Station, TX (Ocean Drilling Program).

Larsen, H.C., Saunders, A.D., Clift, P., Beget, J., Wei, W., Spezzaferri, S., and ODP Leg 152 Scientific Party, 1994. Seven million years of glaciation in Greenland. *Science*, 264:952-955.

Larsen, H.C., Saunders, A.D., Larsen, L.M., Lykke-Andersen, H., ODP Leg 152 shipboard party, Marcussen, C., and Clausen, L., 1994. ODP activities on the South-East Greenland margin: Leg 152 drilling and continued site surveying. *Rapp. Grønlands Geologiske Undersøgelse*, 160:25-81.

Larsen, L.M., Watt, W.S., and Watt, M., 1989. Geology and petrology of the lower Tertiary plateau basalts of the Scoresby Sund region, East Greenland. *Grønlands Geologiske Undersøgelse Bulletin*, 157:1-164.

Lawver, L.A., and Müller, R.D., 1994. Iceland hot spot track. *Geology*, 22:311-314.

Luyendyk, B.P., and Cann, J.R., 1979. *Init. Repts. DSDP*, 39: Washington (U.S. Govt. Printing Office).

Merriman, R.J., Taylor, P.N., and Morton, A.C., 1988. Petrochemistry and isotope geochemistry of early Paleogene basalts forming the dipping reflector sequence SW of Rockall Plateau. *In* Morton, A.C., and Parson, L.M. (eds.) *Early Tertiary volcanism and the opening of the North Atlantic.* Spec. Publ. - Geol. Soc. London, 39:123-134.

Morton, A.C., Dixon, J.E., Fitton, J.G., Macintyre, R.M., Smythe, D.K., Taylor, P.N., 1988. Early Tertiary volcanic rocks in Well 163/6-1A, Rockall Trough. *In* Morton, A.C., and Parson, L.M. (eds.) *Early Tertiary volcanism and the opening of the North Atlantic.* Spec. Publ. - Geol. Soc. London, 39:293-308.

Mütter, J.C., 1993. Tectonics; margins declassified. *Nature*, 364:405.

Mütter, J.C., Buck, W.R., and Zehnder, C.M., 1988. Convective partial melting; 1, A model for the formation of thick basaltic sequences during the initiation of spreading. *J. Geophys. Res.*, 93:1031-1048.

Mütter, J.C., Talwani, M., and Stoffa, P.L., 1982. Origin of seaward-dipping reflectors in oceanic crust off the Norwegian margin by "subaerial sea-floor spreading". *Geology*, 10:353-357.

Myers, J.S., 1980. Structure of the coastal dike swarm and associated plutonic intrusions of East Greenland. *Earth Planet. Sci. Letters*, 46:407-418.

Myers, J.S., Gill, R.C.O., Rex, D.C., and Charnley, N.R., 1993. The Kap Gustav Holm Tertiary Plutonic Centre, East Greenland. *J. Geol. Soc. London*, 150:259-276.

Nielsen, T. F. D., 1978. The Tertiary dike swarm of the Kangerdlugssuaq area, East Greenland. *Contrib. Mineral. Petrol.*, 67:63-78.

Nielsen, T.F.D., Soper, N.J., Brooks, C.K., Faller, A.M., Higgins, A.C., and Matthews, D.W., 1981. The pre-basaltic sediments and the lower lavas at Kangerdlugssuaq, East Greenland: Their stratigraphy, lithology, paleomagnetism and petrology. *Meddelelser om Grønland Geoscience*, 6:25.

Pálmason, G.J., 1980. A continuum model of crustal generation in Iceland, kinematic aspects. *J. Geophys.*, 47:7-18.

Pálmason, G., 1986. Model of crustal formation in Iceland, and application to submarine mid-ocean ridges. *In* Vogt, P.R., and Tucholke, B.E. (eds.) *The Geology of North America.* Geol. Soc. Am., 87-98.

Saunders, A.D., Storey, M., Kent, R.W., and Norry, M.J., 1992. Consequences of plume-lithosphere interactions. *In* Storey, B.C., Alabaster, T., and Pankhurst, R.J. (eds.) *Magmatism and the causes of continental breakup.* Spec. Publ. - Geol. Soc. London, 68:41-60.

Schilling, J.G., 1973. Iceland mantle plume; Geochemical study of Reykjanes Ridge. *Nature*, 242:565-571.

Soper, N.J., Higgins, A.C., Downie, C., Matthews, D.W., and Brown, P.E., 1976. Late Cretaceous-early Tertiary stratigraphy of the Kangerdlugssuaq area, East Greenland, and the age of opening of the northeast Atlantic. *J. Geol. Soc. London*, 132:85-104.

Stolper, E., and Walker, D., 1980. Melt density and the average composition of basalt. *Contrib. Mineral. Petrol.*, 74:7-12.

Storey, M., Mahoney, J.J., Kroenke, L.W., and Saunders, A.D., 1991. Are oceanic plateaus sites of komatiite formation? *Geology*, 19: 376-379.

Talwani, M., and Eldholm, O., 1977. Evolution of the Norwegian-Greenland Sea. *Bull. Geol. Soc. Am.*, 88:969-999.

Viereck, L.G., Taylor, P.N., Parson, L.M., Morton, A.C., Hertogen, J., and Gibson, I.L., 1988. Origin of the Paleogene Vøring Plateau volcanic sequence. *In* Morton, A.C., and Parson, L.M. (eds.) *Early Tertiary volcanism and the opening of the North Atlantic.* Spec. Publ. - Geol. Soc. London, 39:69-83.

Viereck, L.G., Hertogen, J., Parson, L.M., Morton, A.C., Love, D.A., and Gibson, I.L., 1989. Chemical stratigraphy and petrology of the Vøring Plateau tholeiitic lavas and interlayered volcaniclastic sediments at ODP Hole 642E. *In* Eldholm, O., Thiede, J., Taylor, E., et al., *Proc. ODP, Sci. Results*, 104: College Station, TX (Ocean Drilling Program), 367-396.

White, R.S., Spence, G.D., Fowler, S.R., McKenzie, D.P., Westbrook, G.K., and Bowen, A.N., 1987. Magmatism at rifted continental margins. *Nature*, 330:439-444.

White, R.S., and McKenzie, D. 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. *J. Geophys. Res.*, B94:7685-7729.

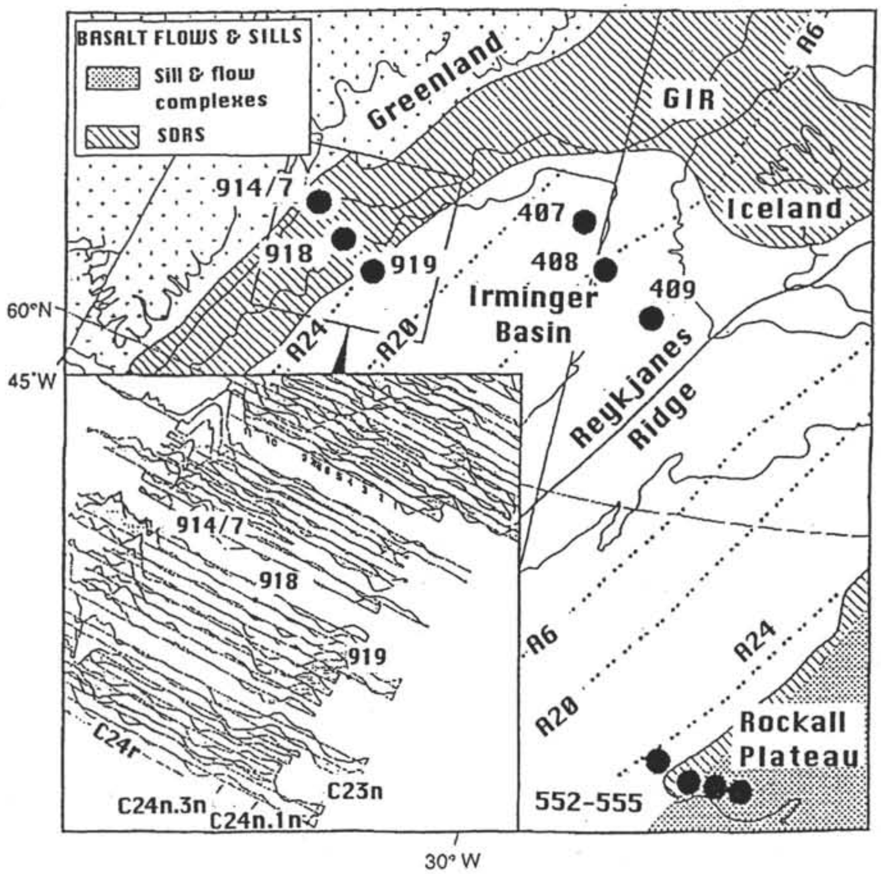


Figure 1. Aeromagnetic profiles over the Southeast Greenland margin. Position of Leg 152 drill sites (Sites 914 to 919) shown. Seafloor spreading anomalies C23n, C24n.1n (C24n.2n indistinguishable), and C24n.3n are easily identifiable and form well defined lineations that links with the regional North Atlantic seafloor spreading anomaly pattern (Talwani and Eldholm, 1988). A deep, broad magnetic low is present landward of C24n and can be correlated with C24r. Low amplitude positive anomalies occur within this low, and form a linear array not dissimilar to seafloor spreading anomalies. They are tentatively correlated with the cryptochrons of Cande and Kent (1992). The preliminary identification made here is consistent with Leg 152 drilling data, and implies initial spreading rates about 7 cm/yr abating to around 3 cm/yr at C24n to C23n times (Larsen and Jakobsdóttir, 1988; Larsen, 1980).

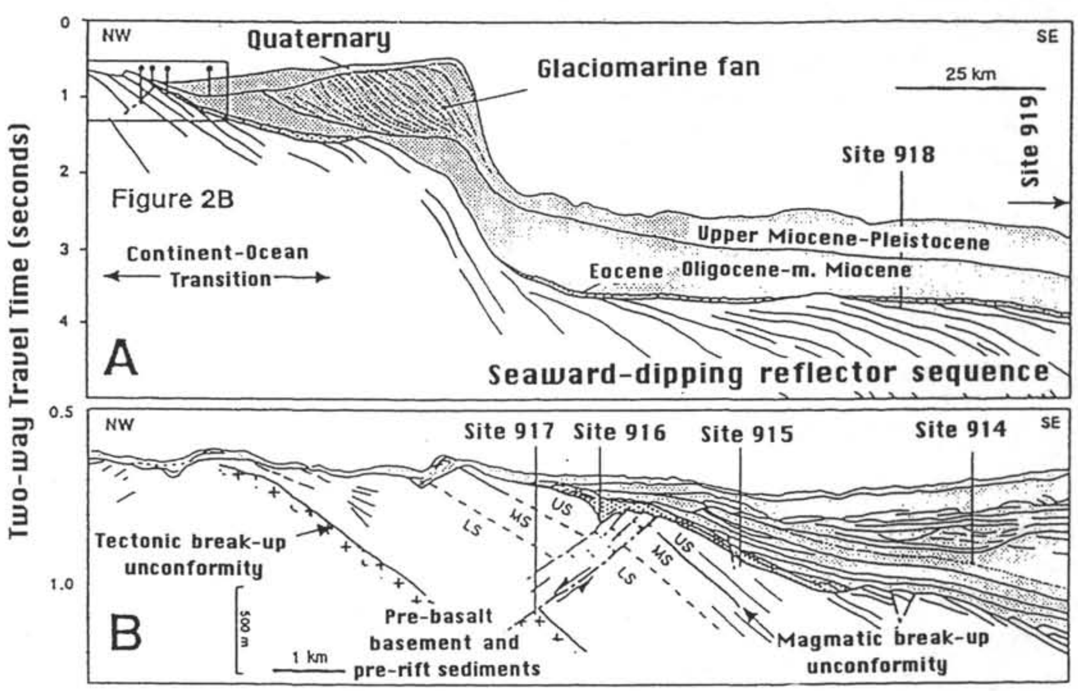


Figure 2. Interpreted seismic section across the Southeast Greenland margin at 63°N, showing the location of the Leg 152 drill sites.

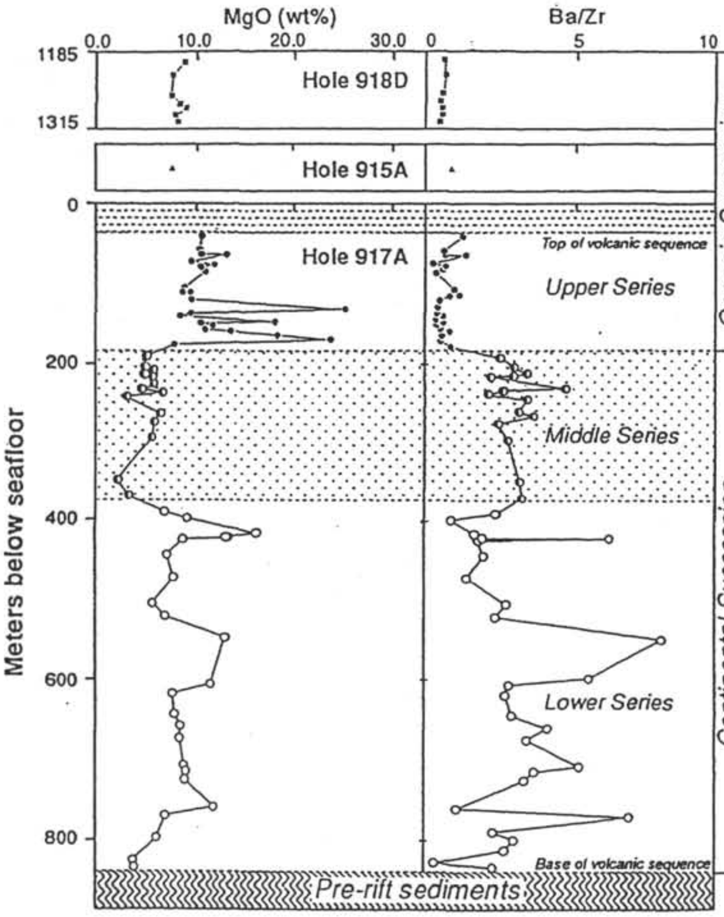
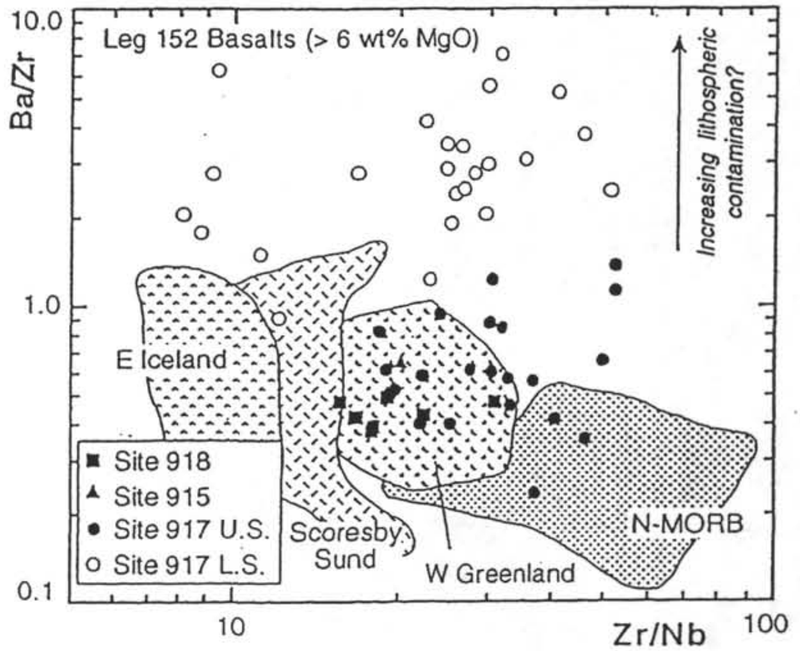


Figure 3. Variation in MgO content and Ba/Zr in igneous rocks from Sites 915, 917, and 918. The plots arranged to show the temporal variation from Site 917 (old) to Site 918 (younger) across the SDRS. Note the presence of high-Mg rocks in the Upper Series at Site 917, and the switch from high Ba/Zr to low Ba/Zr at the boundary of the Middle and Upper Series. Because of the latter, enrichment in Ba and other incompatible elements within the Lower and Middle Series is interpreted as contamination by the continental lithosphere and not a primary plume feature. Likewise, the general parallelism within the Lower Series between MgO enrichment (representing new magma pulses) and increased Ba/Zr cannot be taken as evidence for Ba-enrichment in the primary magma. This is because a systematic correlation at the level of individual flows do not exist (plot of MgO versus Ba/Zr show no systematic correlation). Rather, the emplacement of new magma pulses somehow may cause expulsion of more contaminated material. Systematic isotope data (in prep.) are needed for resolving this question.

Figure 4. Zr/Nb versus Ba/Zr for basalts (MgO > 6%) from Leg 152 and other areas in the North Atlantic (Morton et al., 1988; Joron et al., 1984; Merriman et al., 1988; Viereck et al., 1988, 1989). The Greenland basalts can be interpreted as being derived from a mixture of 'depleted" (MORB-like) mantle, and less depleted, or plume, mantle. The elevated Ba/Zr ratios in the Site 917 basalts are thought to represent contamination from the continental lithosphere (Figure 3). Data sources: Iceland Tertiary basalts from Hardarson and Fitton (unpubl.); West Greenland (Holm et al., 1993); East Greenland (Scoresby Sund) (Larsen et al., 1989); and MORB from A.D. Saunders (unpubl.).



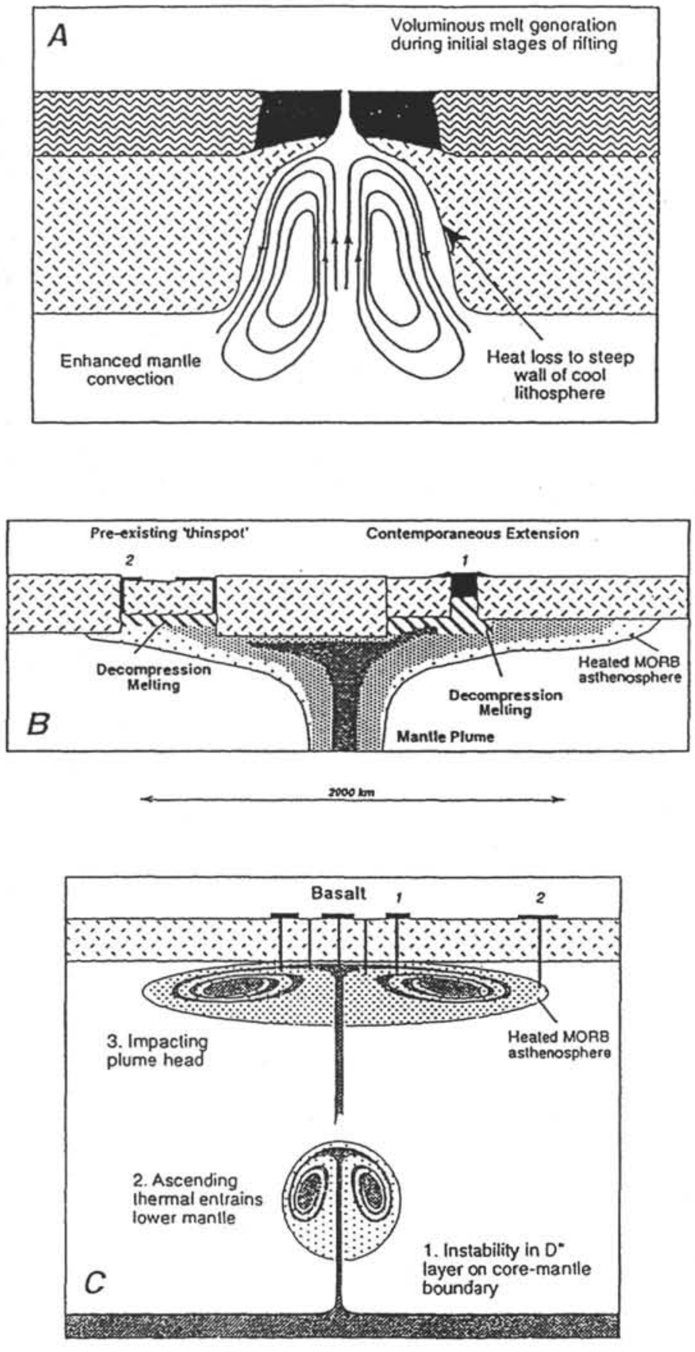


Figure 5. Different models for generation of large amounts of asthenospheric melts during breakup.

A: Enhanced convection was proposed by Mutter et al. (1988) as a possibility not requiring anomalously high temperatures. This model is not supported by the recent Leg 152 data which strongly suggests the presence of a significant thermal anomaly.

B and C: (cf., Campbell and Griffiths, 1991; Duncan and Richards, 1990; White and McKenzie, 1989) both involve a thermal anomaly requiring the presence of an underlying mantle plume. The structure and emplacement history of such plumes are poorly constrained and is one of the main topics to be addressed by drilling volcanic rifted margins and other LIP's. Studies of the North Atlantic LIP show that the thermal anomaly was laterally extensive.

Key questions are: did the impact of a large plume head (C) instigate breakup, or could the plume have been around for quite a long time and have developed a large thermal head (B) over which more passive rifting took place? Is it realistic to view plumes as narrowly fed, circular structures? If the plume were around for a geological significant time prior to breakup, relative movement between the overlying plate and the plume stem would be expected to create variations with time in the input of lower mantle, plume material at points close the plume track. In East Greenland this would be at points close to the Iceland Greenland Ridge (EG66 transect).

At present, model B seems to be most consistent with observations, including Leg 152 data, but the Paleogene center of the plume in terms of lower mantle enriched material has not yet been identified. This will be investigated by drilling closer to the presumed plume axis along the EG66 transect which also will test if the plume axis passed below the margin after, and not during, breakup.

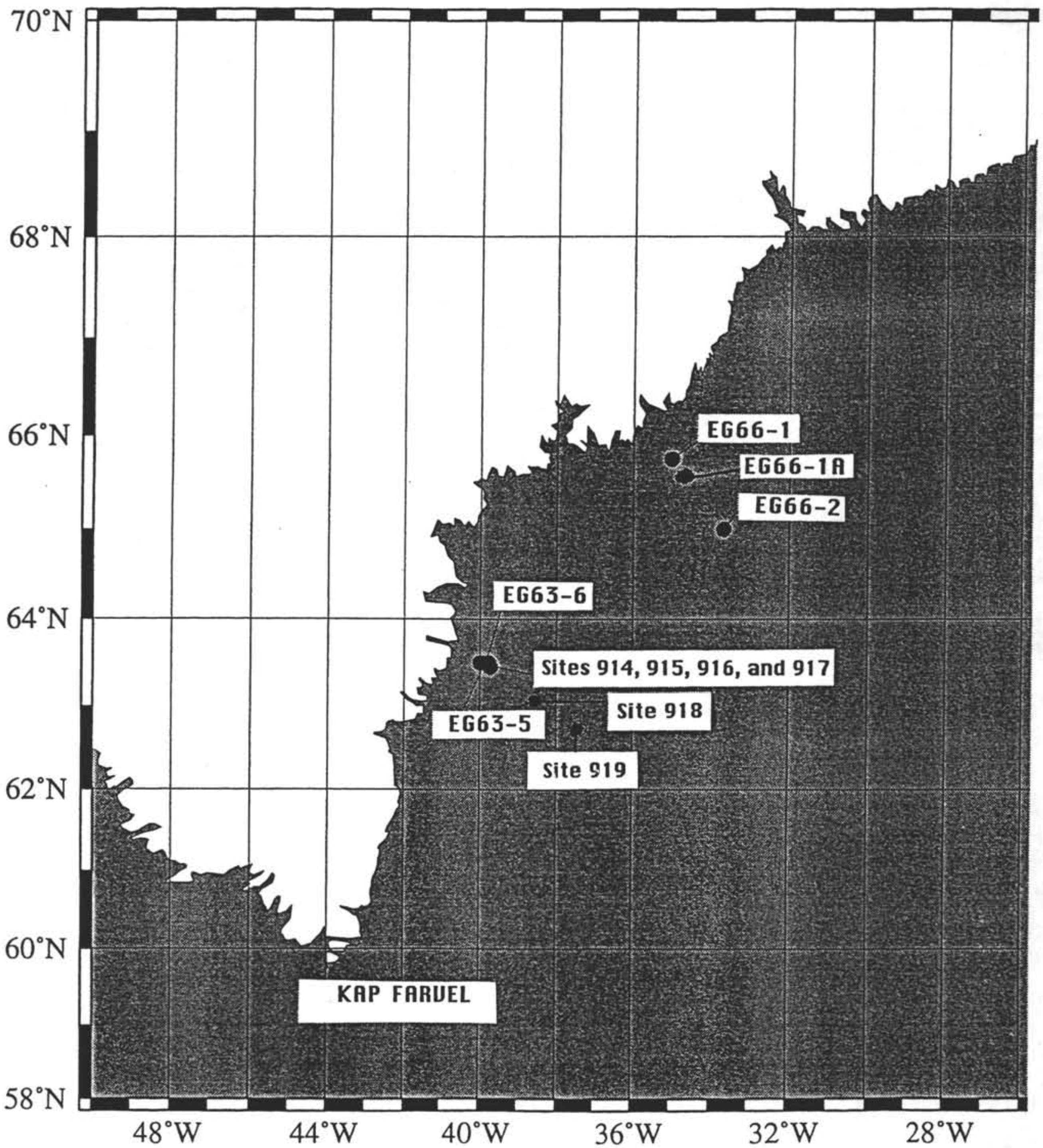


Figure 6. Location of Leg 152 sites and Leg 163 proposed drill sites.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: EG66-2	**PRIORITY**:	**POSITION**: 64°58.09'N, 33°03.63'W
WATER DEPTH: 1660 m	**SEDIMENT THICKNESS**: 520 m	**TOTAL PENETRATION**: 720 m
SEISMIC COVERAGE: Line GGU/EG93-20B. GGU/EG93-20. GGU/EG93-22.		

Objectives: To recover a 200-m-long section of lavas from oceanic basement approximately 7 m.y. younger than initial breakup and in a plume proximal location.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: Standard logs and FMS and BHTV.

Nature of Rock Anticipated: Glaciomarine overlying Paleogene shelf and Neogene slope sediments; basaltic lavas.

SITE: EG66-1	**PRIORITY**:	**POSITION**: 65°44.81'N, 34°59.41'W
WATER DEPTH: 260 m	**SEDIMENT THICKNESS**: 5 m	**TOTAL PENETRATION**: 280 m
SEISMIC COVERAGE: Line GGU/EG93-20. GGU/EG93-20A. GGU/EG93-21.		

Objectives: To sample the earliest volcanism, the breakup unconformity, and underlying continental crust in a plume proximal location.

Drilling Program: RCB.

Logging and Downhole Operations: Standard logs and FMS and BHTV.

Nature of Rock Anticipated: Glaciomarine sediments and 200 m of basalts overlying continental crust.

SITE: EG66-1A	**PRIORITY**:	**POSITION**: 65°42.08'N, 34°52.17'W
WATER DEPTH: 270 m	**SEDIMENT THICKNESS**: 20 m	**TOTAL PENETRATION**: 520 m
SEISMIC COVERAGE: Line GGU/EG93-20. GGU/EG93-20A.		

Objectives: To recover a long section of basaltic lava from the early oceanic SDRS succession in a plume proximal location.

Drilling Program: RCB.

Logging and Downhole Operations: Standard logs and FMS and BHTV.

Nature of Rock Anticipated: Glacial sediments and basalts.

SITE: 915 (deepening)	**PRIORITY:**	**POSITION**: 63°28.285'N, 39°46.909'W
WATER DEPTH: 533 m	**SEDIMENT THICKNESS**: 197 m	**TOTAL PENETRATION**: 447 m
SEISMIC COVERAGE: Line GGU/EG92-24.		

Objectives: To sample the transition from transient picritic volcanism into supposedly steady-state N-MORB volcanism.

Drilling Program: RCB.

Logging and Downhole Operations: Standard logs and FMS and BHTV.

Nature of Rock Anticipated: Glacial sediments (85 m) and Eocene shelf sediments; basalts.

SITE: EG63-6	**PRIORITY:**	**POSITION**: 63°31.34'N, 39°54.7'W
WATER DEPTH: 460 m	**SEDIMENT THICKNESS**: 5-10 m	**TOTAL PENETRATION**: 410 m
SEISMIC COVERAGE: Line GGU/EG92-24. Line GGU/EG93-11.		

Objectives: To sample the oldest part of the SDRS, penetrate the tectonic breakup unconformity, and sample the continental crust below the unconformity.

Drilling Program: RCB.

Logging and Downhole Operations: Standard logs and FMS and BHTV.

Nature of Rock Anticipated: Glacial sediments and 250 m of basalts overlying a dike complex or pre-rift sediments.

SITE: EG63-5	**PRIORITY:**	**POSITION**: 63°31.8'N, 39°55.64'W
WATER DEPTH: 473 m	**SEDIMENT THICKNESS**: 5-10 m	**TOTAL PENETRATION**: 210 m
SEISMIC COVERAGE: Line GGU/EG92-24. Line GGU/EG93-10.		

Objectives: To identify the nature and deformation of continental crust below the tectonic breakup unconformity.

Drilling Program: RCB.

Logging and Downhole Operations: Standard logs and FMS and BHTV.

Nature of Rock Anticipated: Glacial sediments and dikes in gneiss or low-temperature pre-rift sediments.

LEG 164
Gas Hydrate Sampling

LEG 164

GAS HYDRATE SAMPLING ON THE BLAKE RIDGE AND CAROLINA RISE

Modified From Proposal 423 Submitted By

Ryo Matsumoto: Co-Chief **Charles Paull: Co-Chief**

To Be Named: Staff Scientist

ABSTRACT

Gas hydrates are a solid phase composed of water and low molecular weight gases (predominantly methane) which form under conditions of low temperature, high pressure, and gas saturation; conditions that are common in the upper few hundred meters of rapidly accumulated marine sediments (Claypool and Kaplan, 1974; Sloan, 1989). Although gas hydrates may be a common phase in the shallow geobiosphere, they are unstable under normal surface conditions, and thus surprisingly little is known about them. The in situ characteristics of gas-hydrated sediments can best be studied by drilling where gas hydrates are as extensive as possible and their influence on sediment properties are largest. The Blake Ridge - Carolina Rise gas hydrate field is an excellent area for a gas hydrate drilling program because it is associated with sediments that have especially high interval velocities and distinct reflection characteristics, is well surveyed, contains one of the worlds most laterally extensive gas hydrate fields including a well developed BSR (bottom-simulating-reflector), and lacks tectonic influences that complicate hydrate distribution and fluid circulation in accretionary prisms.

Drilling in the Blake Ridge - Carolina Rise area will 1) determine the amounts of gas trapped in extensively hydrated sediments, 2) contribute to an understanding of the lateral variability in the extent of gas hydrate development, 3) investigate the distribution and fabric of gas hydrates within sediments, 4) establish the physical property changes associated with gas hydrate formation and decomposition in continental margin sediments, 5) assess whether the gas captured in gas hydrates is produced locally or has migrated in from elsewhere, 6) measure changes in the porosity (and permeability?) structure associated with gas hydrate cemented sediments, and 7) determine the role of gas hydrates in stimulating or modifying fluid circulation.

INTRODUCTION

Enormous volumes of natural gas may be associated with gas hydrated sediments (Kvenvolden and Barnard, 1983; Kvenvolden, 1988a). Large quantities of gas may be stored in the gas hydrate cemented sediments because up to 164 times the saturation concentration of gas at STP condition exists in these solid phases per unit volume (Sloan, 1989). It is estimated that there are about 10^4 Gt (Gt = 10^{15} gm) of carbon stored in gas hydrates, which is about two times the estimate for the carbon in all other fossil fuel deposits (Kvenvolden 1988b). Moreover, there may be considerable volumes of free gas trapped beneath the overlying solid gas hydrate-cemented zones that are associated with the BSR. However, we know too little about hydrates at present to be confident about these estimates (Kvenvolden, 1988b).

Sedimentary and Geochemical Importance of Gas Hydrates

One explanation for some of the major slumps on continental rises relates to instability of the sediments from the break down of gas hydrates (Summerhayes et al., 1979; Embley, 1980; Carpenter, 1981; Cashman and Popenoe, 1985; Prior et al., 1989). Seismic data near some slump areas show that there are numerous normal faults that sole out at or near the BSR (Paull et al., 1989). If gas hydrates comprise a significant portion of the volume of rise prism sediments above the BSR (Heling, 1970; Harrison and Curiale, 1982), the physical properties of sediments will change dramatically when gas hydrates decompose. Solid gas hydrates decompose to water plus (over-pressured?) gas (Kayen, 1988). Sediment instability and failure are likely to be concentrated along this lubricated horizon. The gas hydrates may play an important role in sediment tectonics, strengthening the sediments above and weakening the sediments at and below the BSR. Thus, the potential for physical property changes that significantly alter the mechanical strength of the margin will best be understood by establishing the extent of the gas hydrate formation in the overlying sediments and the physical characteristics of the sediments both at and beneath the BSR.

Effects on Fluid Circulation

At present our collective knowledge about the processes, rates, and plumbing involved in fluid exchange between the porous sedimentary flanks of continents and the adjacent ocean water is rudimentary. Considerable interest has been generated by the patterns of fluid circulation and the associated seawater-rock exchange at ocean ridges. However, the importance of fluid exchange between the ocean and its edges is unknown and cannot be resolved without additional knowledge of fluid circulation systems in a variety of settings (National Research Council, 1989). Extensively hydrated rise prism sediments are one of the sediment types that need to be understood.

Modification of Fluids

Methane and saline fluids may be expelled from abyssal sediments as a consequence of gas hydrate formation and deterioration. In the process of gas hydrate formation, water and low molecular weight gases (i.e., methane) form a crystalline solid which cements the sediment, leaving the remaining pore fluids enriched in salts (Hesse and Harrison, 1981; Harrison and Curiale, 1982). At greater depths gas hydrates break down and add methane and fresh water back into the pore waters, decreasing the salinity and increasing the methane concentration. Gas hydrate decomposition leaves a porous zone that is charged with methane beneath the stable gas hydrate zone. If gas hydrate formation is extensive, it may be exerting a strong influence on the composition of continental margin pore fluids.

Drilling Hazard

Due to safety reasons the various academic drilling projects have generally avoided drilling in areas where well-developed BSR's are known to occur. Safety panels are concerned with gas blowouts related to the decomposition of gas hydrates or the release of free gas from beneath the gas hydrates. Thus, most gas hydrate samples have come from the edges of the hydrated areas where it can be assumed that hydration is not as extensive (Jenden and Gieskes, 1983). Whether these safety concerns are realistic or not is simply unknown; however, academic drilling in hydrated areas will be impeded until more is known about gas hydrate structure and until techniques are established that can assess the potential risk of blowouts in particular areas. Unfortunately, the drilling of many other scientific targets are being stymied because they occur beneath hydrated sediments.

Paleoceanographic Importance of Gas Hydrates

Storage of a Greenhouse Gas

The stability of continental rise gas hydrates will be affected by the change in pressure that is associated with substantial sea level changes. During the Pleistocene glaciations sea level was more than 100 meters lower than it is today and the associated pressure change would cause the lower limit of gas hydrate stability to rise about 20 meters. This may have created a weak "lubricated" zone along the rise at the base of the BSR that could have resulted in frequent sediment failures. Thus, when sea level drops, large volumes of methane (a greenhouse gas) may be released. Conversely, when sea level rises, the lower limit of gas hydrate stability will migrate downward and may trap more gas. These changes in the stability field will change the size of the marine gas hydrate reservoir by a few percent. Given that there are about 3.6 Gt of methane carbon in the modern atmosphere, a release of one tenth of one percent of the carbon from the gas hydrate reservoir would be equivalent to the anthropogenic inputs of the last century! Scenarios can be constructed that suggest the exchange between the gas hydrate reservoir and the atmosphere may determine the limits of glaciation (Nisbet, 1990; MacDonald, 1990; Paull et al.,1991). Unfortunately, neither the volumes of gas that are involved, nor their dynamics are well enough understood to assess whether or to what degree marine gas hydrates act as a buffer or accentuator to climatic change.

THE STUDY AREA

Nature and Detection of Gas Hydrates

Seismic Detection of Marine Gas Hydrates

Gas hydrates are usually detected in marine sediments with seismic reflection data because they produce a bottom simulating reflector. The BSR often cuts across normal sediment bedding planes, thus clearly distinguishing itself as an acoustic response to a diagenetic change rather than a depositional horizon. The BSR may represent the base of the gas hydrate stability zone which occurs between about 200 and 600 meter depths below sea floor on continental rises. The pores of sediments above the BSR are partly filled with gas hydrates, which may increase the sediment density, while deeper sediments may contain free gas. The Carolina Rise, particularly along the Blake Ridge, was the area where marine gas hydrates were first identified on the basis of a BSR and is an area where gas hydrates appear to be especially extensive (Figure 1) (Markl et al., 1970; Tucholke et al., 1977; Shipley et al., 1979; Paull and Dillon, 1981; Dillon and Paull, 1983; Markl and Bryan, 1983) and might be considered the "type section" for marine gas hydrates.

Where gas hydrates have been detected in seismic reflection data, the BSR is a very high amplitude reflector that is associated with a phase reversal (Shipley, et al., 1979; White, 1979). Phase reversals are diagnostic of a change from high acoustic impedance (density x velocity) above to lower impedance below. This phase reversal may indicate that the upper sediments are extensively cemented with gas hydrates while another zone exists at or beneath the BSR where the gas hydrates have decomposed (or trapped gas from below) and released free gas back into the sediment pores. The published velocity measurements in sediments from the Carolina Rise indicate very high velocities above the BSR and very low velocities just below the BSR (Figure 2). These low velocities have been attributed to gas-charged sediments and it has been hypothesized that the gas hydrates may be a seal for a significant natural gas reservoir (Dillon et al., 1980). While similar velocity structures have been found elsewhere (Andreassen et al., 1990), lesser velocity contrasts occur at the BSR at some other sites (Miller et al., 1991; Hyndman and Spence, 1992).

Sampling of Marine Gas Hydrates

Gas hydrates are believed to be common in continental margin sediments because seismic reflection data have indicated their presence in every ocean basin (Kvenvolden and Barnard, 1983; Kvenvolden, 1988a, b). Gas hydrates are well known from permafrost drilling (Makogon, 1981; Collett and Kvenvolden, 1987; Kvenvolden and Grantz, 1991) and have been recovered from piston cores (Yefremova and Zizhchenko, 1975; Brooks et al., 1984; Brooks et al., 1991); they have also been sampled in DSDP and ODP holes (i.e. Legs 67, 68, 76, 84, 96, & 112).

An attempt to drill a strong BSR was made on DSDP Leg 11 on the Blake Ridge. At the time the origin of the BSR was a mystery. Very gassy sediments that self-extruded from their core liners were recovered at Sites 102, 103, and 104. Although the conclusion at the time was that the level of the BSR had been penetrated and it corresponded with a hard layer at the base of the hole (Hollister et al., 1972), this interpretation was based on estimates of sediment velocity that are lower than subsequent work has indicated occur at this site. Therefore, we question whether DSDP Leg 11 actually penetrated to the level of the BSR.

DSDP Site 533 was successfully drilled on the flanks of the Blake Ridge to sample hydrated sediments. Site 533 was intentionally located on the periphery of the major gas hydrate field, and did not penetrate into sediments associated with significant seismic blanking that is indicative of extensive hydrate formation. Nevertheless significant amounts of hydrate were encountered (Kvenvolden et al., 1983). Seismic reflection profiles only identify well developed gas hydrates, while the smaller patches of gas hydrate remain undetected. Thus inventories of the extent of gas hydrates based on seismic reflection data should be treated as minimum estimates.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To determine the amounts of gas trapped in extensively hydrated sediments.

2) To understand the lateral variability in the extent of gas hydrate development.

3) To investigate the distribution and fabric of gas hydrates within sediments.

4) To establish the physical property changes associated with gas hydrate formation and decomposition in continental margin sediments.

5) To assess whether the gas captured in gas hydrates is produced locally or has migrated in from elsewhere.

6) To measure changes in the porosity (and permeability?) structure associated with gas hydrate cemented sediments.

7) To determine the role of gas hydrates in stimulating or modifying fluid circulation.

Specific Objectives and Methodology

Quantity of Gas Hydrates

The amount of methane that may be stored as gas hydrate within marine sediments is at present poorly known. One large step toward assessing the size of this inventory is to establish the amount of methane that exists in the most extensively hydrated areas. Unambiguous estimates of in situ gas hydrate volumes can best be determined by pressure core sampling (PCS). Multiple runs of the PCS tool will be required to adequately characterize the extent of variation, especially with stratigraphic and lithologic changes. However, other types of detailed subsurface information and geophysical techniques can be calibrated here to estimate the amounts of gas hydrate in other areas.

Spatial Variation of Gas Hydrate Development.

To date, most studies on the distribution and occurrence of gas hydrates have been directed at regional distribution patterns that are inferred from BSR characteristics. However, seismic reflection profiles also show that there is an enormous amount of local lateral variability in the strength of the BSR and extent of the acoustically blank zone above the BSR within individual gas hydrate containing regions The causes of these variations are not understood and merit further study via the drilling of closely-spaced holes.

The subsurface depth of the BSR in multichannel seismic reflection profiles from the Carolina Rise - Blake Ridge gas hydrate field shows the predicted linear increase with increasing water depth (Figure 3). However, there are considerable variations on this trend, which should not occur in a homogeneous system. Thus, there are either errors of ±25% in the velocities that are used to calculate the depth to the BSR (perhaps related to lateral variabilities in the extent of hydration), local changes in the composition of the subsurface gases and fluids, local changes in the thermal structure of the sediment column, or zones where gas hydrates have not reached equilibrium with local conditions. The relative importance of these parameters in causing BSR depth variations needs to be examined.

Fabric and In Situ Distribution of Gas Hydrates

The physical characteristics of the gas hydrates that have been sampled from marine sediments also suggest that gas hydrate distribution is quite patchy in a vertical sense. At present, little is known about the effects of either grain size or lithology on gas hydrate formation. Hydrates may form as either veins or lenses that have some horizontal continuity, or as isolated gas hydrate nodules within the sediment matrix. If they are in fact laterally continuous layers, they may control the local permeability and velocity structure. In some hydrate-containing cores, the gas hydrates form layers up to several cm in thickness, particularly in coarser grained sediments, suggesting an association with more permeable conduits. The relative importance of finely disseminated gas hydrates in terms of the size of the hydrate pool is difficult to assess. Finely disseminated gas hydrates may be under-sampled because they are not visually detected and leave only slight chemical signatures in normal core samples. More and better fabric data on gas hydrate occurrences are needed to improve the quality of gas hydrate volume estimates and to understand the effects of the gas hydrates on the structure of the sediments, which will require detailed sampling and in situ experiments in different settings.

Seismic Velocity Estimates

By measuring the acoustic velocities of hydrated sediments it may be possible to assess the amounts of gas hydrate that exists in the subsurface. The inferred occurrence of gas hydrate in the sediment is adequate to increase the sediment interval velocities by ~25% in some places, which suggests the amount of gas hydrate must be extensive. However, the consequences of adding high velocity material to the sediment column are difficult to predict, especially without knowing whether the gas hydrates can be best thought of as a pervasive cement or discrete nodules in otherwise unaltered sediments (Toksoz et al., 1976).

Various elastic wave velocities have been reported for experimentally grown gas hydrates that range from 2.4 to 3.8 km/sec (Stoll, Ewing, and Bryan, 1971; Stoll and Bryan, 1979; Davidson et al., 1983; Pandit and King, 1982). However, these measurements have all been made on systems containing pure propane and ethane gas hydrates (type II) which may not be representative of the methane gas hydrates (type I). Thus, the relationship between gas hydrate amounts and sediment velocities needs to be calibrated in situ.

The addition of gas hydrates to sediments may be analogous to cementation of the sediments and is believed to decrease the impedance contrast between the sediment layers above the BSR and produce the amplitude blanking zone that is observed above the BSR. These changes in the acoustic impedance have been used to model the amount of gas hydrates that are in the sediments (Dillon et al., 1991; Miller et al., 1991; Lee, in prep.). Modeling estimates indicate large amounts of gas hydrate are required to produce the observed acoustic blanking in the sediment, especially in the Carolina Rise Blake-Ridge area (Dillon et al., 1991).

Determining the in situ sediment velocities in areas of extensive gas hydrates will require special care to collect and integrate data from the different techniques for velocity measurement. Well log data provide accurate information on the velocity structure that occurs within a few meters of the hole. Vertical seismic profiles (VSP) can provide data on the interval velocities (Hardage, 1985; Shipboard Scientific Party, 1990). Thus, differences between the averaged values (VSP) and the well log velocities will indicate how typical the core site is of the surrounding sediments. Shipboard physical property measurements are frequently done after the gas hydrates have started to or are completely decomposed. Comparisons with velocity log data and velocimeter measurements may provide insight into the velocity change associated with gas hydrate decomposition.

Sources of the Gas (in situ Production or Upwards Migration?)

We are interested in assessing whether the gas hydrate system is sustained by in situ production or requires gas to migrate from elsewhere. In order to have gas hydrate formation, saturation of methane or another hydrate-forming gas is required. Because the existing isotopic and compositional data on the Blake Ridge suggest that this gas is biogenic methane (Brooks et al., 1983; Galimov and Kvenvolden, 1983), it is frequently assumed that the gas is produced locally beneath surficial, sulfate-reducing sediments. Thus, between the zone of sulfate depletion and the BSR, the onset of gas hydrate formation (~100 mM CH_4 concentrations under in situ P/T conditions) must occur. Depth-concentration profiles of microbial byproducts will indicate whether there has been adequate amount of local microbial gas production (Claypool and Kaplan, 1974) to account for the observed methane concentrations.

Conversely, if the in situ production of methane and other gases is not adequate to generate saturation at shallow depths, then there must be addition of gas from below (Hyndman and Davis, 1992). Biogenic gas may accumulate as a result of recycling of gas at the base of the gas hydrate stability zone. As continental rise sediments are progressively buried, they experience an increase in temperature associated with the geothermal gradient. At some point the sediments will leave the gas-hydrate stability field. Gas bubbles produced by gas hydrate decomposition would be expected to move upward and reenter the gas-hydrate field above. If the recapture of the gas that is mobilized into the sediments above by the gas hydrates is perfectly efficient, the gas will never get out of the system. Thus, the gas that is above the BSR may have been produced at any time in the history of the rise. The gas hydrates which form the ~3 m thick layer in the Middle America Trench (Kvenvolden and McDonald, 1985) almost certainly formed in a flow conduit.

Another approach to discriminate between locally produced gas and migrated gas may come from the depth distribution of gas hydrates. If the gas hydrates are produced locally in favorable lithologies, there should be a gradual increase in the amount of gas-hydrate with depth. However, if the gas is advected up from below gas-hydrate amounts will increase dramatically near the base of their stability field (i.e., near the BSR).

Physical Property Changes in the Sediments

The formation of gas hydrates within sediment pores may significantly alter the mechanical properties of the sediment in a number of ways: 1) the pore volume will be decreased by authigenic mineral (hydrate and carbonate) formation and will lead to a reduction in the porosity and presumably the permeability structure of the sediments; 2) the authigenic addition of the gas hydrate will also change the mechanical properties and consolidation pathways of the sediments; and 3) the low thermal conductivity of gas hydrates will alter the thermal structure of hydrated sediments.

Very little data are available on the porosity structure of hydrated sediments. Shipboard physical property data suggest that the normal porosity reduction may have taken place by gas hydrate in-filling. For example, data collected by DSDP at Site 533 indicate the porosity remains near 57% right to the base of the hole (399 m), which is surprisingly high for silty-claystones (Gregory, 1977).

Changes in the velocity structure of hydrated sediments suggest that either the volumes of gas hydrate are very high or the gas hydrates are very efficient at binding the sediments together to produce a high velocity medium. At present we do not know whether the gas hydrates preferentially grow in the voids or at grain contacts or how effective they are at binding sediment together. However, the growth of gas hydrates in the sediment pores will inevitably affect the sediment's compaction history. Thus samples that were extensively hydrated, but have passed out of the gas-hydrate stability realm, should be under-consolidated and mechanically weak, especially if the pore spaces are now gas charged. The potential change in physical properties related to dehydration needs to be assessed as a mechanism for causing slope failure (Kayen, 1988; Paull et al., 1991).

The thermal conductivity of gas hydrates is lower than that of the pore waters they replace (Stoll and Bryan, 1979; Sloan, 1989) and the thermal conductivity of free gas layers is very low. Thus areas where there is any appreciable volume of gas-hydrate (above the BSR) and gas (at or beneath the BSR), may act as a thermal insulator within continental margin sediments. Lateral variations in the thermal characteristics of sediment may occur because zones of extensively hydrated sediment will be better insulated than less hydrated areas. Heat may be refracted toward less extensively hydrated sediments. If lateral thermal gradients exist, then they may stimulate fluid circulation.

Some heat flow measurements from the Carolina Rise were made in 1991. The existing data show that the gradients are between 20° and 40°C/km. While adjacent measurements tend to be similar, there are larger than expected variations along transects which may be related to lateral variations in hydrate development.

Hydrologic Circulation within Gas Hydrated Sediment Sections

Sediments associated with extensive gas hydrate formation may have undergone a significant porosity reduction. As a consequence, the gas hydrate cemented sediments in the Blake Ridge - Carolina Rise gas hydrate field may act as a barrier for pore water exchange between the continental margin sediments and the adjacent ocean waters. Any fluid flow which is in response to regional gradients (Manheim and Horn, 1968; Manheim and Paull, 1981) will be concentrated into breaks in the gas hydrate seal. Moreover, local circulation systems might be stimulated as a consequence of hydration processes because 1) saline fluids in the hydrated zone will be heavy and will tend to sink, or conversely, waters associated with the natural breakdown of gas hydrates in the subsurface will be buoyant with respect to seawater and thus will rise, 2) the lower thermal conductivity of the free gas beneath the gas hydrates will refract heat away from areas that are extensively hydrated toward areas that are less hydrated (thermal differences may stimulate small circulation systems, Kohout, 1967), and 3) compactive expulsion of pore waters from sediments (Shi and Wang, 1986) may occur either above or below the gas hydrates. Compactive expulsion may be particularly active underneath the gas hydrates as the sediments undergo a porosity and pore fluid pressure increase as a consequence of dehydration and the release of gas (Kayen, 1988). Fluids may migrate laterally to escape upward at breaks in the overlying seal.

If there are circulation cells within the hydrated sediments, their internal characteristic may be indicated by patterns of velocity variations in the sediment, pore waters and heat flow gradients that overlie these cells. A close relationship between sediment physical properties and pore water advection may exist in hydrated regions of continental margins which will require closely spaced holes that are carefully sited with respect to known lateral changes in reflection characteristics.

Chemical Changes Associated with Gas Hydrated Sediment Sections

Effects of Ion Exclusion During Gas Hydrate Formation on Continental Rise Pore Waters

The ionic concentration of pore fluids increases as gas hydrate formation proceeds because the gas hydrates remove water and gas (e.g., methane) and leave behind the residual salts. Thus, the composition of continental rise pore waters (especially Cl^- concentration) may be used as a predictor of gas hydrate presence and extent (Figure 4). Moreover, if no anomalies exist, then either there is no appreciable amount of gas hydrate formation, or fluid circulation has wiped out the anomalies.

Isotopic Fractionation and Signature of the Pore Water Sources

During the formation of gas hydrates, there is a tendency for the heavy molecules of water ($H_2{}^{18}O$ or $DH^{16}O$) to become preferentially concentrated in the gas hydrate lattice, while the isotopically lighter molecules of water ($H_2{}^{16}O$) are left in the residual water (Davidson et al., 1983). This phenomenon has been employed to explain deep-sea sediment cores that contain water with higher $\delta^{18}O$ content and lower salinities than seawater as having been generated by the recent breakdown of gas hydrates (Hesse and Harrison, 1981; Harrison and Curiale, 1982), and other pore waters from deeper cores that are isotopically light and saline as resulting from the expulsion of fluids during gas hydrate formation (Kvenvolden and Kastner, 1989).

Solid Phase Records

At present we do not have techniques to indicate whether gas hydrates were once developed in ancient sediments. However, there is a largely unassessed potential for significant diagenetic changes (e.g., Wada et al., 1981) to occur as a consequence of gas hydrate formation and decomposition. For example, the oxygen isotope ratios in diagenetic siderite found on the Blake Ridge are believed to be related to gas hydrate decomposition (Matsumoto, 1989). Thus, these materials may contain a record of paleo-BSR positions. To evaluate these materials, we need more sampling from sedimentary units that have experienced the diagenetic changes associated with extensive gas hydrate formation.

Calibrating the BSR as a Temperature-Pressure-Composition Indicator

The BSR pins the boundary at which three phases (hydrate-gases-water) co-exist. Thus, in theory, if one knows the chemical composition and the depth at the BSR one can calculate the temperature from gas hydrate phase data (Figure 5) and use the BSR as a tracer of sediment temperatures. Unfortunately the gas hydrate phase equilibria is very sensitive to the composition of the pore fluids and gases and trace levels of various microbial or thermogenic gases (e.g., H_2S, CO_2, CH_4, C_2H_6) and ions (e.g., Cl^-) which shift the phase boundaries (Deaton and Frost, 1946; Kobayashi et al., 1951; de Roo et al., 1983).

Because the ionic concentration of pore fluids increases as gas hydrate formation proceeds, the hydrate-gases-water phase boundary will shift toward higher pressure and lower temperature.

In situ data on the characteristics of gas hydrates are needed. While a considerable research effort is being directed toward hydrate research using surface techniques, ultimately the only way to unequivocally establish the in situ characteristics of the gas hydrated sediments is by drilling in areas that are well surveyed and where the influence of hydrates is most dramatic (Max et al., 1991).

DRILLING PLAN/STRATEGY

Two different types of drilling strategies can be envisioned to investigate the properties of extensive gas hydrates; 1) holes could be drilled through the entire hydrated section and well into the sediments below, or 2) drilling can be targeted to sample extensively hydrated sediments above the BSR, but stop before the base of the gas hydrate zone (as indicated by the BSR) is penetrated. Proposals to drill through the entire hydrate zone in areas that may be associated with extensive gas hydrates may be stymied by safety concerns. Thus, a program that pursues option 2 and poses minimal safety concerns is outlined here. The proposed drilling strategy stresses closely spaced holes, pressure core sampling, downhole fluid sampling, and borehole geophysical experiments.

Drilling is proposed along transects in three areas in the Blake Ridge - Carolina Rise gas hydrate field where the geology and topography are relatively simple, so that the basic properties of the hydrated sediments and their spatial variation can be addressed (Table 1). These areas have been selected for detailed gas hydrate studies from the extensive regional seismic survey data because they are areas where the patterns around the BSR and of the seismic blanking are especially clear. However, rapid lateral changes occur along the proposed transects from areas where the BSR's are extremely well-developed to areas where the influence from gas hydrates are minimal or undetectable in seismic data.

The three areas have been selected to contrast the influences of gas-hydrate properties under different continental rise settings. These include an area where the gas for the hydrates may have been produced in situ, an area where the gas for hydrate formation may have migrated from below, and an area where the hydrates have been disturbed and may have decomposed within the sediment column.

Special efforts will be devoted to in situ sampling using the PCS and WSTP (water sampler and temperature probe) tools during the drilling of these hole. A high priority will given to running a full suite of logs and to conducting VSPs before leaving these holes. Exact site selection should include input from the safety panel.

Area I is on the crest of the Blake Ridge (Figure 1), a major sediment drift (Tucholke et al., 1977). This area has been selected because 1) it is a topographically simple area, 2) it is expected to have very extensive gas hydrates because it is associated with the highest interval velocities that have been reported for a gas hydrate-cemented area, 3) the crest of the ridge provides structural closure on the BSR surface which should make an effective seal that prevents gas escape so that extensive free gas could be trapped beneath the BSR, 4) it lies on old oceanic crust (Klitgord and Behrendt, 1979) so that heat flow should be uniform, and 5) the sources of gas are more limited than in Areas II and III because the sedimentary section is thin and there is no obvious source of migrated gas. Moreover piston core data indicate that sulfate depletion and the advent of microbial methane production occurs at shallow depths (~10 m) on the Blake Ridge, which suggests that gas-hydrates may have been produced by in situ methane production at this site.

The strategy in Area I is to drill holes at three closely spaced sites down the northern flank of the Blake Ridge (proposed sites BRH-1a, BRH-2a, and BRH-3a) in regions where the sedimentary units dip upward toward the sea floor. Here the same sedimentary units can be sampled and compared over short lateral distances, but where they apparently contain varying amounts of hydrate. Also this transect will enable the assessment of the lateral hydrate variations due to local lithologic, chemical, and hydrologic factors.

Area II is on the upper Carolina Rise (Figure 1). This area has been selected because 1) it is on a normal section of the rise rather than a sediment drift, 2) it corresponds with an extremely well-developed BSR that is crossed by stratal reflectors making the lithologic control identifiable, 3) it is about the topographically smoothest area on the rise and is not associated with diapirs or slump scarps, and 4) at these sites, the potential for migration of gas through various layers will be examined. This area overlies the thickest section of the Carolina Trough which is composed of rift-stage crust overlain with ~8 km of continental shelf strata before being capped by the modern rise sediments (Hutchinson et al., 1982). As a consequence, Area II will have different sources of fluids than Area I. Existing piston core data indicate that the pore fluid sulfate concentration gradients are much more gentle in Area II than in Area I, which suggests, that the potential for microbial methane production is much less at this site. In Area II, the sedimentary layers slope upward toward the sea floor through the hydrate stability field. Beneath the BSR an appreciable thickness of very reflective layers are observed on seismic reflection profiles. These reflective layers apparently are sediment beds of variable porosity and grain size. Where these beds cross the BSR they lose their reflectivity in the blank zone, but they again become clearly traceable in the section a few hundred meters above the blank zone. Here the same layers can be penetrated and cored over a short lateral distance. Thus the physical properties of individual sediment layers can be compared between closely spaced sites where geophysical data indicate a lateral transition from non-hydrated to hydrated sediment.

Area III is on the upper rise (Figure 1) in the same geologic setting as Area II, but it is associated with the sole of a major slump scar and the crest of an exhumed diapir. Piston core and dredge samples from the top of the diapir contain hemipelagic materials of diverse Tertiary ages. The continuity of the BSR is lost near the diapir. Thus, the diapir apparently produced a "hole" in the regional gas hydrate field. In contrast to Areas I and II, this "hole" in the gas hydrate field has a tectonic origin that is associated with slumping and/or the emplacement of a diapir. Area II will serve as a "background" control of what Area III samples were like before the tectonic disturbance to the hydrate system.

PROPOSED SITES

Area I

Proposed site BRH-1a is located on the crest of the Blake Ridge (CH-06-92, line 31 - 31°50.59'N, 75°28.12'W) in 2722 m of water. Here, a well developed BSR is at 0.54 sec subbottom. DSDP Site 102 was drilled to a depth of 661 m nearby, where the BSR occurs at 0.62 sec. Experience from DSDP Site 102 indicates that bore holes can approach, and perhaps penetrate, the BSR in this area without safety problems. At 1850 m/sec (a low velocity which minimizes the chances of encountering the level of the BSR unintentionally) the BSR originates from at least 499 m subbottom. We are proposing that one hole be drilled at proposed site BRH-1a into the thick section of acoustically "transparent" sediments to 480 m. If gas has slowly infused into the overlying sediments from below the BSR, hydrate development may be at an extreme in this hole. At the highest velocities that have been suggested (2500 m/sec), the BSR would be penetrated prior to 675 mbsf. Thus, at proposed site BRH-1a ext, a hole would be drilled to 750 m.

Proposed site BRH-2a is located on the upper flank of the Blake Ridge (on CH-06-92, line 31 - 31°49.85'N, 75°25.11'W) in 2825 m of water. The BSR is not evident at this site although strong BSR's exist at the up- and down-slope proposed sites, BRH-1a and BRH-3a. Thus, a "hole" in the BSR's surface exists at this site. However, a series of strong reflections that are apparently related to stratigraphic horizons beneath the predicted level of the BSR (~0.55 sec sub-bottom as projected up and down slope) occur here. The hole drilled at proposed site BRH-2a should penetrate well below the level of hydrate stability, into these reflective sediments. With a range of sediment velocities between 1850 and 2500 m/sec, the inferred base of the hydrate stability zone would lie between 509 and 688 m, respectively. To be sure that this level is penetrated, the proposed depth of the hole is 800 m.

Proposed site BRH-3a is located on the upper flank of the Blake Ridge (on CH-06-92 line 31 - 31°54.40'N, 75°23.02'W) in 2965 m water. Here, a BSR is at 0.57 sec subsurface. Assuming a velocity of 1850 m/sec, the BSR is at 527 m sub-bottom depth. We are proposing to drill through the upper 500 m at this site into a thick section of acoustically "transparent" sediments. This bore hole is intended to obtain a direct comparison of the same stratigraphic horizons above the BSR that were sampled below the projected level of the BSR at proposed site BRH-2a. The horizons which extend to the shallower depths from proposed sites BRH-2a to BRH-3a are acoustically transparent at the latter, but reflective at the former. From the discontinuous nature of the BSR, this site is inferred to have the least amount of free gas near the BSR. Now assuming a high velocity of 2500 m/sec, the BSR is at 684 m sub-bottom. Thus, at proposed site BRH-3a ext, a hole would be drilled to 750 m.

If these extended holes are approved for drilling, it is suggested that the drilling order be changed so that the BSRs of increasing strength are drilled sequentially. Thus, the reference holes at proposed sites BRH-2a and CRH-1 should be drilled first followed by extended holes at proposed sites BRH-3a (BRH-3a ext.), CRH-2 (CRH-2 ext) and finally BRH-1a (BRH-1a ext).

Area II

In Area II, holes are proposed at two sites (proposed sites CRH-1 and CRH-2). Proposed site CRH-1 is at SP 100653 on CH-06-92 line 41 (32°46.88'N, 75°57.4'W) in 2647 m water. No BSR exists here. However, there are a series of reflective horizons at 0.6 to 0.8 sec that are below the inferred level of hydrate stability. The hole at this site is planned to penetrate 800 m.

Proposed site CRH-2 is at SP 100539 on CH-06-92 line 41 (32°46.76'N, 75°55.20'W) in 2732 m water. The BSR is at 0.55 sec. The proposed depth of the hole at this site is 540 m. This hole is intended to obtain a direct comparison of the same stratigraphic horizons above and below the projected level of the BSR. The units in proposed site CRH-1 project to the shallower depths and can be sampled in proposed site CRH-2 above the level of the BSR. However, these units are acoustically transparent at the latter, but reflective at the former. The strategy at proposed sites CRH-1 and CRH-2 is similar to that at proposed sites BRH-2 and BRH-3, but the inferred source of the gas in areas I and II may be substantially different. Thus, a hole at proposed site CRH-2 ext, a hole would be drilled to 750 m and, even at the higher range of proposed sediment velocities, the hole would penetrate well into the section beneath the BSR.

Area III

A transect of shallow drill holes (50 m deep) through the sole of a major slump on the flank of the Cape Fear Diapir are proposed (proposed sites CFD-1, CFD-2, CFD-3, and CFD-4) in Area III. One of the objectives of drilling this transect is to establish the tectonic, thermal, and hydrologic influence of the diapir on gas hydrates. In addition, samples will be obtained from a structural transect from sediments that are beneath the sole of a major slump, crossing upturned strata and to the crest of the diapir. These sample should have been exposed to differing degrees of hydrate formation and decomposition. The zone of deformed sediments that rims this diapir may provide a conduit for fluid flow from deeper zones including the fluids from beneath the zone of hydrate stability. Shallow samples from the crest of this diapir will provide information on the conditions deeper in the rise. We will also examine the nature of fluid and gas transport through the sole of this major sediment scar. These strata were buried to more than 140 m depths before being exhumed by slumping and the process of re-equilibration to new shallower conditions may provide great insight into the sensitivity of hydrated sediment to changes in the physical conditions and to the dynamics of gas-hydrate venting. Although this and other Atlantic diapirs are believed to be salt structures, the existence of salt has not been documented and the previous sampling on top of these structures has not produced data to confirm this assumption. Drilling in Area III should establish the nature of these diapirs.

Proposed site CFD-1 is at SP 1873 on CH-15-91 line 10 (33°00.95'N, 75°56.75'W) in 2690 m of water and the hole at this site will penetrate into Plio-Pleistocene sediments that are not directly affected by diapirism. Proposed site CFD-2 is at SP 1808 on CH-15-91 line 10 (33°00.3'N, 75°55.8'W) in 2700 m of water at the edge of the diapir. Proposed site CFD-3 is at SP 1765 on CH-15-91 line 10 (32°59.9'N, 75°55.18'W) in 2650 m of water on the middle of the diapir's flank. Proposed site CFD-4 is at SP 1708 on CH-15-91 line 10 (32°59.3'N, 75°54.25'W) in 2590 m of water, near the crest of the diapir where a melange of materials are expected.

This transect covers a horizontal distance of only 3600 m and may not require that the drill string be pulled between holes. Although these holes are being proposed to only 50 m sub-bottom because of safety concerns, these sections will be adequate to develop meaningful two dimensional picture of the compositional and chemical gradients associated with gas hydrate cemented sediments that have been deformed by slumping and diapir emplacement. Experience with surface ship piston coring has shown that the diapiric material is too firm for wire-line coring techniques. A Deep-Tow survey of the crest of this diapir will be conducted in October 1993 which may result in modification of the individual hole locations.

ADDITIONAL CONSIDERATIONS

Drilling Safety

The potential existence of free gas beneath the BSR represents a significant drilling safety concern. Whether these concerns are realistic or not can only be assessed on a site-specific basis. However, uncertainty about hydrate properties will remain if drilling is limited to marginal sites and areas where the geophysical anomalies do not suggest the presence of gas. Thus, to understand the full significance of hydrated sediments, we need to cautiously approach sites of major hydrate formation.

Site-specific information suggests that appreciable amounts of free gas do not exist beneath the BSR in the areas that were approved for drilling. Over-pressured gas pockets, which cause blow-outs, are unlikely near the BSR, because an increase in the gas pressure would extend the range of the hydrate stability, causing the boundary between gas and hydrate to migrate downward until a new equilibrium is re-established.

REFERENCES

Abbott, D.H., Hobart, M.A., and Embley, R.M., 1986. Heat flow and mass wasting in the Wilmington canyon region: U.S. continental margin. *Geo-Mar. Lett.*, 6:131-138.

Andreassen, K., Hogstad, K., and Berteussen, K.A., 1990. Gas hydrates in the Barent Sea, indicated by a shallow seismic anomaly. *First Break*, 8:235-245.

Bernard, B.B., Brooks, J.M., and Sackett, W.M., 1977. A geochemical model for characterization of hydrocarbon gas sources in marine sediments. *Proceeding of the Ninth Annual Offshore Technology Conference*, OTC 2934, Houston, Texas:435-438.

Brooks, J.M., Bernard, L.A., Weisenburg, D.A., Kennicutt, M.C., and Kvenvolden, K.A., 1983. Molecular and isotopic compositions of hydrocarbons at Site 533, Deep Sea Drilling Project Leg 76. In Sheridan R.E., Gradstein, F.M., et al., *Init. Repts. DSDP*, 76:Washington (U.S. Government Printing Office), 377-390.

Brooks, J. M., and Bryant, W.R., 1985. *Geological and Geochemical Implications of Gas Hydrates in the Gulf of Mexico*. U.S. Department of Energy, DOE, MC, 21088-1964.

Brooks, J.M., Field, M.E., and Kennicutt, M.C., 1991. Observations of gas hydrates offshore Northern California. *Mar. Geol.*, 96:103-109.

Brooks, J.M., Kennicutt, M.C., Bidigare, R.R., and Fay, R.A., 1985. Hydrates, oil seepage, and chemosynthetic ecosystems on the Gulf of Mexico slope. *Eos*, 66(10):106.

Brooks, J.M., Kennicutt, M.C., Fay, R.A. McDonald, T.C., and Sassen, R., 1984. Thermogenic gas hydrates in the Gulf of Mexico. *Science*, 225:409-411.

Carpenter, G., 1981. Coincident sediment slump/clathrate complexes on the U.S. Atlantic continental slope. *Geo-Mar. Lett.*, 1:29-32.

Cashman, K.V., and Popenoe, P., 1985. Slumping and shallow faulting related to the presence of salt on the Continental Slope and Rise off North Carolina. *Mar. Pet. Geol.*, 2: 260-272.

Claypool, G.E., and Kaplan, I.R., 1974. Methane in marine sediments. *In* Kaplan, I.R. (Ed.), *Natural Gases in Marine Sediments*: New York (Plenum Press), 99-139.

Claypool, G.E., and Threlkeld, C.N., 1983. Anoxic diagenesis and methane generation in sediments of the Blake Outer Ridge, Deep Sea Drilling Project Site 533, Leg 76. *In* Sheridan R.E., Gradstein, F.M., et al., *Init. Repts DSDP*, 76: Washington (U.S. Government Printing Office), 591-594.

Collett, T.S., and Kvenvolden, K.A., 1987. Evidence for naturally occurring gas hydrates on the North Slope of Alaska. *U.S. Geol. Surv.,* Open File Report, 87-225:8.

Davidson, D.W., Leaist, D.G., and Hesse, R., 1983. Oxygen-18 enrichment in the water of a hydrate. *Geochim. Cosmochim. Acta*, 47:2293-2295.

Deaton, W.M., and Frost, E.M., 1946. Gas hydrates and their relation to the operation of natural gas pipe lines. *U.S. Bur. Mines Monograph,* 8.

de Roo, J.L., Peters, C.J., Lichtenthaler, R.N., and Diepen, G.A.M., 1983. Occurrence of methane in hydrated sediments and undersaturated solutions of sodium chloride and water in dependence of temperature and pressure. *American Institute of Chemistical Engineers Journal*, 29:651-657.

Dillon, W.P., Fehlhaber, K.L., Lee, M.W., Booth, J.M., and Paull, C.K., 1991. Methane hydrate in sea floor sediments off of the Southeastern U.S.; amounts and implication for climate change. *Geol. Soc. Am. Abstr. Progr.*, 23:23.

Dillon, W.P., Grow, J.A., and Paull, C.K., 1980. Unconventional gas hydrate seals may trap gas off the Southeastern U.S. *Oil & Gas J.*, January 7:124-130.

Dillon, W.P., and Paull, C.K., 1983. Marine gas hydrates: II Geophysical Evidence. *In* Cox, J.L. (Ed.), *Natural Gas Hydrates, Properties, Occurrence and Recovery*: Woburn, Mass. (Butterworth), 73-90.

Dillon, W.P., Popenoe, P., Grow, J.A., Klitgord, K.D., Swift, B.A., Paull, C.K., and Cashman, K.V., 1982. Growth faulting and salt diapirism: Their relationship and control in the Carolina Trough, Eastern North America. *In* Watkins, J. S., and Drake, C. L. (Eds.), *Studies of Continental Margin Geology*, AAPG Mem., 34:21-46.

Embly, R.W., 1980. The role of mass transport in the distribution and character of deep-ocean sediments with special reference to the North Atlantic. *Mar. Geol.*, 38:28-50.

Galimov, E.M., and Kvenvolden, K.A., 1983. Concentrations of carbon isotopic compositions of CH_4 and CO_2 in gas from sediments of the Blake Outer Ridge, Deep Sea Drilling Project Site 533, Leg 76. *In* Sheridan R.E., Gradstein, F.M., et al., *Init. Repts. DSDP*, 76:Washington (U. S. Government Printing Office), 403-410.

Gregory, A.R., 1977. Aspects of rock physics from laboratory and log data that are important to seismic interpretation. *In* Payton, C.E. (Ed.), *Seismic Stratigraphy - Applications to Hydrocarbon Exploration*, AAPG Mem., 26:15-46.

Hand, J.H., Katz, D.L., and Verma, V.K., 1974. Review of gas hydrates with implication for oceanic sediments. *In* Kaplan, I.R. (Ed.), *Natural gases in marine sediments*: New York (Plenum Press), 179-194.

Hardage, B.A., 1985. Vertical Seismic Profiling- A measurement that transfers Geology to Geophysics. *In* Berg, O.R., and Woolverton, D.G. (Eds.), *Seismic Stratigraphy II, An Integrated Approach*, AAPG Mem., 26:13-36.

Harrison, W.E., and Curiale, J.A., 1982. Gas hydrates in sediments of Holes 497 and 498A, Deep Sea Drilling Leg 67. *In* Aubouin, J., and von Huene, R., et al., *Init. Repts. DSDP*, 67:Washington (U. S. Government Printing Office), 591-595.

Heling, D., 1970. Microfabrics of shales and their rearrangement by compaction. *Sedimentology*, 15:247-260.

Helmberger, D.V., 1968. The crust-mantle transition in the Bering sea. *Bull. Seis. Soc. Am.*, 58: 179-214.

Hesse, R., and Harrison, W.E., 1981. Gas hydrates (Clathrates) causing pore-water freshening and oxygen isotope fractionation in deep-water sedimentary sections of terrigenous continental margins. *Earth Planet. Sci. Lett.*, 55:453-462.

Hollister, C.D., et al., 1972. Sites, 102, 103, 104, Blake-Bahama Outer Ridge (Northern End). *In* Hollister, C.D., Ewing, J.I., et al.,*Init. Repts.DSDP*, 11:Washington (U.S. Government Printing Office), 135-218.

Hovland, M., and Judd, A.G., 1988. *Seabed Pockmarks and Seepages: Impact on Geology, Biology and the Marine Environment:* London (Graham and Trotman).

Hutchinson, D.R., Grow, J.A., Kiltgord, K.D., and Swift, B.A., 1982. Deep structure and evolution of the Carolina Trough. *In* Watkins, J.S., and Drake, C.L. (Eds.), *Studies of Continental Margin Geology*, AAPG Mem., 34:129-152.

Hyndman, R.D., and Davis, E.E., 1992. A mechanism for formation of methane and seafloor bottom-simulating reflectors by vertical fluid expulsion. *J. Geophys. Res.*, 97, B5:7025-7041.

Hyndman, R.D., and Spence, G.D., 1992. A seismic study of methane hydrate marine bottom simulating reflectors. *J. Geophys. Res.*, 97, B5:6683-6698.

Jenden, P.D., and Gieskes, J.M., 1983. Chemical and isotopic composition of interstitial water from Deep Sea Drilling Project Sites 533 and 534. *In* Sheridan R.E., Gradstein, F.M., et al., *Init. Repts. DSDP*, 76:Washington (U. S. Government Printing Office), 453-461.

Katzman, R., Holbrook, W.S., Purdy, G.M., and Paull, C.K., 1992. A combined vertical-incidence and wide-angle seismic study of a gas hydrate zone Blake Outer Ridge. *Eos*, 73:356.

Kayen, R.E., 1988. The mobilization of Arctic Ocean landslides by sea level fall induced gas hydrate decomposition [MS thesis]. Stanford University.

Klitgord, K.D., and Behrendt, J.C., 1979. Basin structure in the U. S. Atlantic margin. *In* Watkins, J.S., Montadert, L., and Dickerson, P. W., *Geological and Geophysical Investigations of Continental Margins*, AAPG Mem., 29:85-112.

Kobayashi, R., et al., 1951. Gas Hydrate formation with brine and ethanol solutions. *Proc. 30th Annual Conference Natural Gasoline Association of America*, 27-31.

Kohout, F.A., 1967. Ground-water flow and the geothermal regime of the Floridian Plateau. *Transactions of the Gulf Coast Association of Geological Societies*, 17:339-343.

Kvenvolden, K., 1988a. Methane hydrates and Global Climate. *Global Biochemical Cycles*, 2:221-229.

Kvenvolden, K., 1988b. Methane hydrate - A major reservoir of carbon in the shallow geosphere? *Chem. Geol.*, 71: 41-51.

Kvenvolden, K., and Barnard, L.A., 1983. Hydrates of natural gas in continental margins. *In* Watkins, J.S., and Drake, C.L. (Eds), *Studies in Continental Margin Geology*, AAPG Mem., 34:631-640.

Kvenvolden, K., Barnard, L.A., and Cameron, D.H., 1983. Pressure core barrel: Application to the study of gas hydrates, Deep-Sea Drilling Project Site 533, Leg 76. *In* Sheridan R.E., Gradstein, F.M., et al., *Init. Repts. DSDP*, 76: Washington (U.S. Government Printing Office), 367-375.

Kvenvolden, K.A., and Grantz, A., 1991. Gas hydrates of the Arctic Ocean region. *In* Grantz, A., Johnson, L., and Sweeney (Eds.), *The Arctic Ocean Region, The Geology of North America*, v. L., Geological Society of America, Washington, D.C., 539-549.

Kvenvolden K.A., and Kastner, M., 1989. Gas hydrates of the Peruvian outer continental margin. *In* Suess, E., and von Huene, R., et al., *Proc. ODP, Sci. Results*, 112:College Station, TX (Ocean Drilling Program), 517-526.

Kvenvolden, K.A., and McDonald, T.J., 1985. Gas hydrates in the Middle America Trench. *In* von Huene, R., Aubouin, J., et al., *Init. Repts. DSDP*, 84:Washington (U.S. Government Printing Office), 667-682.

MacDonald, G.J., 1990. Role of methane clathrates in past and future climates. *Clim. Change*, 16:247-281.

Makogon, Y.F., 1981. *Hydrates of Natural Gas*: Tulsa, Oklahoma (Penn Well Books).

Manheim, F.T., and Horn, M.K., 1968. Composition of deeper subsurface waters along the Atlantic continental margin. *Southeastern Geology*, 9:215-236.

Manheim, F.T., and Paull, C.K., 1981. Patterns of groundwater salinity changes in a deep continental - oceanic transect off the southeastern Atlantic coast of the U. S. A. *J. Hydrology*, 54:95-105.

Markl, R.G., and Bryan, G.M., 1983. Stratigraphic evolution of the Blake Outer Ridge. *AAPG Bull.*, 67: 663-683.

Markl, R.G., Bryan, G.M., and Ewing, J.I., 1970. Structure of the Blake-Bahama Outer Ridge. *J. Geophys. Res.*, 75:4539-4555.

Martens, C.S., and Berner, R.A., 1974. Methane production in the interstitial waters of sulfate-depleted sediments. *Science*, 185:1167-1169.

Matsumoto, R., 1989. Isotopically heavy oxygen-containing siderite derived from the decomposition of methane hydrate. *Geology*, 17:707-710.

Max, M.D., Dillon, W.P., Malone, R.D., and Kvenvolden, K.A., 1991. National workshop on gas hydrates. *Eos*, 72 (44):476-479.

Miller, J.J., Lee, M.W., and von Heune, R., 1991. A quantitative analysis of gas hydrate phase boundary reflection (BSR), offshore Peru. *AAPG Bull.*, 75:910-924.

National Research Council, 1989. *The Margin Initiative: Interdisciplinary Studies of Processes Attending Lithospheric Extension and Convergence*, Proceedings of a Workshop Sponsored by the National Research Council, Irvine, California, November 20-23, 1988.

Nisbet, E.G., 1990. The end of the ice age. *Can. J. Earth Sci.*, 27:148-1157.

Pandit, B.I., and King, M.S., 1982. Elastic wave velocities of propane gas hydrates. *In* French, H.M. (Ed.), *Proceedings of the Canadian Permafrost Conference: the Roger J.E. Brown Memorial Volume*: Ottawa, Canada (Canadian National Research Council), 335-352.

Paull, C.K., and Dillon, W.P., 1981. Appearance and distribution of the gas hydrate reflector in the Blake Ridge Region, Offshore southeastern United States. *USGS Miscellaneous Field Studies Map*, 1252.

Paull, C.K., Schmuck, E.A., Chanton, J., Manheim, F.T., and Bralower, T.J., 1989. Carolina Trough Diapirs: Salt or Shale? *Eos*, 70:370 (Abstract).

Paull, C.K., Ussler, W., and Dillon, W.P., 1991. Is the extent of glaciation limited by marine gas-hydrates? *Geophys. Res. Lett.*, 18:432-434.

Prior, D.B., Doyle, E.H., and Kaluza, M.J., 1989. Evidence for sediment eruption on deep sea floor, Gulf of Mexico. *Science*, 243:517-519.

Sayles, F.L., Manheim, F.T., and Waterman, L.S., 1972. Interstitial water studies on small core samples, Leg 11. *In* Hollister, C.D., Ewing, J.I., et al., *Init. Repts. DSDP*, 11:Washington (U.S. Government Printing Office), 997-1008.

Shi, Y., and Wang, C., 1986. Pore pressure generation in sedimentary basins: Overloading versus aquathermal. *J. Geophys. Res.*, 91, B2:2153-2162.

Shipboard Scientific Party, 1990. Site 794. *In* Ingel, J.C., Jr., Suyehiro, K., von Breymann, M.T., et al., *Proc. ODP, Init. Repts.*, 128:College Station, TX (Ocean Drilling Program), 67-120.

Shipley, T.H., Houston, M.H., Buffler, R.T., et al., 1979. Seismic reflection evidence for widespread occurrence of possible gas-hydrate horizons on continental slopes and rises. *AAPG Bull.*, 63:2204-2213.

Sloan, E.D., 1989. *Clathrate Hydrates of Natural Gases*: New York (Marcel Decker, Inc.).

Sloan, E.D., and Parrish, W.R., 1983. Gas hydrate phase equilibrium. *In* Cox, J.L. (Ed.), *Natural Gas Hydrates, Properties, Occurrence and Recovery*, Butterworth, Woburn, Mass., 17-34.

Stoll, R.D., and Bryan, G.M., 1979. Physical properties of sediments containing gas hydrates. *J. Geophys. Res.*, 84:1629-1634.

Stoll, R.D., Ewing, J., and Bryan, G.M., 1971. Anomalous wave velocities in sediments containing gas hydrates. *J. Geophys. Res.*, 76:2090-2094.

Summerhayes, C.P., Bornhold, B.D., and Embley, R.W., 1979. Surficial slides and slumps on the continental slope and rise of South West Africa: A reconnaissance study. *Mar. Geol.*, 31:265-277.

Toksoz, N., Cheng, C.H., and Timur, A., 1976. Velocities of seismic waves in porous rocks. *Geophysics*, 41:621-645.

Tucholke, B.E., Bryan, G.M., and Ewing, J. I., 1977. Gas hydrate horizon detected in seismic reflection-profiler data from the western North Atlantic. *AAPG Bull.,* 61:698-707.

Wada, H, Niitsuma, N., Nagasawa, K., and Okada, H., 1981. Deep sea carbonate nodules from the America Trench Area off Mexico, Deep Sea Drilling project Leg 66. *In* Watkins, J.S., Moore, J.C., et al., *Init. Repts. DSDP*, 66:Washington (U.S. Government Printing Office),453-464.

White, R.S., 1979. Gas hydrate layers trapping free gas in the Gulf of Oman. *Earth Planet. Sci. Lett.*, 42:114-120.

Whiticar, M.J., and Faber, E., 1986. Methane oxidation in sediment and water column environments - Isotopic evidence. *Org. Geochem.*, 10:759-768.

Yefremova, A.G., and Zhizhchenko, B.P. 1975. Occurrence of crystal hydrates of gases in sediments of modern marine basins. *Dokl. Acad. Sci. USSR, Earth Sci. Section* (English Translation), 214:219-220.

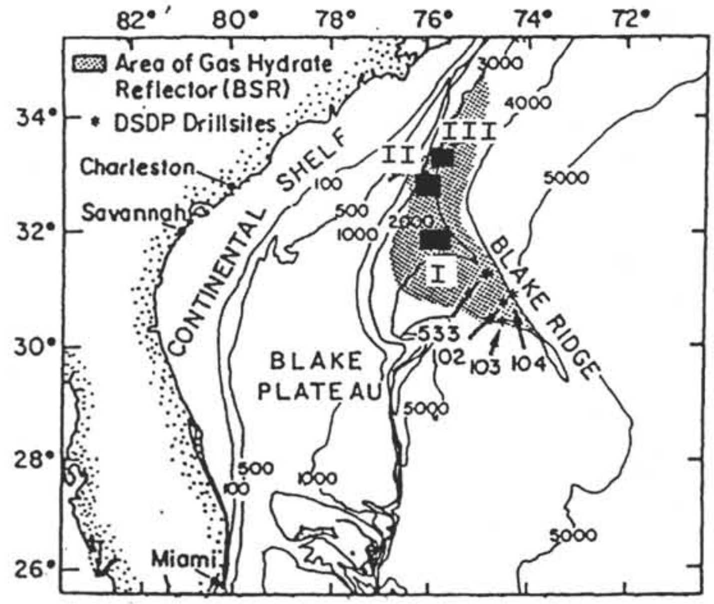


Figure 1. Distribution of bottom-simulating reflectors (BSRs) off the southeastern United States. Bathymetric contours are in meters. The areas proposed for drilling are indicated by boxes. From Dillon and Paull, 1983

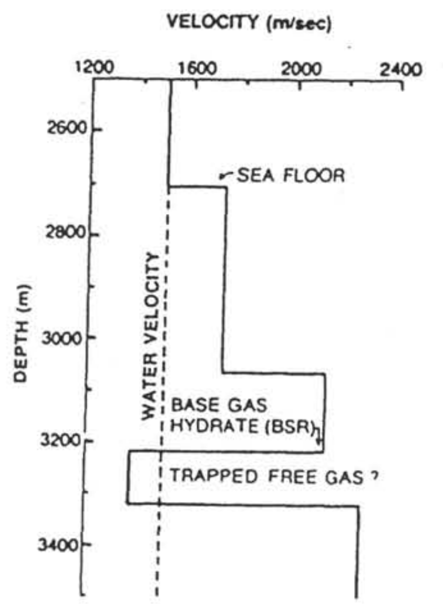


Figure 2. Velocity analysis of CDP data across the BSR. High velocities are indicated above the BSR and average velocities less than seawater occur in the interval beneath the BSR. Resolution of the velocities is at best limited to zones that are about 100 m thick (from Dillon and Paull, 1983).

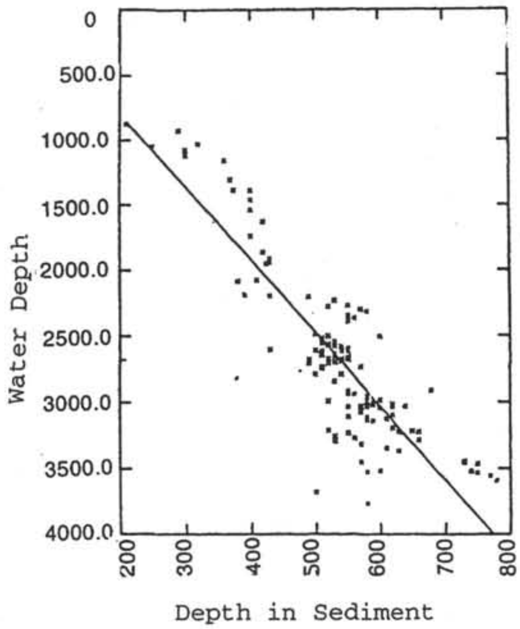


Figure 3. The sub-bottom depth to the base of the gas hydrate layer (BSR) compared with the water depth in meters for the Carolina Rise gas hydrate field (Fig. 1). The velocity of the sediments above the BSR is assumed to be 2000 m/s. The scatter from the best fit line indicates variations in the extent of hydration, variations in the sediment lithologies, fluid circulation patterns, differing pore water gas and fluid compositions, or variations in subsurface temperature.

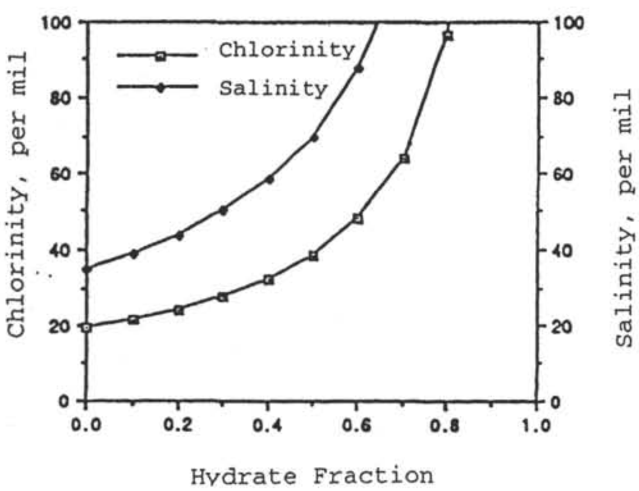


Figure 4. Theoretical relationship between pore water salinity and chlorinity with the amount of gas hydrate formation, assuming the sediment pore spaces are a closed system. Note that the seismic velocity estimates (Dillon et al., 1991; Miller et al., 1991) suggest that more than 50% (0.5 hydrate fraction) of the pore spaces are commonly filled with hydrate. Thus elevated sediment salinities should occur in extensively hydrated sediments.

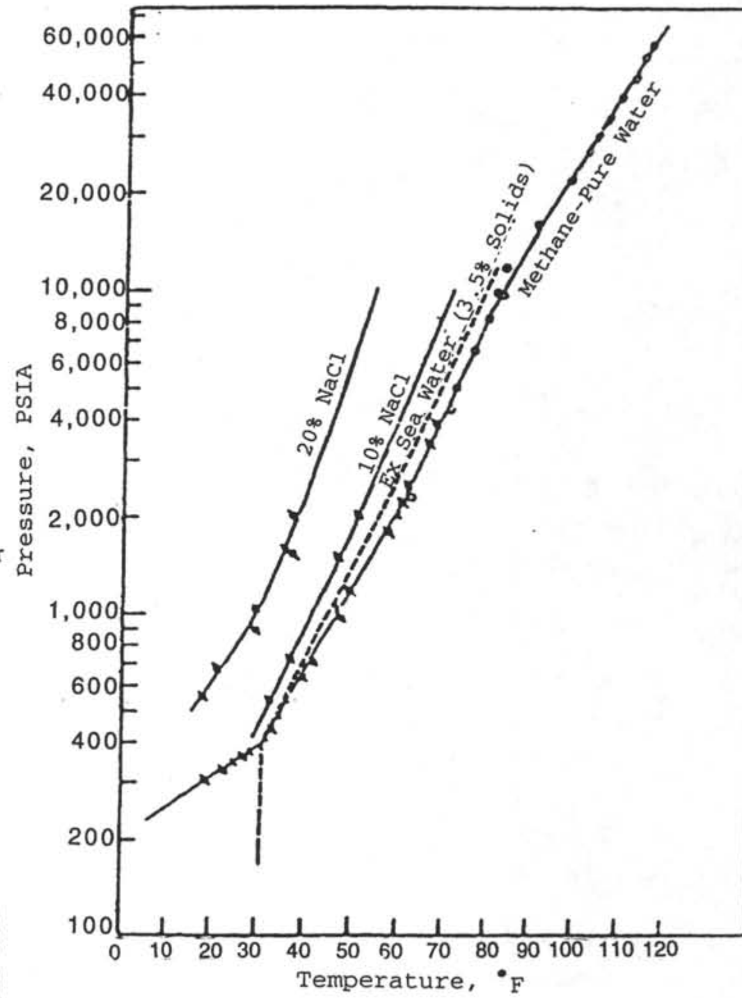


Figure 5. The stability filed of hydrate-gases-water system is shown as a function of temperature and pressure. The effect of NaCl on the methane gas hydrate phase boundary is also given in this plot (data from Kobayashi et al., 1951; figure from Hand et al., 1974). The salinity of the pore waters exerts a significant effect on the location of the BSR.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: BRH-1a	**PRIORITY**:	**POSITION**: 31°50.59'N, 75°28.12'W
WATER DEPTH: 2722 m	**SEDIMENT THICKNESS**: ~2 km	**TOTAL PENETRATION**: 480 m
SEISMIC COVERAGE: CH-06-92 line 31		

Objectives: To sample a thick section of acoustically "transparent" sediments on the crest of Blake Ridge where gas hydrates may be extensive.

Drilling Program: XCB, PCS and RCB coring.

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: BRH-1a ext.	**PRIORITY**:	**POSITION**: 31°50.59'N, 75°28.12'W
WATER DEPTH: 2722 m	**SEDIMENT THICKNESS**: ~2 km	**TOTAL PENETRATION**: 750 m
SEISMIC COVERAGE: CH-06-92 line 31		

Objectives: To sample the sediments and gases that are associated with a string BSR.

Drilling Program: XCB, PCS and RCB coring.

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: BRH-2a	**PRIORITY**:	**POSITION**: 31°52.84'N, 75°25.11'W
WATER DEPTH: 2828 m	**SEDIMENT THICKNESS**: ~2 km	**TOTAL PENETRATION**: 800 m
SEISMIC COVERAGE: CH-06-92 line 31		

Objectives: To drill through the base of the hydrate stability field and into the sediments below which are in an area associated with a "hole" in the BSR.

Drilling Program: APC, XCB, and RCB coring

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: BRH-3a	**PRIORITY**:	**POSITION**: 31°54.40'N, 75°23.02'W
WATER DEPTH: 2965 m	**SEDIMENT THICKNESS**: 2 km	**TOTAL PENETRATION**: 500 m
SEISMIC COVERAGE: CH-06-92 line 31		

Objectives: To sample the same stratigraphic units as proposed sites BRH-2a, but where they are believed to contain gas hydrates because they are acoustically "transparent".

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

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: BRH-3a ext.	**PRIORITY:**	**POSITION**: 31°54.40'N, 75°23.02'W
WATER DEPTH: 2965 m	**SEDIMENT THICKNESS**: 2 km	**TOTAL PENETRATION**: 750 m
SEISMIC COVERAGE: CH-06-92 line 31		

Objectives: To sample the sediments and gases that surround a weak BSR.

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

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CRH-1	**PRIORITY:**	**POSITION**: 32°46.88'N, 75°57.4'W
WATER DEPTH: 2647 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 800 m
SEISMIC COVERAGE: CH-06-92 line 41		

Objectives: To drill into sediments beneath the projected level of gas hydrate stability in an area that is not associated with a BSR.

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

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CRH-2	**PRIORITY:**	**POSITION**: 32°46.74'N, 75°55.20'W
WATER DEPTH: 2732 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 540 m
SEISMIC COVERAGE: CH-06-92 line 41		

Objectives: To sample the same stratigraphic units as at proposed site CRH-1 but where they are believed to contain less gas hydrates because they are acoustically "transparent".

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

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CRH-2 ext.	**PRIORITY:**	**POSITION**: 32°46.74'N, 75°55.20'W
WATER DEPTH: 2732 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 750 m
SEISMIC COVERAGE: CH-06-92 line 41		

Objectives: To sample the sediments and gases that are associated with a moderately strong BSR.

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

Logging and Downhole Operations: Logging and VSP.

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CFD-1	**PRIORITY:**	**POSITION**: 33°00.95'N, 75°56.75'W
WATER DEPTH: 2690 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: CH-15-91 line 10		

Objectives: To carry out background sampling along a transect into the diapir. The hole will penetrate the sole of a major slide.

Drilling Program: RCB coring.

Logging and Downhole Operations:

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CFD-2	**PRIORITY:**	**POSITION**: 33°00.3'N, 75°55.8'W
WATER DEPTH: 2700 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: CH-15-91 line 10		

Objectives: To sample beds at the edge of the diapir where the disturbance associated with the diapir is at an extreme.

Drilling Program: RCB coring.

Logging and Downhole Operations:

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CFD-3	**PRIORITY:**	**POSITION**: 32°59.5'N, 75°55.18'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: CH-15-91 line 10		

Objectives: To sample beds at the edge of the diapir where the disturbance associated with the diapir is at an extreme.

Drilling Program: RCB coring.

Logging and Downhole Operations:

Nature of Rock Anticipated: Hemipelagic silt and clay.

SITE: CFD-4	**PRIORITY:**	**POSITION**: 32°59.3'N, 75°54.25'W
WATER DEPTH: 2590 m	**SEDIMENT THICKNESS**: ~8 km	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: CH-15-91 line 10		

Objectives: To sample surface sediments on the crest of an exhumed diapir.

Drilling Program: RCB coring.

Logging and Downhole Operations:

Nature of Rock Anticipated: Salt? Hemipelagic silt and clay.

LEG 165
Caribbean Ocean History

LEG 165[1]

CARIBBEAN OCEAN HISTORY

Modified from Proposal 415-Rev2 Submitted By

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To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

The Caribbean region presents a wide array of geologic problems related to its plate tectonic evolution, nature of the oceanic crust or basement, ocean history, and the opening and closing of Atlantic-to-Pacific seaways. With the exception of DSDP Site 502, the Caribbean has not been targeted by the Ocean Drilling Program or Deep Sea Drilling Project for more than two decades. A fresh impetus has now been given to Caribbean drilling by the recent discovery of a strewn field of unaltered impact glass spherules or tektites in Haiti and Mexico at the Cretaceous/Tertiary boundary, and the identification of their source in the 180 to 300 km-wide Chicxulub impact crater in the Yucatan.

Leg 165 represents new drilling to broadly address two major themes; the nature of the Cretaceous/Tertiary boundary, and Caribbean paleoceanography. During Leg 165, drilling at seven primary sites will provide important insights into the dispersal of ejecta from the K/T impact (proposed at Chicxulub Crater, Mexico) and its environmental consequences. Transects of new sites within the Caribbean will be used to examine paleoceanographic problems such as the nature and variability of Cretaceous climate, low-latitude sea-surface temperatures (SST's) and heat transport in Eocene oceans, the chronostratigraphy of Cretaceous and Paleogene oceans, the Neogene initiation and evolution of the Caribbean current, and high-resolution variability of Quaternary tropical climate.

[1] May become Leg 166 if currents in the Santaren Channel are more favorable for Bahamas Transect (currently Leg 166) during Leg 165.

INTRODUCTION

The principal hypothesis put forward to account for the world-wide Cretaceous/Tertiary boundary mass extinctions is the impact of a large bolide on the Earth. The recent discovery of fresh impact glasses at the K/T boundary in the Beloc Formation of Haiti (Sigurdsson et al., 1991a; Izett, 1991), the Mimbral sequence of northeastern Mexico (Margolis et al., 1991) and DSDP Sites 536 and 540 in the Gulf of Mexico (Alvarez et al., 1991) provides evidence for a major impact event in the Caribbean region. Geochemical evidence from these glasses also yields constraints for an impact site on continental crust, overlain by evaporite-rich sediments (Sigurdsson et al., 1991b), which is consistent with the stratigraphy near the 180 km (Hildebrand et al., 1990) to 300 km (Sharpton et al., 1994) Chicxulub impact crater on the Yucatan Peninsula of Mexico.

The discovery of impact glass-bearing deposits in the circum-Caribbean region indicates that sediments within the Caribbean Sea have an excellent potential for yielding K/T boundary layers similar to the rare sections exposed on land. Leg 165 will drill a series of sites in the Caribbean Sea and on the margins of the Yucatan Basin for the purpose of penetrating and recovering the K/T interval and for studies of Caribbean paleoceanography (Figure 1). Since the critical K/T boundary deposit may not be recovered at all of these sites, Leg 165 includes a drilling program that is broad-based and addresses a number of important paleoceanographic and paleoclimatic problems.

Recovery of relatively complete Cretaceous and Cenozoic sedimentary sequences in the Caribbean will greatly advance our knowledge of a wide range of major paleoceanographic and paleoclimatic problems. Chief among these are 1) the tropical dominance of Cretaceous oceans, 2) low-latitude SST's and heat transport in Eocene oceans, 3) the number and climatic effects of late Eocene impacts, 4) the chronostratigraphy of Cretaceous and Paleogene oceans, 5) Neogene initiation and evolution of the Caribbean current, 6) variations of intermediate water masses in the Caribbean, 7) linkages between sub-millennial climatic events of northern latitudes (i.e., Heinrich events), modes of deep-water formation, and Quaternary tropical climate, and 8) environmental conditions of anoxic basin development.

These specific problems collectively address several issues that are critical to our understanding of the coupled ocean-climate system, including the rates and magnitude of tropical climate change during both 'icehouse' and 'greenhouse' climate intervals, the interdependence of tropical oceanic conditions and the global ocean-climate system, the relative importance of latitudinal heat transport and atmospheric concentrations of greenhouse gases for controlling climate equability, and the effect of large impacts on the oceans and climate.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To study the nature and variability of Cretaceous climate, low-latitude SST's, and heat transport in Eocene oceans.

2) To study the chronostratigraphy of Cretaceous and Paleogene oceans.

3) To study the Neogene initiation and evolution of the Caribbean current, and high-resolution variability of Quaternary tropical climate.

Specific Objectives and Methodology

The K/T Boundary in the Caribbean Region

Study of the K/T boundary by drilling in the Caribbean region has become even more compelling following the discovery of a thick impact ejecta deposit in Haiti (Hildebrand and Boynton, 1990), the find of unaltered impact glass or tektite spherules in the deposit (Sigurdsson et al., 1991a, 1991b), and the recognition of the Chicxulub crater at the north end of the Yucatan peninsula of Mexico as the locus of bolide impact (Pope et al., 1991; Hildebrand et al., 1991). The evidence is now unambiguous that Chicxulub represents the impact site; the current debate is about the size of the crater. Sharpton et al. (1994) view the geophysical data and preliminary Pemex drilling results as an indication that the Chicxulub represents a multi-ring impact basin, with a diameter of about 300 km, whereas Hildebrand et al. (1994) have interpreted similar data as indicating that the Chicxulub is a simple impact crater of about 180 km diameter.

The major outstanding issue regarding the K/T boundary event is the exact relationship between the bolide impact and the associated extinctions. This issue relates to bolide size, impact angle, ejecta dispersal and perhaps, most important, geochemistry of the impact terrain. It turns out that the Yucatan terrain has geologic features that are likely to have brought about uniquely severe environmental effects of the impact. Evidence from the geochemistry of impact glasses or tektites indicates that two dominant geologic formations were melted; Paleozoic continental crust (producing black high-silica glasses) and Cretaceous chemical sediments of evaporites and carbonates (producing sulfur-rich high-Ca yellow glasses; Sigurdsson et al., 1991a, 1991b; Koeberl and Sigurdsson, 1992).

Total Ejecta Mass

Ejecta from the bolide impact consist of three principal components: a) melt ejecta, in the form of impact glass spherules or tektites, b) gases from vaporized target material, dominantly water, CO_2 and SO_2 which has converted to a stratospheric aerosol, and c) crustal rock ejecta or "dust", consisting of proximal breccia, and distal crystal fallout (shocked quartz, hornblende, etc.).

The dominant material composing the boundary layer in the distal ejecta blanket is smectite, which is shown from the study of the boundary layer in Haiti to be the alteration product of ejecta glass. Three previous estimates have been made of total ejecta mass. Originally the impact ejecta mass was estimated as $2x10^{19}$ g on the basis of the magnitude of the Ir anomaly at the K/T boundary (Alvarez et al., 1980). Adopting a model with a 10 km-diameter bolide and impact velocity of 20 km/sec, Roddy et al. (1991) predicted a transient crater of 100 km diameter and ejecta mass of $1.9x10^{20}$ g. On the basis of observed ejecta deposit thickness, Hildebrand and Stansberry (1992) arrived at a total ejecta mass of $6.9x10^{19}$ g. The thickness/distance data for the K/T ejecta deposit does not fit well the simple log/log relationship proposed by Hildebrand and Stansberry (1992) (Figure 2a). We have applied a method used in volcanology for volume calculation of the total observed ejecta deposit (Fierstein and Nathenson 1992), assuming an axisymmetric distribution (Figure 2b). The distribution of deposit thickness versus the square root of the area is best fitted by two linear segments, with an intercept at a distance of about 1400 km from the source. The distinct break in slope of the distribution is likely to represent two dominant modes of dispersal. This is typical for fallout deposits from volcanic eruptions and is generally attributed to the "corner" between the vertical eruption column and the near-horizontal high-altitude anvil or plume. This method thus yields a total ejecta volume of 4.17×10^4 km^3 or ejecta mass of 8.3×10^{19} g. The distribution of solid ejecta fallout is therefore highly uneven on the Earth (Figure 2c). The volume of the deposit described by the first line segment is 4.11×10^4 km^3 and the volume associated with the second line segment 677 km^3. It is partitioned into two regions, namely the proximal solid ejecta within 1400 km radius, or 8.29×10^{19} g on 1.2% of Earth's surface, and distal ejecta fallout on 98.8% of Earth's surface with mass of 1.35×10^{18} g. The ejecta fallout loading of solid matter on most of the Earth's surface is thus about 0.27 g/cm^2. In comparison, Pollack et al. (1983) adopted a 1 g/cm^2 mass loading of "dust" in their assessment of climatic effects of K/T boundary impact ejecta. Our results thus suggest that previous estimates of a high atmospheric mass loading at the K/T boundary due to large amounts of rock "dust" may be high by a factor of 4, and that rock "dust" was therefore probably not a major climate-forcing factor in the wake of the impact. As discussed below, a stratospheric aerosol created from the volatile component of ejecta can form a much larger atmospheric mass loading.

The proposed drilling will provide much-needed constraints on the solid ejecta mass distribution, as the proposed sites form a transect that crosses the transition between the thick proximal ejecta within 1400 km from source, and the thin distal ejecta. Drilling will also contribute to our knowledge of the dispersal pattern. Most current models assume an axisymmetric distribution of the ejecta blanket deposit, but the recent proposal of Schultz (1994), that the Chicxulub structure represents an oblique impact, implies that the ejecta distribution would be asymmetric. The fan-shaped distribution of proposed drill sites could help address this hypothesis.

Ejecta Dispersal Mechanisms

Our study of the well-preserved and thick (0.5-1 m) Haiti K/T boundary sections indicates that the ejecta deposit consists of three principal units which reflect different depositional processes. A basal 20 cm unit is composed of impact glass spherules and their smectite alteration products and is normally graded. The large grain size of glass spherules (up to 8 mm diameter) indicates that they cannot have been transported as fallout from thermal plumes, but rather as ballistic fallout. Ballistic fallout modeling of the formation of this unit, constrained by observed impact spherule size distribution and distance from the Chicxulub source, promises to provide a measure of the fireball height at the source (Espindola et al., submitted). This unit is overlain by a 20-50 cm thick cross-bedded smectite and carbonate-rich unit, which contains large glass spherules as well as sediment rip-up clasts. We have interpreted this as a density current deposit or turbidite, which may be related to a giant impact-generated tsunami or seiche event, such as has been proposed for similar debris flow deposits at the K/T boundary in northern Mexico (e.g., Smit et al., 1994). The uppermost unit is a 0.5-2 cm thick reddish-brown smectite layer which contains the iridium anomaly and minute shocked quartz grains. It most likely represents late-stage fallout of aerosols and atmospherically suspended impact "dust".

The proposed drilling will provide additional information on these lithologic units, their complex depositional mechanisms, and possible facies variations in the ejecta layer as a function of distance from source.

Volatile Components and Extinction Mechanisms

The geochemical evidence from the Haiti impact glasses or tektites, on the nature of the impact terrain, shows that volatile emission from the target rocks was an important feature of the K/T boundary event, and this feature may account for the uniquely severe environmental effects and high extinction rate which marks this geologic boundary. The high sulfur content (up to 1 wt.%), high oxygen fugacity (Oskarsson et al., 1991) and isotopic composition (Chaussidon et al., 1994) of the high-Ca yellow impact glasses are conclusive evidence of their formation by fusion of evaporite and carbonate in the presence of a silicate melt. The geologic constraints indicate that the impact volatilized sedimentary rocks and pore fluids to produce a large stratospheric vapor plume consisting of the potent brew of CO_2, SO_2, and H_2O in about equal proportions. Those inferences are fully supported by the geologic evidence of the Cenozoic stratigraphy of the Yucatan peninsula, which contains a 3 km-thick succession of evaporite, carbonate, and dolomite sediments at the site of impact (Lopez Ramos, 1981).

The most conservative estimate of volatile emission from impact is the mass of volatiles degassed from the impact melt which remains in the crater, but this parameter is known from impact crater scaling and from empirical observations on other craters on Earth. The melt volume for craters in the Chicxulub size range of 180-350 km final diameter is very large (> 10^5 km^3) (Cintala and

Grieve, 1991). If we consider only the degassing of a 2-km-thick surface sediment layer of carbonate and evaporite composition, we arrive at a sulfur emission of the order 10^{18}-10^{19} g, only by degassing of the melted mass, which would correspond to a global atmospheric loading by a sulfate aerosol of the order 0.2-2 g/cm^2. The atmospheric loading from an impact-generated sulfate aerosol is thus equal to, or possibly greater by an order of magnitude, than the rock "dust" lofted by the impact. It seems very likely that a very large sulfate aerosol must have formed after impact, with major global surface cooling. The mass of CO_2 emission would be comparable to, or larger than, that of the SO_2 emission. O'Keefe and Ahrens (1989) have estimated 10^{19} g CO_2 emission for a 10 km impactor from a 1 km layer of carbonate, or within the range of our results. Because of the prodigious amount of CO_2 released, a number of investigators have proposed a sudden, and even harmful, greenhouse warming at the time of impact. However, as indicated by Pollack et al. (1983), in the presence of a dense stratospheric aerosol, no warming by a greenhouse effect is possible under these conditions, despite the greatly enhanced infrared opacity of the atmosphere.

The proposed Caribbean drilling sites will potentially benefit studies of K/T boundary environmental effects in two ways. Firstly, the proposed high core recovery of the boundary is likely to yield glass spherules for further geochemical analysis. To date, only the Haiti site and the Mimbral site in Mexico have yielded unaltered glass from the boundary. Additional glass samples are needed for further quantitative evaluation of the possible role of evaporites and carbonate sediments in the formation of the impact melt.

Cretaceous/Paleogene Paleoceanography

Tropical Dominance of Cretaceous Oceans?

The paleoceanographic conditions of Cretaceous low latitudes, although presently poorly defined, played a very important role in Late Cretaceous climate. The Late Cretaceous is widely considered to be characterized by relatively equable climate conditions. During the Maastrichtian, high-latitude surface waters of Southern oceans were about 10°C (Barrera et al., 1987; Barrera and Huber, 1990), contrasting strongly with near-zero present-day temperatures. Possible causes of the relatively high temperature of Late Cretaceous high-latitude waters include increased paleoatmospheric concentrations of greenhouse gasses and increased paleoheat transport from low to high latitudes. The relative importance of these factors can be assessed by isotopic documentation of tropical SST's (Crowley and North, 1991). The Caribbean seafloor contains Late Cretaceous sequences that would be very suitable for such documentation.

There is a longstanding hypothesis of low-latitude warm salty bottom-water (WSBW) formation in the Late Cretaceous (Saltzman and Barron, 1982; Brass et al., 1982). The presumed sources of such deep water would have been the extensive low- and mid-latitude epicontinental seas of the Cretaceous (i.e., the Western Interior of North America, Northern South America, North Africa...). Such hypotheses are consistent with global circulation modelling of Cretaceous oceans and climate, many of which suggest strong precession-scale variation in evaporation-precipitation balances of such regions (i.e., the Western Interior of North America) (Barron et al., 1985; Glancy et al., 1986; Oglesby and Park, 1989; Park and Oglesby, 1991). Caribbean sequences appear to contain records of Milankovitch-scale sedimentary variation. Analysis of sedimentologic and faunal data from such sequences in the Caribbean will document the sensitivity of low-latitude Late Cretaceous oceans to Milankovitch-band forcing and may document the presence of threshold events in Late Cretaceous paleoceanographic and paleoclimatic history. Recovery of Cretaceous sequences from the Caribbean would greatly aid in isotopic testing of the hypothesis of low-latitude WSBW since the Caribbean is likely to have been close to such sources of deep water and its deep waters may have been depleted in ^{12}C relative to those of previously drilled high and mid-latitude sequences, and of the recent hypothesis that expression of a precessional "double-beat" in the mid-latitude South Atlantic resulted from equatorial dominance of mid-latitude Late Cretaceous paleoceanographic records (Park et al., 1993).

Caribbean drill sites could also provide an appropriate sequence for analysis of chrono-stratigraphically well-constrained stable isotopic trends in low-latitude Late Cretaceous oceans, allowing isotopic testing for the global or regional extent of large climate steps in the Late Cretaceous greenhouse. Such steps are presently known from oxygen and carbon isotopic records of the high- and mid-latitude southern oceans (Barrera and Huber, 1990), but are not yet known from low-latitude sequences.

Low-Latitude SST's, Atmospheric pCO_2, and Heat Transport in Eocene Oceans

Floral and faunal evidence suggest that the early Eocene was marked by the warmest global climate of the Cenozoic (Dawson et al., 1976; Haq et al., 1977; Axelrod, 1984; Wolfe, 1985; Rea et al., 1990). Furthermore, $\delta^{18}O$ data indicate that the deep ocean and high-latitude surface oceans were at their warmest Cenozoic values in the early Eocene (Savin, 1977; Miller et al., 1987; Stott and Kennett, 1990). Despite these results, previous $\delta^{18}O$ studies of Eocene low-latitude surface sea waters suggest that low-latitude sea-surface waters may have been either considerably cooler (5°-8°C) or considerably saltier than those of present-day equatorial oceans (Figure 3) (Keigwin, 1980; Boersma and Shackleton, 1981; Saunders et al., 1984; Zachos et al., 1990, 1994). The juxtaposition of data indicating relatively warm high latitude regions and cool or saline low-latitude regions suggests that early Eocene equator-to-pole thermal gradients may have been more heavily affected by latitudinal heat transport and less dependent on atmospheric concentrations of greenhouse gases than present coupled atmosphere-ocean models generally assume (Barron, 1987; Rind and Chandler, 1991).

Isotopic records indicate that the warm early Eocene followed a period of gradual warming in the late Paleocene, punctuated by a geologically rapid warming event at high southern latitudes (Miller et al., 1987; Rea et al., 1990; Kennett and Stott, 1991). The gradual decrease in benthic $\delta^{18}O$ values is accompanied by a long-term decrease in planktonic and benthic $\delta^{13}C$ values (Shackleton et al., 1984; Miller et al., 1987), while the rapid southern ocean $\delta^{18}O$ event is associated with major benthic foraminiferal extinctions and a drastic negative shift in planktic and benthic $\delta^{13}C$ values (Kennett and Stott, 1991). This rapid warming event has been interpreted as resulting from the replacement of cool high-latitude deep water sources by warm saline deep-water sources (Kennett and Stott, 1991). The early Eocene warm interval was in turn followed by a long middle to late Eocene cooling (Keigwin and Corliss, 1986; Zachos et al., 1990). This cooling appears to have resulted from geographic and thermal isolation of Antarctica (Kennett, 1977). During this cooling interval, wholesale replacement of late Paleocene and early Eocene plankton assemblages occurred (Corliss et al., 1984).

Prior isotopic studies of low-latitude Eocene sequences have been limited to a few Indo-Pacific sites and an outcrop on Barbados. Recent plate reconstructions suggest that surface-water temperatures at these sites may have been strongly influenced by upwelling of cool deeper waters (Zachos et al., 1994). Furthermore, selective dissolution of near-surface taxa may have led to underestimation of sea-surface paleotemperatures (Zachos et al., 1994). Recovery of relatively complete Caribbean Paleogene sequences would allow verification of relatively positive $\delta^{18}O$ values in the Eocene low-latitude Caribbean, closely constrain the regional presence and timing of gradual and abrupt changes in surface and deep $\delta^{18}O$ and $\delta^{13}C$ trends, and elucidate low-latitude relationships between such changes in stable trends, Paleocene/Eocene benthic foraminiferal extinctions, and the planktic extinctions of the mid and late Eocene.

The Number and Climatic Effects of Late Eocene Impacts

Recovery of relatively complete Caribbean Paleogene sequences would provide good chrono-stratigraphic control of late Eocene microtektite (impact) events and any associated paleo-environmental effects. Although those microtektite events were first documented from DSDP Leg 15 cores (Donnelly and Chao, 1973), the total number of such late Eocene events and their paleoenvironmental and paleobiological effects remain unsettled, largely due to diachronous biostratigraphic data and an absence of good paleomagnetic data at late Eocene microtektite-bearing sequences (Glass and Zwart, 1977; Keller et al., 1987; Miller et al., 1991).

Chronostratigraphy of Cretaceous and Paleogene Oceans

The Cretaceous and Paleogene record of low-latitude oceans remains poorly known. While early DSDP legs drilled such sequences in the Caribbean (Legs 4 and 15), poor drilling recovery and a general absence of magnetostratigraphy renders it difficult to assess diachronism of Late Cretaceous and Paleogene biostratigraphic data or to correlate low-latitude sequences at sub-million-year time scales to the relatively well-constrained Tethyan Gubbio sequences and mid- and high-latitude Southern hemisphere sequences (DSDP Site 516 and ODP Sites 689 and 690) (Alvarez et al., 1977; Barker et al.,1988, 1990; Monechi and Thierstein, 1985). This limited chronostratigraphic control makes it difficult to measure rates of paleoceanographic and paleoecologic change or to correlate between sites. Successful recovery of such sequences from this region will provide valuable paleomagnetic and biostratigraphic records for development of low-latitude Cretaceous and Paleogene chronostratigraphic control at sub-million-year time scales.

Development of relatively high-resolution low-latitude chronostratigraphy may be aided by the presence of Milankovitch sedimentary variation in Late Cretaceous and Paleogene Caribbean sequences. The recovered Maastrichtian and Paleocene sections of Sites 146 and 153 exhibit alternating light and dark intervals that closely resemble coeval precessional cycles described from South Atlantic and Indian Ocean sequences (Maurasse, 1973; Borella, 1984; Herbert and D'Hondt, 1990; Huang et al., 1992). Similar Milankovitch-scale variation has been successfully used for high-resolution Plio-Pleistocene and K/T stratigraphy (i.e., Imbrie et al., 1973; Johnson, 1982; Shackleton et al., 1990; Herbert and D'Hondt, 1990)

Neogene/Quaternary Climatic and Oceanographic History

The tectonic history of the Caribbean is intimately linked to circulation and climatic history of the oceans. Uplift and, during the Pliocene, final emergence of the Isthmus of Panama are the most obvious examples. However, the Aves Swell and Northern Nicaragua Rise (NNR) may have also been important barriers in the past. Based upon recent studies, the NNR is thought to have been covered by a shallow carbonate platform until the middle Miocene and its partial foundering in the late middle Miocene may have initiated the Caribbean Current and thus contributed at that time to the intensification of the Gulf Stream (Droxler et al., 1991). Recovery of cores in the main Caribbean basins north and south of the Nicaragua Rise will test Neogene models for surface and deep circulation related to the opening and closure of gateways and shed some light on mixing of the world ocean and regulation of climate in high latitudes at low and high frequencies.

The general paucity of Caribbean high-resolution Neogene records stands in stark contrast to other equatorial regions of the world ocean, where ODP drilling has recovered astonishingly complete Plio-Pleistocene records and greatly increased our potential for understanding global and regional paleoceanographic and paleoclimatic variation (i.e., Indian Ocean Legs 115-117, 121, Pacific Leg 138, and Atlantic Leg 154). Drilling of Caribbean depth transects between 1,100 and 3,000 m would provide one of the last major pieces in the global array of high-resolution equatorial monitors of surface- and deep-water circulation. Such drilling will allow us to address several questions of both regional and global paleoceanographic, paleoclimatic, and paleobiological significance: What is the history of the Caribbean Current? When was it established? How did the strength of its flow relate to tectonic events within the Caribbean region? How has Neogene variation in the Caribbean Current influenced the evolution of North Atlantic surface, intermediate, and deep water circulation, and consequently the climate of the North Atlantic Ocean? What has been the evolutionary and ecological response of planktonic biota to the partial demise of the carbonate mega-bank along the NNR and the closure of the Central American Seaway? What is the history of intermediate waters in the North Atlantic Ocean? How has the chemistry of Antarctic Intermediate Water (AAIW) versus Upper North Atlantic Deep Water (NADW) responded to changes in global ocean circulation during the late Neogene on glacial-interglacial time scales and higher frequency periods?

Initiation and Evolution of the Caribbean Current

The Neogene history of the Caribbean oceanic surface circulation has been significantly modified by two major tectonic events. The first event, possibly related to a reorganization of the spreading within the Cayman Trough, was responsible for the opening in the middle Miocene of a new gateway for the North Atlantic Western Boundary Current through the partial demise of a carbonate mega-bank that covered, during the Oligocene and early Miocene, the full length of the NNR (Figure 4). The seaway's opening during the middle Miocene along the NNR is supposed to have had a direct impact on the initiation of the "modern" western boundary current with some potential link to the onset of the NADW formation at 11-12 Ma (e.g., Crowley and North, 1991).

The development of a strong North Atlantic Western Boundary Current in the Caribbean sometime in the middle Miocene is clearly documented in the Gulf of Mexico and in the Straits of Florida. Mullins et al. (1980) showed, based upon their interpretation of a high resolution seismic grid, that a major erosional event clearly truncated clinoforms and produced a major seismic reflector along the Miocene shelf margin in the eastern Gulf of Mexico. The authors interpreted this erosional event (sometime between 12 and 15 Ma) as a consequence of flow intensification of the Loop Current along the eastern margin of the Gulf of Mexico.

The proposed mid-Miocene intensification of the Loop Current/Gulf Stream circulation is supported by other observations down-current along the Gulf Stream. A major current intensification possibly occurred in the ?middle Miocene in the eastern southern Straits between

Cay Sal and Southern Florida, where the development of contourite current deposits and associated moats is observed on seismic lines (Denny, 1992; Denny et al., in press). The middle Miocene strengthening of the Gulf Stream may also correspond to erosion on the Pourtales Terrace (Gomberg, 1974) and on the Miami Terrace (Mullins and Neumann, 1979). Studies of ODP Site 626 drilled in the middle of the northern Straits of Florida, show that the Gulf Stream, flowing already in the late Oligocene (possibly even in the Late Cretaceous or at least during the Paleogene; Sheridan et al., 1981), had to significantly strengthen to explain the decrease by 50% of sediment accumulation rates in the middle Miocene (Austin et al., 1986). Sediment drifts in the northern Straits of Florida prograded over flat ?mid-Miocene reflectors (Mullins et al., 1980) and the "most pronounced Neogene Gulf Stream Cut" (Popenoe, 1985) is illustrated by a "rugged" mid-Miocene unconformity on the Blake Plateau.

The second tectonic event is the final closure of the Central American Seaway (Isthmus of Panama) at the early/late Pliocene boundary, based on near-shore marine records of Costa Rica and western Panama (Coates et al., 1992; Figure 4). This estimate corresponds quite well with the conclusions by Saito (1976) and Keigwin (1978) that surface water circulation appears to have stopped by 3.3-3.0 Ma based upon biogeographic differences in planktic foraminifers from both sides of the Central American Seaway. Keller et al. (1989) suggested a slightly younger age for the final closure; using faunal evidence these authors infer that the surface connection existed until 2.4 Ma. The final closure of the Central American Seaway is expected to have significantly strengthened the Western Boundary Current and diverted northwards large volumes of low latitude warm and salty waters that are potentially linked to the initiation of the northern hemisphere glaciations at 3.0-2.4 Ma (e.g., Raymo et al., 1989).

In pelagic microfossils, closure of the Central American Seaway is accompanied by changes in coiling directions in planktonic foraminifers, temporary disappearance of certain foraminifers from the Atlantic Ocean, and initial appearance of several new species, which are largely restricted to the Atlantic Basin (Saito, 1976; Keigwin, 1978, 1982: Keller et al., 1989). The final closure also coincides with the beginning of the sequential disappearance and repopulation events that affected foraminifer assemblages in the tropical Atlantic, but are absent from the Indo-Pacific region (e.g., Ericson and Wollin, 1956; Jones, in press). The Neogene sequences are needed in the Caribbean to document changes in faunal assemblages that accompanied the formation of distinct

Caribbean water masses and to test relationships between oceanographic history and the disappearance and repopulation of plankton in the Atlantic during glacial and interglacial stages.

In the context of these two Neogene tectonic events, three Neogene oceanic settings need to be distinguished (Figure 4).

1) The early Miocene Caribbean paleoceanography, prior to the middle Miocene partial foundering of the NNR, was characterized, in the area south of the Nicaragua Rise mega-bank, by a well-developed circumtropical Current connecting the low latitudes of the North Atlantic and Pacific Oceans. At that time, the area of the Cayman Trough, the Yucatan Basin, the Gulf of Mexico, and the Southern Straits of Florida would have been isolated by the Nicaragua Rise mega-bank. A weak North Atlantic Western Boundary Current (the "proto" Gulf Stream and Antilles Currents) would be expected outside of the Caribbean region.

2) The late Miocene/early Pliocene Caribbean paleoceanography was characterized by a newly developed Western Boundary Current within the Caribbean region, including the Caribbean Current/Loop Current/Gulf Stream system. Though the Central American Seaway began to close by about 13 to 12 Ma (Keller and Barron, 1983), deep water circulation was largely cut off by about 6 Ma based on the differences in $\delta^{13}C$ between the Caribbean and the Pacific (Keigwin, 1982). Upwelling began in the western Caribbean by about 6.2 Ma, presumably because of constricted intermediate water transport through the central American gateway (Brunner, 1983). The region north of the NNR at that time became less isolated, whereas a weakened circumtropical Current connecting the low latitudes of the North Atlantic and Pacific Oceans characterized the region south of the NNR.

3) The "modern" late Pliocene/Quaternary Caribbean paleoceanography, post final closure of the Central American Seaway, is characterized by a well-developed and strong North Atlantic Western Boundary Current. This current has been a critical path for the variable surface return flow of the global thermohaline circulation, especially during interglacial stages as it is today, to compensate for an optimum production of the NADW in the Norwegian Sea. During glacial stages, when the production of the NADW was considerably diminished or totally stopped, the Caribbean Current became more a part of the North Atlantic Western Boundary Current and lost its role as pathway

for the inter-hemisphere heat exchange between the South and the North Atlantic oceans. In addition, isotopic evidence suggest that intermediate waters and the main thermocline were rapidly ventilated during glacial stages while the production of NADW was depressed (Boyle and Keigwin, 1987; Cofer-Shabica and Peterson, 1986; de Menocal et al., 1992; Slowey and Curry, 1992; Oppo and Lehman, 1993).

Variations of Intermediate Water Masses (AAIW and UNADW)

The presence of relatively shallow sills separating the major basins in the Caribbean make each basin a sensitive monitor for the history of intermediate waters in the open Atlantic Ocean. Because different parts of the Caribbean Sea are silled at depths that presently range from 1400-1900 m, sediments deposited in the deep Caribbean basins below, at, and several hundred meters above, sill depths are thought to have recorded flux variations of both AAIW and Upper NADW (UNADW). At the latitude of the Lesser Antilles, UNADW and AAIW range in water depths today from 800-1,100 m and from 1,200-2,000 m, respectively (Bainbridge, 1981). The relative proportions of these source waters in the low latitudes of the western North Atlantic can be monitored by studying carbonate preservation in the Caribbean basins (Figure 5).

Haddad (1994) has developed a Composite Dissolution Index (CDI) to establish the late Quaternary variation in preservation of metastable carbonate (bank-derived high magnesian calcite and pteropods) in water depths ranging from 1,100-1,900 m. His results demonstrate an excellent correlation between metastable carbonate preservation at 1,200 m of water depth and $\delta^{13}C$ records from the Venezuela Basin (Figure 6). This indicates that Caribbean carbon chemistry has been similar during the past 200 k.y. from 1,200 m to abyssal depths. This in turn suggests that AAIW influences deep Caribbean $\delta^{13}C$ and CO_3 more than previously envisioned.

There is excellent agreement between appearances and disappearances of *Globorotalia tumida* and Caribbean records of carbonate dissolution (Figure 6c). The Atlantic reappearance of *G. tumida* during the last deglaciation has been related to the renewed surface water connection between the Indian and Atlantic oceans through the Agulhas and Benguela currents at ~ 9 ka (Jones, in press). The connection likely coincided with the modern thermocline and AAIW circulation (Jones, in press) in which these waters flow east into the Indian Ocean, loop back through the Agulhas

Retroflection, and re-enter the Atlantic in the Benguela Current (Gordon et al., 1992). Gordon et al. (1992) have suggested that salt and heat acquired during this may "precondition" the Atlantic for NADW formation. Thus, there may be a direct link between the presence of *G. tumida* in the Caribbean and the onset of upper layer return flow of the thermohaline circulation cell (Jones, in press). Assuming the proposed linkages, low influx of AAIW should correspond to low concentration of *G. tumida*, good preservation of metastable carbonates on the Nicaragua Rise, and low production of NADW, whereas high flux of AAIW should correspond to high concentrations of *G. tumida*, poor preservation of metastable carbonates, and high production of NADW. This is indeed the relationship observed in Haddad's late Quaternary records (Figure 6a-c). Extension of these records to older intervals of time should document Neogene paleoceanographic linkages between Caribbean surface water flow and NADW rates of formation. In turn, this will shed important light on our understanding of how Caribbean tectonics have controlled the global "conveyer belt" of surface and deep ocean flow, and hence, the evolution of Neogene climate.

Leg 165 will drill depth transects of several sites in water depths ranging between 1,200 and 3,000 m, on both up-current and down-current location relative to the NNR to establish the variations through time of the water column stratification in the Caribbean at intermediate water depths.

Quaternary Climate Variations

The rates and magnitudes of tropical climate change are poorly resolved on interannual to millennial time scales. Drilling of annually-laminated Cariaco Basin sediments will provide an important late Quaternary record of tropical climate change on those time scales. Such records will further our understanding of global climate change and forcing mechanisms by providing a well-constrained basis for theoretical and temporal linkage of tropical paleoclimate to paleoclimatic events and processes of other regions (i.e., Laurentide meltwater events and the Younger Dryas cold event of the North Atlantic basin). In particular, these records of regional paleoceanographic variation should provide high-resolution documentation of late Quaternary variability in trade-wind intensity and position of the intertropical convergence zone (ITCZ).

Recent studies have documented considerable variability in climatic and paleoceanographic records of glacial stages. Bond et al. (1993) identified a succession of SST oscillations in the North

Atlantic during the last glaciation.These cycles culminated in very cold events marked by layers of ice-rafted debris and carbonate-barren zones (Heinrich layers) that can be correlated over much of the North Atlantic. The SST changes and shedding of Laurentide ice into the Atlantic are correlated with high-frequency climate oscillations in Greenland ice cores (Bond et al., 1993), Antarctic ice cores (Dansgaard et al., 1993), Florida pollen records (Grim, 1993), and glacial advances in Chile (Lehman, 1993). It has been suggested that the Heinrich events resulted from catastrophic collapse of the Laurentide ice sheet (Lehman, 1993), and in turn, caused cessation of deep water (lower NADW) formation in the North Atlantic (Bond et al., 1993; Keigwin and Lehman, 1994). If this occurred, the change in deep-water formation should have affected deep-water chemistry of the Caribbean. For example, rates of formation of North Atlantic Intermediate water may have increased, thereby reducing penetration of the deep Caribbean by corrosive Antarctic Intermediate Bottom Water. Hence, the distal consequences of this and other "Heinrich event hypotheses" can be tested by examination of high-resolution records from the Cariaco Basin and other Caribbean sites with relatively high accumulation rates (> 6 cm/k.y.).

<u>Relationships between Environmental Change and Sedimentary and Geochemical Properties in Modern and Cretaceous Anoxic Basins</u>

Drilling of annually-laminated Cariaco Basin sediments will also allow documentation of relationships between environmental change and sedimentary and geochemical properties in modern large anoxic basins. This basin may provide a reasonable analogue for the older anoxic basins of the Caribbean Plate. For example, middle and Late Cretaceous black shales are known from south Central American marine sedimentary sequences (i.e., Tribovillard et al., 1991). Deposition of these black shales is likely to have been largely controlled by Caribbean tectonics. During the Cretaceous and Paleogene, this region was marked by a large "Cretaceous basalt province" and island arc complexes that were at least locally subaerially exposed (Escalante, 1990; Lundberg, 1991). As likely barriers to regional deep-water flow and possible causes of extensive Cretaceous upwelling in this region, they undoubtedly affected regional paleoceanographic conditions. At present, our understanding of both the arc complexes and the black shales is derived primarily from land-based Central American outcrops. Hence, Cretaceous causes of Caribbean black shale deposition presently remain enigmatic due to the complex regional tectonic history, post-depositional diagenesis of land-based outcrops, our incomplete understanding of relationships between oceanographic conditions and the sedimentary and geochemistry of Recent anoxic basins (i.e., the Cariaco Basin), and the need for offshore records to test possible relationships between regional Cretaceous paleogeography, black shale deposition, and paleoceanographic conditions (including paleo-upwelling and paleo-productivity).

PROPOSED SITES

Primary Sites

Proposed site S-2a is in a critical geographic location, both with respect to studies of the K/T boundary impact event and the Caribbean Current. It is relatively proximal to the Yucatan Peninsula and downstream of the Nicaragua Rise. Proposed site S-2a is the primary site most proximal to the K/T impact crater. Since the Caribbean Current is a primary source of the Gulf Stream, documentation of its initiation and downstream history will critically constrain our understanding of oceanic heat transport and paleoclimate of the late Neogene and Quaternary. The site will be used to reconstruct temperature and salinity of the mixed layer, intermediate, and deep water of the Yucatan Basin prior to founding of the mega-bank on the NNR. In addition, the variations in intermediate water in the Cayman Trough will be examined using carbon and oxygen isotope records.

Proposed site S-3 represents a return to DSDP Site 152. Previous drilling of Site 152 documented that there is a strong probability of recovering a relatively complete K/T boundary (the earliest Paleocene of Site 152 contains the *P. eugubina* Zone and is complete on about a 100 k.y. time scale) and very good Paleocene carbonate preservation and generally good Late Cretaceous carbonate preservation (rendering the Cretaceous and Paleogene sediments suitable for isotopic study). A stratigraphically well-constrained site is critical for reconstructing Late Cretaceous equatorial sea-surface properties and thereby constraining models of Late Cretaceous greenhouse climate.

Proposed site S-6 is positioned along UTIG MCS line CT1-12. Bowland (1984) has proposed a series of seismic stratigraphic units based on studies of the western Colombia Basin and correlation with reflectors A" and B" in other parts of the Caribbean. Of particular interest is unit CB5 which directly overlies basement in this area. It is believed to be Upper Cretaceous pelagic carbonates and clays deposited in an open marine environment. The total thickness of the sequence is about 350 m. Overlying this deposit are seismic units CB4 and CB1.

Nearby piston core V19-19 had late Pleistocene accumulation rates of 5 cm/k.y. (allowing for relatively high resolution Pleistocene studies). If these sedimentation rates hold throughout the Pleistocene, this site could provide an important Caribbean counterpart to the equatorial Pleistocene records of Eastern Pacific Leg 138 and Atlantic Leg 154. This site is located on top of an un-named rise northeast of Mono Rise in order to avoid turbidite deposition as much as possible.

Proposed site S-7 represents a return to DSDP Site 146. Despite poor recovery, the earliest Paleocene at Site 146 appears to be complete on an approximately 100 k.y. scale (since it contains the *P. eugubina* Zone). Hence, there is a strong probability of recovering a relatively complete K/T boundary. The upper Cretaceous record at Site 146 exhibits what appears to be strong Milankovitch variation in magnetic susceptibility and carbonate content (S. D'Hondt and J. King, unpubl.). This could provide critical information on the Milankovitch-scale sensitivity of Late Cretaceous climate to low-latitude ocean-climate processes. Burial depth of the Neogene and upper Paleogene sediments is potentially low enough to allow isotopic analysis of those intervals. Carbonate dissolution is strong and planktonic foraminiferal faunas impoverished throughout most of the Late Cretaceous and Cenozoic record of Site 146 (probably due to paleodepth well below the lysocline).

At proposed site CB-1, high sediment accumulation rates and low bioturbation will permit interannual and millennial resolution of the low-latitude late Quaternary record.

Proposed site NR-1/2 is located toward the southwest of Pedro Channel. Based on seismic stratigraphy and the 420-k.y. record of piston-core CH9204-PC42 (10.9 m), this site should provide a continuous upper Neogene periplatform record.

Comparisons between proposed sites NR-1/2 and NR-4 are essential in order to estimate the possible diachronous formation of Pedro Channel and Walton Basin through partial drowning of the mega-bank, in addition to the differences and similarities in the history of the Caribbean Current between both basins. Otherwise, its late Neogene and Quaternary paleoceanographic utility should be similar to that of proposed site NR-1.

Alternate Sites

Some of the sites listed below are either suitable alternates for some of the primary sites or sites of secondary interest.

Proposed site S-1 (a possible alternate for proposed site S-2a) is located on an extension of the Yucatan platform and post-impact plate movements may not have significantly changed its position relative to the proposed impact site.

Proposed site B-1 (a secondary site and possible alternate for proposed site S-7 [DSDP Site 146]), provides a good possibility of recovering a complete K/T boundary sequence since seismic horizons A" and B" appear to be present. The site is a few hundred kilometers west of proposed site S-7 and would recover a less distal K/T impact deposit. Seawater depth at proposed site B-1 is 935 m shallower than at Site 146 and is therefore probably much less affected by carbonate dissolution. Burial depth of the Neogene and upper Paleogene sediments is probably low enough to allow isotopic analysis of those intervals.

Proposed site S-3a is a possible alternate for proposed site S-3 (DSDP Site 152) and proposed site B-1. The Paleogene and Cretaceous section not as well constrained as at proposed site S-3 (the stage-level stratigraphy of proposed site S-3a is unknown). Seawater depth is 700 m shallower than at Site 152. Seismic horizons A" and B" appear to be present.

At proposed site S-5/NR-8 (a possible alternate to proposed site S-6), Cretaceous and Paleogene sediments are probably too deeply buried for isotopic study. This site would provide a record of Caribbean intermediate waters at 2000 m present depth. It is part of an up-current depth transect relative to the Nicaraguan Rise and thus is integral to the objectives listed for the proposed site S-6. The primary sites are all either less than 1250 m present depth or greater than 2750 m present depth.

Proposed site NR-9 (a secondary site) would provide a periplatform record of metastable carbonate preservation (generally restricted to waters shallower than 2000 m in the Caribbean). It is slightly upstream of the Caribbean Current relative to proposed sites NR-1/2 and NR-4.

REFERENCES

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., 1980. Extraterrestrial cause for the Cretaceous/ Tertiary extinction. *Science*, 208:1095-1108.

Alvarez, W., Arthur, M.A., Fischer, A.G., Lowrie, W., Napoleone, G., Premoli Silva, I., and Roggenthen, W.M., 1977. Type section for the Late Cretaceous-Paleocene geomagnetic reversal time scale. *Geol. Soc. Am. Bull.*, 88:367-389.

Alvarez, W., Smit, J., Asaro, F., Lowrie, W., Kastner, M., and Margolis, S., 1991. Proximal impact deposits at the Cretaceous-Tertiary boundary in the Gulf of Mexico: reinterpreting DSDP Sites 536 and 540. *Geol. Soc. Am. Abstr.*, A420.

Austin, J.A., Schlager, W., Palmer, A.A., et al., 1986. *Proc. ODP, Init. Repts.*, 101: College Station, TX (Ocean Drilling Program).

Axelrod, D.O., 1984. An interpretation of Cretaceous and Tertiary biota in polar regions. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 45:105-107.

Bainbridge, A., 1981. GEOSECS Atlantic Expedition, Hydrographic Data, 1: Washington, D.C. (U.S. Government).

Barker, P.F., and Kennett, J.P., et al., 1988. *Proc. ODP, Init. Repts.*, 113: College Station, TX (Ocean Drilling Program).

Barker, P.F., and Kennett, J.P., et al., 1990. *Proc. ODP, Sci. Results*, 113: College Station, TX (Ocean Drilling Program).

Barrera, E., Huber, B.T., Savin, S.M., and Webb, P.N., 1987. Antarctic marine temperatures; late Campanian through early Paleocene. *Paleoceanography*, 2(1):21-47.

Barrera, E., and Huber, B.T., 1990. Evolution of Antarctic waters during the Maastrichtian; foraminifer oxygen and carbon isotope rations, Leg 113. *In* Barker, P.F., Kennett, J.P., at al., *Proc. ODP, Sci. Results*, 113: College Station, TX (Ocean Drilling Program), 813-827.

Barron, E.J., 1987. Eocene equator-to-pole surface ocean temperatures: a significant climate problem? *Paleoceanography*, 2(6):729-740.

Barron, E.J., Arthur, M.A., and Kauffman, E.G., 1985. Cretaceous rhythmic bedding sequences; a plausible link between orbital variations and climate. *Earth Planet. Sci. Letters*, 72:327-340.

Boersma, A., and Shackleton, N.J., 1981. Oxygen-and carbon-isotope variations and planktonic-foraminifer depth habitats, Late Cretaceous to Paleocene, Central Pacific, Deep Sea Drilling Project Sites 463 and 465. *In* Thiede, J., Vallier, T.L., et al., *Init. Repts. DSDP*, 62: Washington (U.S. Govt. Printing Office), 513-526.

Bond, G.C., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J., and Bonani, G., 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature*, 365:143-147.

Borella, P.E., 1984. Sedimentology, petrology, and cyclic sedimentation patterns, Walvis Ridge transect, Leg 74, Deep Sea Drilling Project. *In* Moore, T.C., Jr., Rabinowitz, P.D.,et al., *Init. Reports DSDP*, 74: Washington (U.S. Govt. Printing Office), 645-662.

Bowland, C.L., 1984. Seismic stratigraphy and structure of the western Colombian Basin, Caribbean Sea [M.S. thesis]. University of Texas, Austin, TX.

Boyle, E.A., and Keigwin, L.D., 1987. Deep circulation of the North Atlantic over the last 200,000 years, geochemical evidence. *Science*, 218:784-787.

Brass, G.W., Southam J.R., and Peterson, W.H. 1982. Warm saline bottom water in the ancient ocean. *Nature*, 296:620-623.

Brunner, C.A., 1983. Evidence for increased volume transport of the Florida Current in the Pliocene and Pleistocene. *Mar. Geol.*, 54:223-235.

Chaussidon, M., and Sigurdsson, H., 1994. Sulfur isotope study of high-Ca impact glasses from the K/T boundary. *New developments regarding the K/T Event and other catastrophes in Earth history.* LPI Contribution, 825:21-22 [Abstract].

Cintala, M.J., and Grieve, R.A.F., 1991. Differential scaling of cratering phenomena. *22nd Ann. Lun. and Planet. Sci. Conf. Abstr.*, 213-214.

Coates, A.G., Jackson, J.B.C., Collins, L.S., Cronin, T.M., Dowsett, H.J., Bybell, L.M., Jung, P., and Obando, J.A., 1992. Closure of the Isthmus of Panama: the near-shore marine record of Costa Rica and western Panama. *Geol. Soc. Am. Bull.*, 104:841-828.

Cofer-Shabica, N.B., and Peterson, L.C., 1986. Carbon isotope evidence from an O_2-rich glacial deep water in the eastern Caribbean Sea. *Geol Soc. Am. Abstr. Progr. 99th Annu. Mtg.*, 18:567 (Abstract).

Corliss, B.H., Aubry, M.-P., Berggren, W.A., Fenner, J.M., Keigwin, L.D., Jr., and Keller, G., 1984. The Eocene/Oligocene boundary event in the Deep Sea. *Science*, 226:806-810.

Crowley, T.J., and North, G.R., 1991. *Paleoclimatology*: New York (Oxford University Press).

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl, J.D., Gundestrup, N.S., Hammer, C.U., Hvidberg, C.S., Steffensen, J.P., Sveinbjornsdottir, A.E., Jouzel, J., and Bond, G., 1993. Evidence for general instability of past climate from a 250-kyr ice-core record. *Nature*, 364:218-220.

Dawson, M.R., West, R.M., Langston, W., Jr., and Hutchinson, J.H., 1976. Paleogene terrestrial vertebrates: northernmost occurrence, Ellesmere Island, Canada. *Science*, 192:781-782.

de Menocal, P.B., Oppo, D.W., Fairbanks, R.G., and Prell, W.L., 1992. Pleistocene $\delta^{13}C$ variability of North Atlantic Intermediate Water. *Paleoceanography*, 7:229-250.

Denny, W.M., 1992. Seismic stratigraphy and geologic history of mid-Cretaceous through Cenozoic rocks, southern Straits of Florida [M.S. thesis]. University of Texas at Austin, Austin, TX.

Denny, W.M., Austin, J.A., and Buffler, R.T., in press. Seismic stratigraphy and geologic history of mid-Cretaceous through Cenozoic rocks, Southern Straits of Florida. *AAPG Bull.*

Donnelly, T.W., and Chao, E.C.T., 1973. Microtektites of late Eocene age from the eastern Caribbean Sea. *In* Edgar, N.T, Saunders, J.B., et al., *Init. Repts. DSDP*, 15: Washington (U.S. Govt. Printing Office), 607-672.

Droxler, A., Hine, A.C., Hallock, P., Buffler, R., Rosencrantz, E., and Mascle, A., 1991. Northern Nicaragua Rise drilling proposal: testing two new interpretations. ODP Proposal #408.

Ericson, D.B., and Wollin, G., 1956. Correlation of six cores from the equatorial Atlantic and the Caribbean. *Deep-Sea Res.*, 3:104-125.

Escalante, G., 1990. The geology of southern Central America and western Colombia. *In* Dengo, G., and Case, J.E. (eds.) *The Geology of North America* (Vol. H)*: The Caribbean region:* Geol. Soc. Am., 201-230.

Espindola, J.M., Carey, S., and Sigurdsson, H., submitted. Modelling of the dispersal of ejecta from the Cretaceous-Tertiary impact event. *J. Geophys. Res.*

Fierstein, J., and Nathanson, M., 1992. Another look at the calculation of fallout tephra volumes. *Bull. Volcanol.*, 54:56-167.

Glancey, T.J., Barron, E.J., and Arthur, M.A., 1986. An initial study of the sensitivity of modeled Cretaceous climate to cyclical insolation forcing. *Paleoceanography*, 1:523-537.

Glass, B.P., and Zwart, M.J., 1977. North American microtektites, radiolarian extinctions, and the age of the Eocene/Oligocene boundary. *In* Swain, F.M. (ed.) *Stratigraphic micropaleontology of Atlantic basins and borderlands*: Amsterdam (Elsevier), 553-568.

Gomberg, D., 1974. Geology of the Portales Terrace. *Florida Science*, 37 (Supplement 1):15.

Gordon, A.L., Ray, F.W., Smethie, W.M., Jr., and Warner, M.J., 1992. Thermocline and intermediate water communication between the South Atlantic and Indian oceans. *J. Geophys. Res.*, 97:7223-7240.

Grim, E.C., 1993. The Quaternary fossil-pollen record and global change. *Geol. Soc. Am. Abstr. Progr.*, 25:23 (Abstract).

Haddad, G. A., 1994. Calcium carbonate dissolution patterns at intermediate water depths of the tropical oceans [Ph.D. dissert.]. Rice Univ., Houston, TX.

Haq, B., Premoli Silva, I., and Lohmann, G.P., 1977. Calcareous plankton biogeographic evidence for major climatic fluctuations in the early cenozoic Atlantic ocean. *J. Geophys. Res.*, 82:3861-3876.

Herbert, T.D., and D'Hondt, S.L., 1990. Precessional climate cyclicity in Late Cretaceous-early Tertiary marine sediments: a high resolution chronometer of Cretaceous-Tertiary boundary events. *Earth Planet. Sci. Lett.*, 99 (3):263-275.

Hildebrand, A.R., Asaro, F., Attrep, M., et al., 1994. The Chicxulub crater and its relation to the K/T boundary ejecta and impact-wave deposits. *New developments regarding the K/T Event and other catastrophes in Earth history.* LPI Contribution, 825:49-50 (Abstract).

Hildebrand, A.R., and Boynton, W.V., 1990. Proximal Cretaceous-Tertiary boundary impact deposits in the Caribbean. *Science*, 248:843-847.

Hildebrand, A.R., Kring, D.A., Biynton, W.V., Penfield, G.T., and Pilkington, M., 1990. Cretaceous/Tertiary boundary impact site(s) between the Americas. *Geol Soc. Am. Abstr. Progr. 1990 Annu. Mtg.*, 22:280 (Abstract).

Hildebrand, A., Penfield, G.T., Kring, D.A.M., Pilkington, A., Camargo Z., Jacobsen, S.B., and Boynton, W.V., 1991. Chicxulub crater: a possible Cretaceous/ Tertiary boundary impact crater on the Yucatan peninsula, Mexico. *Geology*, 19:867-871.

Hildebrand, A.R., and Stansberry, J.A., 1992. K/T boundary ejecta distribution predicts size and location of Chicxulub crater. *23rd Ann. Lun. and Planet. Sci. Conf. Abstr.*, 537-538.

Huang, Z., Boyd, R., and O'Connell, S., 1992. Upper Cretaceous Cyclic sediments from Hole 762C, Exmouth Plateau, Northwest Australia. *In* von Rad, U., Haq, B.U., et al., *Proc. ODP, Sci. Results*, 122: College Station, TX (Ocean Drilling Program), 259-277.

Imbrie, J., Van Donk, J., and Kipp, N.G., 1973. Paleoclimatic investigation of a late Pleistocene Caribbean Deep-sea core: comparison of isotopic and faunal methods. *Quat. Res.*, 3:10-38.

Izett, G.A., 1991. K/T boundary tektites from near Beloc, Haiti. *22nd Ann. Lun. and Planet. Sci. Conf. Abstr.*, 625-626.

Johnson, R.G., 1982. Brunhes-Matuyama reversal dated at 790,000 yr b.p. by marine-astronomical correlations. *Quat. Res.*, 17:135-147.

Jones, G.A., in press. Timing of the Holocene repopulation of the Atlantic Ocean by *G. menardii* and *G.tumida* and implications for surface watermass paleoceanography. *Deep-Sea Res.*

Keigwin, L.D., Jr., 1978. Pliocene closing of the Isthmus of Panama, based on biostratigraphic evidence from nearby Pacific Ocean and Caribbean Sea cores: *Geology*, 6:630-634.

Keigwin, L.D., Jr., 1980. Paleoceanographic changes in the Pacific at the Eocene-Oligocene boundary. *Nature,* 287:722-725.

Keigwin, L.D., Jr., 1982. Isotopic paleoceanography of the Caribbean and east Pacific: role of Panama uplift in late Neogene time. *Science*, 217:350-353.

Keigwin, L.D., Jr., and Corliss, B.H., 1986. Stable isotopes in late middle Eocene to Oligocene foraminifera. *Geol. Soc. Am. Bull.*, 97:335-345.

Keigwin, L.D., and Lehman, S.J., 1994. Deep circulation linked to Heinrich Event 1 and Younger Dryas in a mid-depth North Atlantic core. *Paleoceanography*, 9:185-194.

Keller, G., and Barron, J.A., 1983. Paleoceanographic implications of Miocene deep sea hiastuses. *Geol Soc. Am. Abstr. Progr. 96th Annu. Mtg.*, 15:609 (Abstract).

Keller, G., D'Hondt, S.L., Gilmore, J.S., Oliver, P.Q., Orth, C.J., Shoemaker, E.M., and Molina, E., 1987. Late Eocene impact microspherules: stratigraphy, age and geochemistry. *Meteoritics*, 22 (1):25-60.

Keller, G., Zenker, C.E., and Stone, S.M., 1989. Late Neogene history of the Pacific-Caribbean gateway. *J. South Am. Earth Sci.*, 2:73-108.

Kennett, J.P., 1977. Cenozoic evolution of Antarctic glaciation, the circum-Antarctic ocean, and their impact on global paleoceanography. *J. Geophys. Res.*, 82:3843-3860.

Kennett, J.P., and Stott, L.D., 1991. Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene. *Nature*, 353:225-229.

Koeberl, C., and Sigurdsson, H., 1992. Geochemistry of impact glasses from the K/T boundary in Haiti: relation to smectites, and a new type of glass. *Geochim. Cosmochim. Acta*, 56:2113-2129.

Lehman, S.J., 1993. Climate change; ice sheets, wayward winds and sea change. *Nature*, 365:108-110.

Lopez Ramos, E., 1981. *Geologia de Mexico, Tomo III.* (2nd ed.):Mexico City (Univ. Nac. Auton. Mex.).

Lundberg, N., 1991. Detrital record of the early Central American magmatic arc: Petrography of intraoceanic forearc sandstones, Nicoya Peninsula, Costa Rica. *Geol. Soc. Am. Bull.*, 103:905-918.

Margolis, S., Claeys, P., Alvarez, W., Montanari, A., Swinburne, N, Smit, J., and Hildebrand, A., 1991. Tektite glass from the Cretaceous-Tertiary boundary, proximal to the proposed impact crater in northern Yucatan, Mexico. *Geol. Soc. Am. Abstr.*, A421.

Maurasse, F., 1973. Sedimentary structures of Caribbean Leg 15 sediments. *In Edgar*, N.T., Saunders, J.B., et al., *Init. Reports DSDP*, 15: Washington (U.S. Govt. Printing Office), 833-846.

Miller, K.G., Berggren, W.A., Zhang, J., and Palmer-Julson, A.R., 1991. Biostratigraphy and isotope stratigraphy of upper Eocene microtektites at Site 612: How many impacts? *Palaios*, 6:17-38.

Miller, K.G., Janecek, T.R., Katz, M.E., and Keil, D.J., 1987. Abyssal circulation and benthic foraminiferal changes near the Paleocene/Eocene boundary. *Paleoceanography*, 2(6): 741-761.

Monechi, S., and Thierstein, H.R., 1985. Late Cretaceous-Eocene nannofossil and magnetostratigraphic correlations near Gubbio, Italy. *Mar. Micropaleontol.*, 9:419-440.

Mullins, H.T., and Neumann, A.C., 1979. Geology of the Miami Terrace and its paleoceanographic implications. *Mar. Geol.*, 30:205-232.

Mullins, H. T., Neumann, A.C., Wilber, R.J., Hine, A.C., and Chinburg, S.J., 1980. Carbonate sediment drifts in the northern Straits of Florida. *AAPG Bull.*, 64:1701-1717.

Oglesby, R., and Park, J., 1989. The effect of precessional insolation changes on Cretaceous climate and cyclic sedimentation. *J. Geophys. Res.*, 94:14,793-14,816.

O'Keefe, J.D., and Ahrens, T.J., 1989. Impact production of CO_2 by the Cretaceous/Tertiary extinction bolide and the resultant heating of the Earth. *Nature*, 338:247-249.

Oppo, D.W., and Lehman, S.J., 1993. Mid-depth circulation of the subpolar North Atlantic during the last glacial maximum. *Science*, 259:1148-1152.

Oskarsson, N., Steinberg, M., Pradel, P., Helgason, O., Sigurdsson, H., and D'Hondt, S., 1991. Oxygen isotope variation, Mossbauer spectra or iron oxidation and volatile content of tektite glasses from the Cretaceous-Tertiary boundary, Haiti. *22nd Ann. Lun. and Planet. Sci. Conf. Abstr.*, 1009.

Park, J., and Oglesby, R.J., 1991. Milankovitch rhythms in the Cretaceous; a GCM modelling study. *Global Planet. Change*, 4:329-355.

Park, J., D'Hondt, S.L., King, J.W., and Gibson, C., 1993. Late Cretaceous precessional cycles in double time; a warm-Earth Milankovitch response. *Science*, 261:1431-1434.

Pindell, J., Cande, S., Pitman, W., Rowley, D., Dewey, J., Labrecque, J., and Haxby, W., 1988. A plate-kinematic framework for models of Caribbean evolution. *Tectonophysics*, 155:21-138.

Pollack, J.B., Toon, O.B., Ackerman, T.P., McKay, C.P., and Turco, R.P., 1983. Environmental effects of an impact-generated dust cloud: Implications for the Cretaceous-Tertiary extinctions. *Science*, 219:287-289.

Pope, K.O., Ocampo, A.C., and Duller, C.E., 1991. Mexican site for K/T impact crater? *Nature*, 351:105.

Popenoe, P., 1985. Cenozoic depositional and structural history of the North Carolina margin from seismic stratigraphic analyses. In Poag, C.W. (ed.) *Geologic evolution of the United States Atlantic margin*: New York (Van Nostrand Reinhold), 125-187.

Raymo, M.E., Rudiman, W.F., Backman, J., Clement, B.M., and Martinson, D.G., 1989. Late Pliocene variation in Northern Hemisphere ice sheets and North Atlantic deep water circulation. *Paleoceanography*, 4/4:413-446.

Raymo, M.E., Ruddiman, W.F., Shackleton, N.J., and Oppo, D.W., 1990. Evolution of Atlantic-Pacific $\delta^{13}C$ gradients over the last 25 m.y. *Earth Planet. Sci. Letters*, 97:353-368.

Rea, D.K., Zachos, J.C., Owen, R.M., and Gingerich, P.D., 1990. Global change at the Paleocene/Eocene boundary: climatic consequences of tectonic events. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 79:117-128.

Rind, D., and Chandler, M., 1991. Increased ocean heat transports and warmer climate. *J. Geophys. Res.*, 96 (D4):7437-7461.

Roddy, D.J., Schmitt, R.A., and Shuster, S.H., 1991. Asteroid and comet impacts on continental and oceanic sites. *22nd Ann. Lun. and Planet. Sci. Conf. Abstr.*, 1129-1130.

Saito, T., 1976. Geologic significance of coiling direction in the planktonic foraminifera *Pulleniatina*. *Geology*, 4:305-309.

Saltzman, E.S., and Barron, E.J., 1982. Deep circulation in the Late Cretaceous; oxygen isotope paleotemperatures from *Inoceramus* remains in DSDP cores. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 40:167-181.

Saunders, J.B., et al., 1984. Stratigraphy of the late middle Eocene to early Oligocene in the Bath Cliff section, Barbados, West Indies. *Micropaleontology,* 30(4):390-425.

Savin, S.H., 1977. The history of the earth's temperature during the past 100 million years. *Annu. Rev. Earth Planet. Sci.*, 5:319-355.

Sen, G., Hickey-Vargas, R., Waggoner, D.G., and Maurasse, F., 1988. Geochemistry of basalts from the Dumisseau Formation, southern Haiti; implications for the origin of the Caribbean Sea crust. *Earth Planet. Sci. Letters*, 87:423-437.

Schultz, P.H., 1994. Visualizing the nature and consequences of the Chicxulub impactor: clues from Venus. *New developments regarding the K/T Event and other catastrophes in Earth history.* LPI Contribution, 825:104-106 [Abstract].

Shackleton, N.J., Berger, A., and Peltier, W. R., 1990. An alternative astronomical calibration of the lower Pleistocene time scale based on ODP Site 677. *Trans. R. Soc. Edinburgh*, 81:251-261.

Shackleton, N.J., Hall, M.A., and Boersma, A., 1984. Oxygen and carbon isotope data from Leg 74 foraminifers. *In* Moore, T.C., Jr., Rabinowitz, P.D.,et al., *Init. Repts. DSDP*, 74: Washington (U.S. Govt. Printing Office), 599-612.

Sharpton, V.L., Marin, L.E., and Schuarytz, B.C., 1994. The Chicxulub multiring impact basin: evaluation of geophysical data, well logs, and drill core samples. *New developments regarding the K/T Event and other catastrophes in Earth history.* LPI Contribution, 825:108-110 [Abstract].

Sheridan, R.E., Crosby, J.T., Bryan, G.M., and Stoffa, P.L., 1981. Stratigraphy and structure of southern Blake Plateau, northern Florida Straits and northern Bahama Platform from multichannel seismic reflection data. *AAPG Bull.*, 65:2571-2593.

Sigurdsson, H., D'Hondt, S., Arthur, M.A., Bralower, T.J., Zachos, J.C., Fossen, M., and Channell, J.E.T., 1991a. Glass from the Cretaceous-Tertiary Boundary in Haiti. *Nature*, 349:482-487.

Sigurdsson, H., Bonté, Ph., Turpin, L., Chaussidon, M., Metrich, N., Steinberg, M., Pradel, Ph., and D'Hondt, S., 1991b. Geochemical Constraints on Source Region of Cretaceous/Tertiary Impact Glasses. *Nature*, 353:839-842.

Slowey, N.C., and Curry, W.B., 1992. Enhanced ventilation of the North Atlantic subtropical gyre thermocline during the last glaciation. *Nature*, 358:665-668.

Smit, J., et al., 1994. Impact-tsunami-generated clastic beds at the K/T boundary of the Gulf coastal plain. *New developments regarding the K/T Event and other catastrophes in Earth history.* LPI Contribution, 825:117-119 [Abstract].

Stott, L.D., and Kennett, J.P., 1990. New constraints on early Tertiary paleoproductivity from carbon isotopes in foraminifera. *Nature*, 350:526-529.

Tribovillard, N.-P., Stehan, J.-F., Manivit, H., Reyre, Y., Cotillon, P., and Jautee, E., 1991. Cretaceous black shales of Venezuelan Andes: preliminary results on stratigraphy and paleoenvironmental interpretations. *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 81:313-321.

Wolfe, J.A., 1985. Distribution of major vegetational types during the Tertiary. *In* Sundquist, E.T., and Broecker, W.S. (eds.) *The carbon cycle and atmospheric* CO_2*: natural variations from the Archean to present.* Am. Geophys. Union Monogr., 32:357-376.

Zachos, J.C., Berggren, W.A., Aubry, M.-P, Mackensen, A., 1990. Isotope and trace element geochemistry of Eocene and Oligocene foraminifers from Site 748, Kerguelen Plateau. *In* Wise, S.W., Jr., Schlich, R., et al., *Proc. ODP, Sci. Results*: College Station, TX (Ocean Drilling Program), 120:839-854.

Zachos, J.C., Stott, L.D., Lohmann, K.C., 1994. Evolution of early Cenozoic marine temperatures. *Paleoceanography*, 9:353-387.

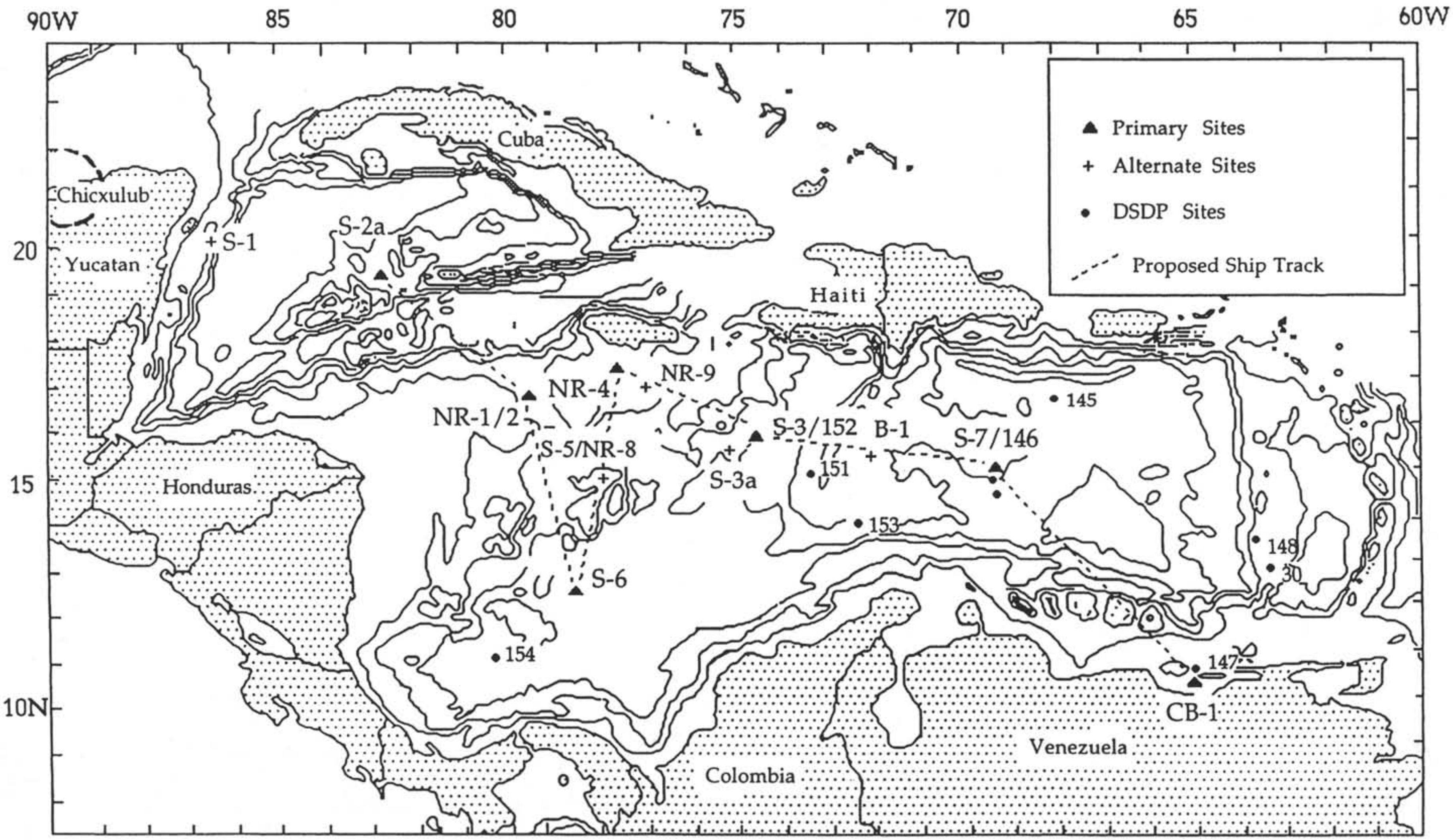
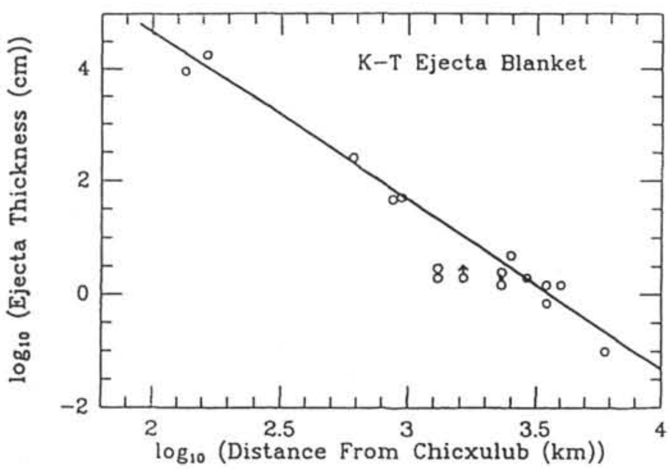


Figure 1. Proposed Caribbean site locations and ship track for Leg 165.



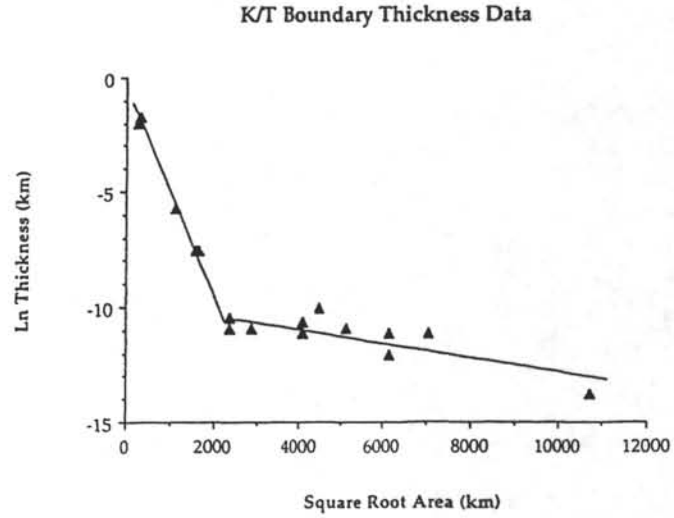


Figure 2a. The relationship between K/T boundary ejecta deposit thickness and distance from the Chicxulub impact crater source was interpreted by Hildebrand and Stansberry (1992) to follow a log/log distribution. As shown in Figure 2b, the thickness data is best fitted by a two-segment line.

Figure 2b. The known global thickness distribution of the K/T boundary ejecta deposit can be best fitted by two line segments, using the method generally applied to volcanic fallout (Fierstein and Nathenson, 1992). Thickness data from Hildebrand and Stansberry (1992) were plotted in the form of ln (thickness) versus square root of isopach area. An assumption was made that the thickness isopachs were circular in shape. The plot shows that the data fall on two linear segments. The fit to the near-source segment is r^2=0.970, and r^2=0.673 for the distal segment. The intersection of the two segments is at a distance of approximately 1400 km from the Chicxulub source.

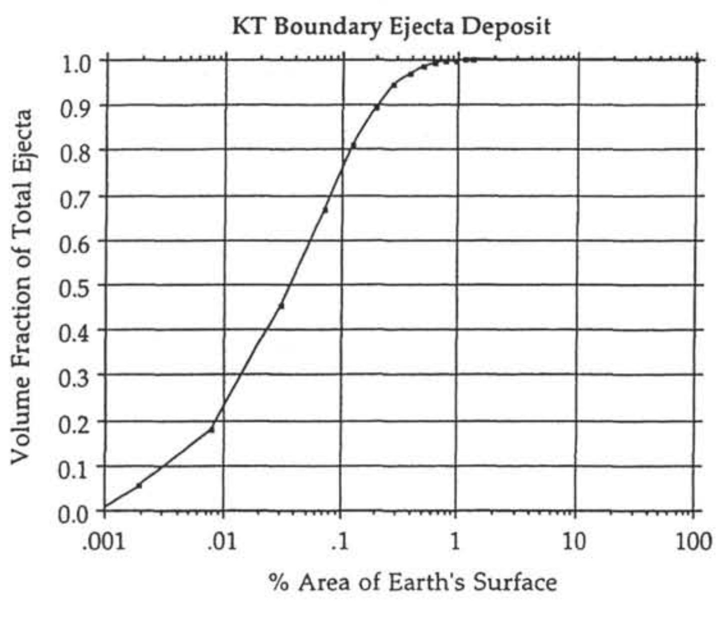


Figure 2c. Distribution of K/T boundary fallout ejecta on the Earth. This figure shows that the vast majority of the ejecta falls within the 1400 km radius of the source, or 8.3×10^{19}g on 1.2% of Earth's surface. The distal ejecta fallout on the remaining 98.8% of Earth's surface has a mass of 1.4×10^{18}g. The ejecta fallout loading of solid matter on most of the Earth's surface is thus about 0.27 g/cm^2 or much less than the value of 1 g/cm^2 atmospheric mass loading of rock "dust" assumed by Pollack et al. (1983) in their assessment of climatic effects of K/T boundary.

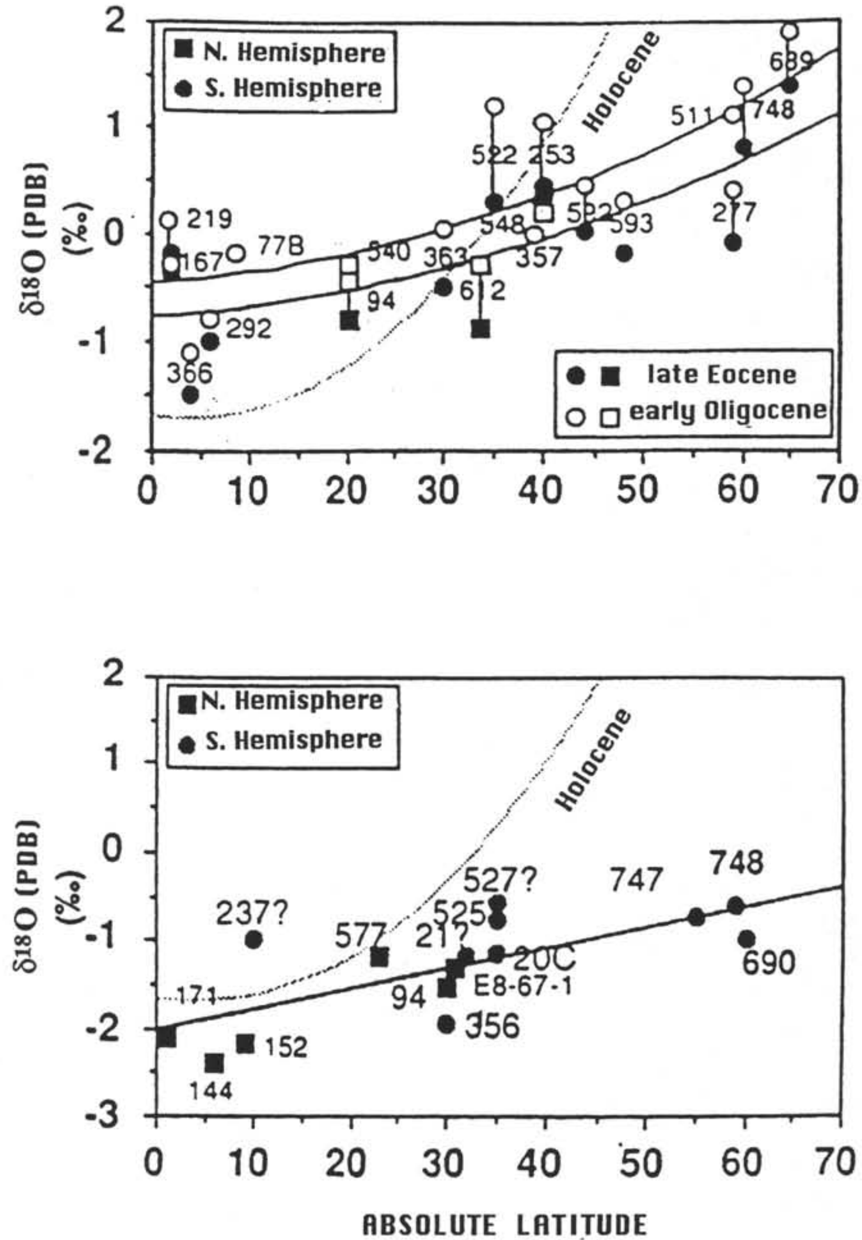


Figure 3. High to low latitude surface water δ18O gradients of (A) the late Eocene and early Oligocene, and (B) the early Eocene. Note the low apparent gradients in both Eocene and early Oligocene oceans (relative to Holocene gradients). Also note the relatively low values in late Eocene and early Oligocene low latitudes. With the exception of one early Eocene sample from poorly recovered Site 152 sediments, none of these data are from the Caribbean. Only two other samples between 0° and 30°N are from the greater Atlantic region, one in the early Oligocene and one in the late Eocene (both in the Gulf of Mexico at 20°N). Figures from Zachos et al. (1990).

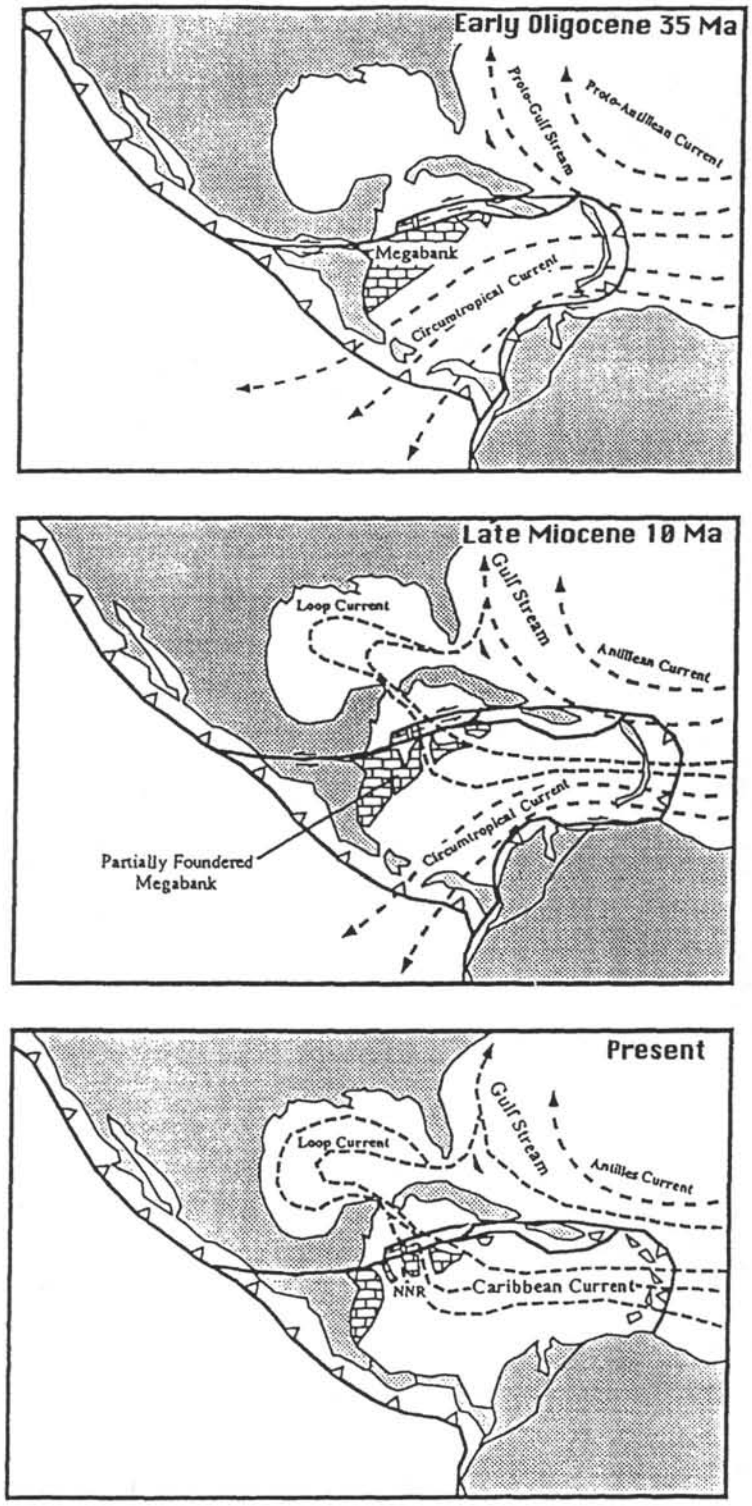


Figure 4. Simplified paleoreconstructions (after Pindell et al., 1988) of the Caribbean, showing the timing of proposed megabank foundering and the resultant current regimes from Oligocene to Holocene (based on model of Droxler et al. (1992)).

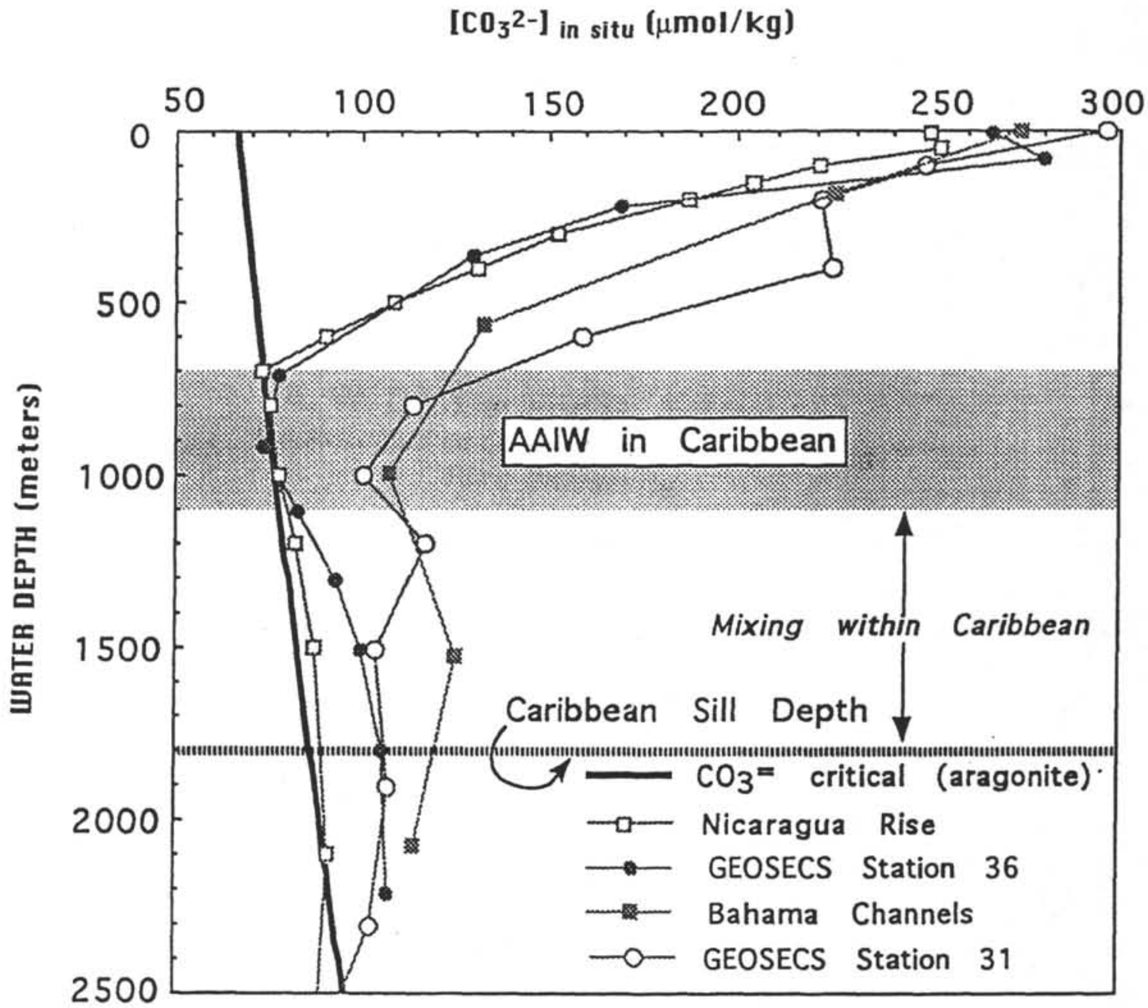


Figure 5. Profiles of in situ $[CO^{-2}_3]$ in µmol/kg as a function of water depth on the Nicaraguan Rise, Bahama Channels and GEOSECS stations 31 and 36.

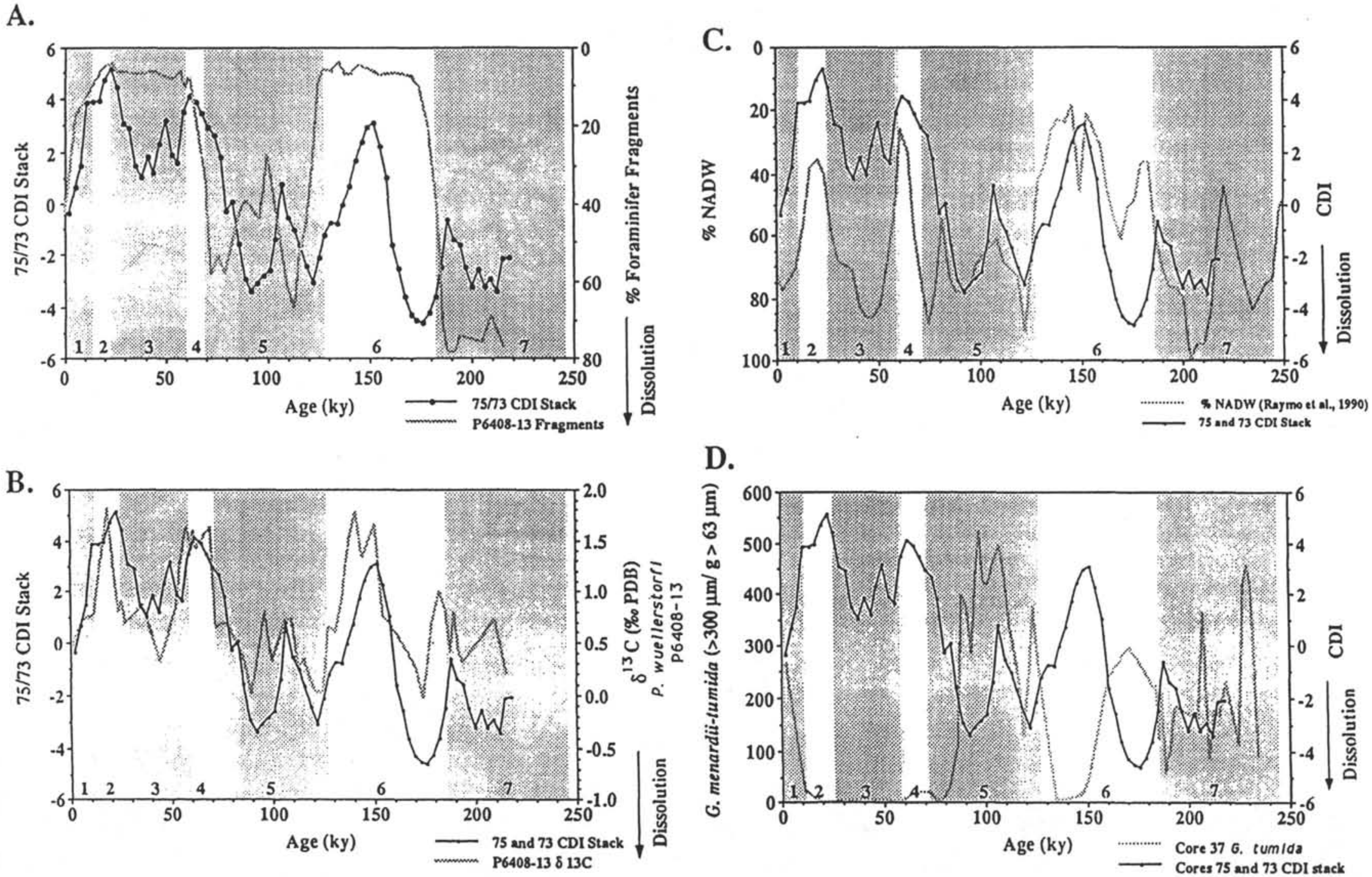


Figure 6. Metastable $CaCO_3$ composite dissolution index (CDI) for Nicaragua Rise cores CH8802-75 (1203 m) and CH8802-73 (1894 m) (Haddad, 1994) compared to (A) % foraminifer fragments and (B) benthic foraminifer $\delta^{13}C$ from the deep Venezuela Basin (Cofer-Shabica and Peterson, 1986). Similarities between these records, particularly between the CDI and $\delta^{13}C$ records, suggest that Caribbean carbon chemistry has been similar from the base of the thermocline to abyssal depths during the last 250 k.y. (C) shows good correlation between the shallow intermediate water CDI record and %NADW calculated by Raymo et al. (1990). High NADW formation corresponds to high AAIW flux into the North Atlantic and Caribbean and poor carbonate preservation. Low NADW formation corresponds to low AAIW flux into the Caribbean and good carbonate preservation. (D) This figure shows that reduced southern source upper water layer advection into the Caribbean during periods of good carbonate preservation is also suggested by the near inverse correlation between *G. menardii-tumida* abundance and the CDI.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: S-2a	**PRIORITY:** 1	**POSITION**: 19°30'N, 82°49.8'W
WATER DEPTH: 3150 m	**SEDIMENT THICKNESS**: 600 m	**TOTAL PENETRATION**: 610 m
SEISMIC COVERAGE: UTIG MCS line GT2-52E (approx.). Site will be located during upcoming surveys.		

Objectives: To investigate the processes of impact deposition at the K/T site proximal to the Chicxulub impact crater on the Yucatan Peninsula. To study Neogene paleoceanographic conditions that document the evolution of the Caribbean and the history of Atlantic intermediate waters in the Yucatan Basin.

Drilling Program: Double APC, XCB, and RCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic and hemipelagic carbonate sediments; basalt.

OR

SITE: S-1	**PRIORITY:** 2 & alternate to S-2a	**POSITION**: 20°19.8'N, 86°25.2'W
WATER DEPTH: 1200 m	**SEDIMENT THICKNESS**: 500 m	**TOTAL PENETRATION**: 510 m
SEISMIC COVERAGE: UTIG MCS line CT1-408, SP 7650.		

Objectives: To investigate the processes of impact deposition at the K/T site proximal to the Chicxulub impact crater on the Yucatan Peninsula. To study Neogene paleoceanographic conditions that document the evolution of the Caribbean and the history of Atlantic intermediate waters in the Yucatan Basin.

Drilling Program: Double APC, XCB, and RCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic and hemipelagic carbonate sediments; basalt.

SITE: S-3	**PRIORITY:** 1	**POSITION**: 15°52.8'N, 74°36.6'W
WATER DEPTH: 3899 m	**SEDIMENT THICKNESS**: 480 m	**TOTAL PENETRATION**: 490 m
SEISMIC COVERAGE: DSDP Site 152 survey data. Additional surveys scheduled.		

Objectives: To retrieve a high-resolution, deep-water K/T sequence, and Late Cretaceous/Paleogene sediments suitable for isotopic reconstruction of surface water temperatures. To establish high-resolution, low-latitude Cretaceous and Paleogene chronostratigraphy and to investigate low-latitude paleoceanographic changes from the Late Cretaceous to Recent. Alternate to proposed site B-1.

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

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic sediments; basalt.

OR

SITE: S-3a	**PRIORITY:** Alternate to S-3 & B-1	**POSITION**: 15°30'N, 75°12'W
WATER DEPTH: 3200 m	**SEDIMENT THICKNESS**: 500 m	**TOTAL PENETRATION**: 510 m
SEISMIC COVERAGE: CASIS MCS line C-01. Additional surveys scheduled.		

Objectives: To retrieve a high-resolution, deep-water K/T sequence, and Late Cretaceous/Paleogene sediments suitable for isotopic reconstruction of surface water temperatures. To establish high-resolution, low-latitude Cretaceous and Paleogene chronostratigraphy and to investigate low-latitude paleoceanographic changes from the Late Cretaceous to Recent. Alternate to proposed site B-1.

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

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic sediments; basalt.

SITE: S-6	**PRIORITY:** 1	**POSITION**: 12°45.6'N, 78°42'W
WATER DEPTH: 2750 m	**SEDIMENT THICKNESS**: 1300 m	**TOTAL PENETRATION**: 1310 m
SEISMIC COVERAGE: UTIG MCS line CT2-12A, SP 4720.		

Objectives: To retrieve a K/T sequence distal from the impact crater and on a different tangent from the impact site. To establish high-resolution, low-latitude Cretaceous chronostratigraphy and to retrieve Paleogene and Neogene sediments suitable for isotopic reconstruction of paleoceanographic events and conditions. To investigate the history of NAIW in the Columbia Basin.

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

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic drape (calcareous and siliceous ooze, clay, chalk, and chert); basalt. Seismic horizon B in Columbia Basin.

OR

SITE: S-5/NR-8	**PRIORITY:** Alternate to S-6	**POSITION**: 15°00'N, 77°37.2'W
WATER DEPTH: 2050 m	**SEDIMENT THICKNESS**: 1000 m	**TOTAL PENETRATION**: 1010 m
SEISMIC COVERAGE: MCS UTIG line CT1-28B, SP 4500.		

Objectives: To retrieve a K/T sequence distal from the impact crater and Neogene carbonates suitable for documenting the "upstream" history of the Caribbean Current.

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

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic carbonate sediments; basalt.

SITE: S-7	**PRIORITY:** 1	**POSITION**: 15°7.2'N, 69°22.8'W
WATER DEPTH: 3949 m	**SEDIMENT THICKNESS**: 762 m	**TOTAL PENETRATION**: 782 m
SEISMIC COVERAGE: DSDP Site 146 survey data. Additional surveys scheduled.		

Objectives: To retrieve a K/T sequence distal from the impact crater. To retrieve Cretaceous and Paleogene sediments suitable for isotopic reconstruction of paleoceanogrphic events and conditions and to document deep-water response to Neogene and Quaternary ocean-climate variation.

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

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic carbonate sediment; basalt. Seismic horizon B".

OR

SITE: B-1	**PRIORITY:** 2 & alternate to S-7	**POSITION**: 15°8.76'N, 72°4.98'W
WATER DEPTH: 3025 m	**SEDIMENT THICKNESS**: 725 m	**TOTAL PENETRATION**: 735 m
SEISMIC COVERAGE: MCS CASIS line B08, SP 2340..		

Objectives: To retrieve a high-resolution, deep-water K/T sequence, and Late Cretaceous/Paleogene sediments suitable for isotopic reconstruction of surface water temperatures. To establish high-resolution, low-latitude Cretaceous and Paleogene chronostratigraphy and to investigate low-latitude paleoceanographic changes from the Late Cretaceous to Recent.

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

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pelagic sediments (ooze, clay, chalk, limestone, chert); basalt. Seismic horizon B".

SITE: CB-1	**PRIORITY:** 1	**POSITION**: 10°39'N, 65°00'W
WATER DEPTH: 920 m	**SEDIMENT THICKNESS**: 1000 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: SCS PLUME Leg 07, *R/V Thomas Washington*, June 1990.		

Objectives: To conduct high-resolution late Quaternary paleoceanographic studies. To investigate upwelling and circulation history, records of fluvial discharge, anoxic variability and its relationship to climate, and the record of organic carbon deposition.

Drilling Program: Triple APC and RCB.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated: Hemipelagic sediments and calcareous silty clay.

SITE: NR-1/2	**PRIORITY**: 1	**POSITION**: 16°33.17'N, 79°51.96'W
WATER DEPTH: 910 m	**SEDIMENT THICKNESS**: 650 m	**TOTAL PENETRATION**: 650 m
SEISMIC COVERAGE: SCS line CH9204-30, SP 1495.		

Objectives: To establish the timing of formation of the Pedro Channel and Walton Basin and to document the history of the Caribbean Current across the Nicaragua Rise.

Drilling Program: Double APC, XCB, and RCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Periplatform ooze and carbonate mega-bank.

SITE: NR-4	**PRIORITY**: 1	**POSITION**: 10°22.83'N, 77°42.52'W
WATER DEPTH: 850 m	**SEDIMENT THICKNESS**: 450 m	**TOTAL PENETRATION**: 450 m
SEISMIC COVERAGE: SCS line CH0288-31, SP 755; crossing with CH0288-36 (approx.).		

Objectives: To establish the timing of formation of the Pedro Channel and Walton Basin and to document the history of the Caribbean Current across the Nicaragua Rise.

Drilling Program: Double APC, XCB, and RCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Periplatform ooze and carbonate mega-bank.

SITE: NR-9	**PRIORITY**: 2	**POSITION**: 17°2'N, 77°14'W
WATER DEPTH: 1200 m	**SEDIMENT THICKNESS**: 400 m	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: SCS line CH0288-42.		

Objectives: To determine the impact of the carbonate mega-bank drowning on development of the Caribbean Current. To assess the variations of intermediate waters at intermediate depths in the Cayman Trough.

Drilling Program: Double APC, XCB, and RCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Periplatform ooze.

LEG 166
The Bahamas Transect

LEG 166[1]

THE BAHAMAS TRANSECT

Modified from Proposals 412, 412-Add2, 412-Add3 Submitted By

Gregor P. Eberli, Donald F. McNeill, and Peter K. Swart

To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

Although sea-level fluctuations are known to have occurred throughout the earth's history, their global synchroneity, amplitude, and rate are still largely unknown. A better understanding of global changes in sea level is contingent upon coverage in a variety of tectonic and sedimentary settings, such as the deep sea, carbonate platforms and atolls, and continental margins.

Two bore holes drilled on the western Great Bahama Bank (GBB) as part of the Bahamas Drilling Project (BDP) represent the shallow sites of a transect through prograding carbonate sequences that were formed in response to sea-level fluctuations. During Leg 166, drilling at four deep-water sites in the Straits of Florida will address fundamental questions regarding sea-level and fluid-flow changes and at a deep hole to the top of the mid-Cretaceous unconformity will investigate oceanic circulation and climatic changes from the mid-Cretaceous to the present. The primary goal of the transect is to document the platform margin record of the Neogene-Recent sea-level changes by determining the ages of the major unconformities and to compare the timing of these unconformities with ages predicted from the oxygen isotope record of glacioeustasy. Core borings along the complete transect will document the facies variations associated with oscillations of sea level and, thus, the sedimentary response of the carbonate environment to sea-level changes. The correlation between the two independent records of sea-level changes, sequence stratigraphy and oxygen isotope proxy, has the potential to evaluate rate and amplitude of eustatic vs. relative sea-level changes, and to establish a causal link between glacioeustasy and the stratigraphic pattern. Leg 166 will also drill a number of short cores through the soft sediments on the upper slope to measure the composition of the recharged waters retained in the sediment for assessing rate and flow mechanisms through the bank. One of the distal sites of the transect will be deepened to the mid-Cretaceous unconformity to assess the cause of the platform demise in the middle Cretaceous, potentially sample the K/T boundary, acquire a low-latitude record of the Paleogene "Doubthouse" and its transition into the Neogene "Icehouse", and determine the onset of Florida Current.

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[1] May become Leg 165 if currents in the Santaren Channel are more favorable at this time.

INTRODUCTION

Analysis of material from the deep sea, carbonate platforms and atolls, and continental margins provides three independent ways to measure sea-level changes.

1) The deep sea sediments provide a proxy for glacioeustasy through variations in foraminiferal $\delta^{18}O$.

2) Aggradational packages separated by exposure horizons on atolls and platforms record variations in sea level like dipsticks.

3) Continental margin sediments preserve the changes of sea-level variations by means of unconformities and stratigraphic patterns within the sediments.

To completely understand changes in sea level, the drilling objectives of transects across the continental margins should address four major issues: 1) dating sea-level-related stratigraphic events; 2) establishing the stratigraphic response to sea-level oscillations; 3) estimating the magnitudes and rates of sea-level changes through time; and 4) understanding the mechanisms of sea-level change.

As a short term strategy, the SL-WG (Sea-Level Working Group) recommended to begin testing synchrony of stratigraphic events in the Neogene, where optimum age control and a calibrated signature of sea level are best constrained. Leg 150 was the first transect in this ODP drilling effort. Drilling the Neogene of the Bahamas is appropriate next step, because it offers a geographically close test of the ability to correlate stratigraphic events between two areas of contrasting sedimentary settings.

THE STUDY AREA

The Potential of the Bahamas Transect to Investigate Global Changes in Sea Level

A major requirement for this study are transects from marginal marine to deep basin environment and, as such, alternative platforms for near-shore sites are necessary. For the Bahamas Transect (Figure 1), these shallow drill sites are in hand. Two core borings drilled from a self-propelled workover barge through these sequences on the shallow top of GBB provide the record at the proximal parts of the sequences (Figure 2). A second requirement also met at the proposed drilling area is a large set of seismic lines to guarantee good stratigraphic resolution and optimal locations for drill sites.

Probably the most important advantage of the proposed Bahamas Transect is its potential to combine all three independent ways of measuring sea-level changes. The GBB is a flat-topped platform on a passive continental margin. Thus, its flat top records sea level as a dipstick, the prograding sequences record sea-level changes in their stratigraphic pattern, and the correlative deep-water deposits encode the $\delta^{18}O$ proxy of sea-level changes in their foraminiferal assemblages. The correlation of the oxygen isotope record with the sequence stratigraphic pattern would for the first time document a causal link between glacioeustasy and stratal pattern. This correlation would also provide insights in how high-frequency sea-level fluctuations are recorded in the sediments and how the stacking of these high-frequency cycles produce the lower order seismic sequences.

The transect is designed to document the facies variations related to sea-level oscillations from shallow water to a water depth of approximately 600 m. This range allows us to fully assess the sedimentary response of carbonates to sea-level changes. Thus, the sediments recovered during the BDP in combination with the proposed Leg 166 sites can be compared with the siliciclastic sequences of the New Jersey Sea Level (ODP Leg 150)/mid-Atlantic margin transect (NJ/MAT) and sequence stratigraphic models (Posamentier and Vail, 1988) to assess the difference in sedimentary response for siliciclastic and carbonate margins. Carbonate depositional sequences are, like their siliciclastic counterparts, unconformity-bounded depositional packages but they record changes of climate and relative change of sea level in their own characteristic way, resulting in a system-specific depositional sequence architecture (Sarg, 1988; Eberli and Ginsburg,1989; Schlager, 1991). For example, flat-topped carbonate platforms and shelves produce and export more sediment during sea-level highstands. This highstand-shedding puts the carbonate environment out of phase with the siliciclastic environment where most of the sediment is exported into deeper water during sea-level lowstands (Mullins, 1983; Droxler and Schlager, 1985; Schlager, 1991). The highstand shedding is most pronounced along steep-sided platforms such as, for example, the modern GBB. However, throughout most of the Neogene, the western margin of GBB had a ramp-like profile. Consequently, the Bahamas Transect offers the opportunity to document the response of the carbonate environment to sea-level changes at different margin profiles.

Timing of unconformities along prograding carbonate platform margins can be achieved by an integrated age-dating effort that includes the incorporation of planktic foraminiferal biostratigraphy, nannofossil biostratigraphy, strontium-isotope stratigraphy and magnetostratigraphy. In the proximal parts of the transect dating was not an easy undertaking, because pulses of platform-derived sediments diluted the microfossil abundance. Nevertheless, within our age resolution we were able to put age constraints on the sequence boundaries and to demonstrate that the seismic reflectors are synchronous. Based on the results from ODP Leg 101 along the slopes of Little Bahama Bank and in Exuma Sound, biostratigraphic dating is not a problem in the slope settings (Melillo, 1988). Thus, precise dating of the sequence boundaries can be expected in the deep-water sites of the Bahamas Transect.

The GBB has a relatively predictable subsidence history (Williams et al., 1988) and thus is suitable for an attempt to evaluate amplitude of sea-level changes. In addition, the light-dependent sediment production of the carbonate environment provides carbonate platforms with an accurate paleobathymetric indicator. Because carbonate production in low-latitudes is an order of magnitude higher than most sea-level changes, carbonate platforms and reefs are able to keep or catch up with sea-level rises and maintain a relatively flat platform top (Kendall and Schlager, 1981; Schlager, 1981). Sea-level falls usually expose the platform top which results in the development of a suite of characteristic features that are easily recognized in the rock record (e.g., karst, red soils, caliche horizons, black pebble horizons, etc.) or as diagenetic zones with a typical petrologic and stable isotope signal (e.g., Halley and Matthews, 1987). On the platform tops, sea-level highstands are recorded in the sediment between these exposure horizons. With the completion of the chronostratigraphy of the shallow drill sites Unda and Clino and of three other core borings from further in the platform (McNeill et al., 1988; McNeill, 1989), recalculation of the subsidence curve of the GBB is possible. Thus, a relatively accurate measurement of the amplitude of sea-level changes can be achieved.

In summary, the Bahamas Transect offers the opportunity to address several fundamental questions regarding sea-level changes and to begin to acquire the global data base needed for evaluating timing and amplitudes of these changes. The proposed transect will provide the sedimentary record of sea-level changes in a carbonate environment on a passive continental margin. In addition, the $\delta^{18}O$ proxy in the foraminiferal assemblages of the basinal deposits can be directly correlated to the sedimentary record of sea-level change.

Results of the Bahamas Drilling Project

BDP operations on the GBB aimed to address 1) the nature of progradation, facies, and the source of sediment, 2) the timing and the rate of progradation, 3) the role of sea level in controlling progradation and/or aggradation/backstepping (and how good of a sea-level signal do these progradational events represent); and 4) the cause of seismic reflectors in such a pure carbonate environment.

The Sedimentary Record

The two cores (Unda and Clino) of the BDP were positioned on the prograding western margin where high sedimentation rate yields a high chronostratigraphic resolution. Clino penetrated mostly inclined slope deposits, whereas Unda, the more proximal site, penetrated platform deposits and a buried platform margin. Continuous cores were made using a wire-line system with a triple tube core barrel 3.05 m (10 ft.) long that recovered cores of 6.3 cm (2.5 in.) in diameter. Core Clino was drilled 677.71 m (2222.0 ft.) below the mud pit datum (7.3 m, 24 ft. above sea level). Recovery in Clino averaged 80.8%. Core Unda was drilled 454.15 m (1489 ft.) below mud pit (5.2 m, 17 ft. above sea level). Recovery in Unda averaged 82.9%.

Detailed sedimentologic studies in two core borings revealed multiple, punctuated depositional sequences with different frequencies that are interpreted as the sedimentary record of relative sea-level changes (Figure 3). In the shallow portions, caliche crusts, karst, and black pebble conglomerates are taken as indicators of exposure horizons, while, in the slope section, changing sediment composition is correlated to fluctuations in sea level.

Unda consists of three successions of shallow-water platform sands and reefal deposits (108.1-8.6 m, 354.7-292.8 m, 453-443.5 m), making up ~40% of the core, that alternate with sand and silt-sized deeper marginal deposits (Figure 3). The upper two platform/reefal intervals show evidence of repeated episodes of shoaling and/or subaerial exposure. The intervals between the three platform/reefal units consist of fine-grained skeletal to mixed skeletal/nonskeletal silts and sands. The intervals are arranged in several successions that are interpreted as depositional sequences reflecting changes in relative sea level. Five of the coarsening-upward successions contain marine Fe/Mn-hardgrounds or condensed layers with concentrations of phosphate and/or reworked benthic foraminifera.

In Clino, a single unit of platform/reefal sediments overlying a thick succession of slope sediments was recovered (Figure 3). The shallow platform section (98.5-21.6 m) has at least seven parasequences, each of which is capped by a horizon of subaerial exposure. In the reefal unit (197.4-98.5 m), there is an upward progression from deep reef/fore slope to fore reef to reef crest and finally back reef. The nearly 480 m of slope sediments (676.6-197.4 m), consist predominantly (80%) of monotonous background sediment of fine sand- to silt-sized skeletal and non-skeletal grains interrupted by twelve intervals of coarse-grained skeletal sands; five of these intervals are associated with marine hardgrounds or firm grounds. The alternating intervals of skeletal interruptions, overlain by intervals of background sediment, reveal a pattern of three larger depositional sequences with an average thickness of ~170 m, each containing two to three smaller-scale sequences with a thickness ranging from 25 to 90 m. The sediment composition of the interruptions with reworked foraminifera, lithoclasts, and coarse skeletal debris is indicative of deposition during sea-level lowstands. Flooding events are expressed as marine hardgrounds and/or deposits of reworked material. Sedimentation during times when the platform is flooded is characterized by the fine-grained mixed skeletal and peloidal packstones and wackestones.

The Seismic Record

The geometry and internal architecture of the eight sequences (Figure 2) is interpreted to reflect the following general relative sea-level history. A lowering of sea level during the deposition of the basal sequence *h* at the middle/upper Miocene boundary(?) shifted the platform edge more than 10 km basinward. This major progradation was followed by two sea-level changes that created little accommodation space on the platform during the rise but deep incisions during the falls of sea level. Thus, the three basal sequences are thought to be deposited during a long-term relative lowstand of sea level. A major backstep of the margin is observed in the following sequence, indicating a high-amplitude sea-level rise (during the late early Pliocene) with which the platform could not keep pace. With a decrease of the rate of rise, the platform was able to fill all the accommodation space in an aggradational/progradational pattern. This platform is overstepped only slightly by the subsequent sea-level rises and, as a result, a situation similar to a forced regression was created that lead to major prograding pulses seen in the upper Pliocene and Pleistocene sequences *c*, *b*, and *a*.

A vertical seismic profile and a synthetic seismic profile derived from the sonic and density-logs were used to tie the cores Unda and Clino to the seismic sequences. Within the resolution of the seismic reflector, all but one seismic sequence boundaries correlated with a lithologic facies change

(Figure 3). The lithologic indications of sea-level changes coincide with the interpretation drawn from the sequence stacking pattern. At the platform interior site Unda, four sequence boundaries are associated with subaerial exposure horizons. Within the slope section Clino, the inferred positions of the seismic sequence boundaries coincide with a hardground and/or an erosional contact (Figure 3). Both surfaces are overlain by coarse-grained redeposited grainstones and packstones that were probably deposited during relative lowstands of sea level.

Chronostratigraphy of the Core Borings[2]

The key samples are from thin pelagic layers intercalated between thick hemipelagic bank-top-derived sediments. A preceding effort to obtain biostratigraphic ages encountered fundamental problems, identified six biostratigraphic units in each hole, partially constrained broad series ages but provided biozonal age alternatives within the series, and resulted in different Pliocene biozones in comparable parts of each hole. The new data define six units in one hole and five in the other, bracket the biozones present and their ages, and show that they are correlative between the holes. The ages range from a maximum of ~12.2 Ma to a minimum of ~1.6 Ma, but include numerous periods of inferred erosion and/or nondeposition. The largest condensed interval/hiatus (~1.2 Ma) occurs at the Miocene/Pliocene boundary.

The biozones range sequentially from middle Miocene *Globoratalia fohsi robusta* Zone N12 to at least the uppermost Pliocene part of *G. crassaformis viola* Subzone N22, but the foraminifera indicate that deposition was not continuous. Recognition of G. *tosaensis tosaensis* Zone N21 is very tentative and suggest that the biozone may have accumulated on the shelf, but its absence on the slope is consistent with a widespread regional unconformity.

Sedimentation rates and positions of series boundaries vary widely in both holes. At the margin, the Miocene/Pliocene boundary lies at a depth of 542 to 532 m in a condensed section; the lower-upper Pliocene boundary lies at or near Alum; and the Pliocene/Pleistocene boundary may lie anywhere within the top 366 m of the hole, a reasonable assessment considering an exceptionally high rate of sedimentation (536 m/m.y.) for the interval. On the bank top, the Miocene/Pliocene boundary lies between 295 and 278 m; the lower/upper Pliocene boundary is more precisely

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2 Submitted to *Mar. Micropaleontol.* by Barbara H. Lidz and Donald F. McNeill. Results discussed here are based purely on biostratigraphic information, as the senior author performed these analyses without knowledge of the other (magnetic, Sr) stratigraphic constraints. The integrated chronostratigraphy employed these biostratigraphic age tie-points.

placed at or near a depth of 236 m; and the Pliocene/Pleistocene boundary lies within the top 110 m in the hole. Bank-top sedimentation rates ranged from near zero at the condensed interval to a late Pliocene high of 279 m/m.y.

The Record of Sea-level Changes and Dynamic Slope Sedimentation[3]

The integrated age-dating effort involved the use of planktic foraminiferal biostratigraphy, nannofossil biostratigraphy, strontium-isotope stratigraphy, and magnetostratigraphy. An understanding of the slope dynamics and depositional system is critical toward interpretation of the biostratigraphic data, as extreme dilution by platform-derived sediments occurs during margin progradation. As such, the occurrence and highest abundance of microfossils is restricted to the thin units of pelagic-rich sediment, deposited during temporary intervals when platform sediment supply was shut down. These microfossil concentrations are likely to result in premature last-appearance datums and delayed first-appearance datums. Microfossil age ranges still do, however, provide the critical age control in these prograding carbonate margin environments.

The availability of a high-resolution chronostratigraphy enables the development of well constrained platform evolution and sea-level records. Three major progradational episodes were delineated using seismic stratigraphy, lithostratigraphy, and depositional age information. Progradation occurred during the late Miocene, late early Pliocene, and latest Pliocene. In the Pliocene shelf/ramp setting, margin progradation initiates during the highstand, but also occurs in a forced regression-type situation during a fall in sea level. Rapid reef progradation occurred near the end of the Pliocene and early Pleistocene when the platform had infilled the proximal slope sufficiently to provide a near horizontal migration surface. The transformation from a shelf/ramp platform topography to a horizontal-top platform started during the late Pliocene and culminated in the middle Pleistocene.

Age constraints across the western margin of GBB indicate that the seismic reflectors that constitute sequence boundaries are synchronous, within our age resolution. As expected in a slope setting, the sequence boundaries represent condensed time periods of erosion and/or non-deposition. Deposition of downslope pelagic-rich onlapping units are correlated to marine hardgrounds further upslope, and are thought to represent periods of falling sea level.

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[3] Submitted to SEPM Concept in Stratigraphy and Paleontology Series Special Volume by Donald F. McNeill, Gregor P. Eberli, Barbara H. Lidz, Peter K. Swart, and Jeroen A.M. Kenter.

Clino to Unda Correlation

Core-to-core correlation is important to better understanding the timing of margin progradation. sea-level history, and synchroneity of seismic reflectors/sequence boundaries. Based on our age correlations, time-lines across the platform margin can be well constrained (Figure 4).

Middle Miocene: The bottom of core Unda is tentatively interpreted to reach the middle Miocene (10.2 Ma boundary, Haq et al., 1988). Deposits of the age in Clino fell just short of the seismic reflector thought correlative to middle Miocene age in Unda. The bottom of Unda consists of platform-type sediments overlain by upper slope deposits. These sediments correlate seismically with onlapping lowstand (?) deposits below the lowermost recovered core at Clino.

Late Miocene: The basal reef in Unda, interpreted as chron 3An (5.9-5.3 Ma), is correlative with deep shelf/slope deposits in Clino. These shelf/slope deposits consist of skeletal-peloidal packstones and grainstones, separated by numerous, thin beds of fine skeletal packstone/grainstone and laminated skeletal-peloidal packstones. These peloidal/skeletal units are sourced mainly from the shallow-water upper shelf and platform. This upper Miocene slope unit also contains three beds of pelagic-rich sediments thought to represent accumulation without an input of shallow platform sediment, and termed "interruptions" by Kenter and Ginsburg (submitted). During this time period, relief between Unda and Clino, at the base and top of chron 3An, was 304.8 m and 243.8 m (1000 and 800 ft.), respectively. Without correcting for differential compaction/ subsidence, this represents a slope of about 1.97° to 1.57°. This time interval represents the earliest progradational episode recovered in core Clino.

Early Pliocene: The early Pliocene (chron 3r) in both Unda and Clino is characterized by non-deposition and/or very condensed sedimentation (Figure 4). In Unda, a transition occurs from reef to subaerial exposure to deeper-water shelf sediments. The same time interval in Clino is comprised of peloidal-skeletal sand capped by a marine hardground. This interval represents initial shallowing in Unda, followed by non-deposition and/or sediment bypass at both sites. Present-day relief on this time horizon is about 259.0 m (850 ft.).

Early/Late Pliocene: A second major progradational episode occurred in the late early Pliocene and early late Pliocene. In Unda, the basal portion of this period of rapid shelf/slope accumulation contains a marine hardground which is constrained in time to an onlapping package of pelagic-rich sediments (an "interruption") in Clino. This lithology/hardground likely represents the maximum flooding and initial sea-level fall which temporarily shut down shallow shelf/ramp sediment production. Following the rapid flooding of the shelf margin and major backstepping of the platform margin facies related to the initial sea-level highstand, shelf/slope deposition (progradation) occurred on the western margin of GBB. Thick accumulations of sediment occurred at Unda (over 122 m, 400 ft.) and Clino (137 m, 450 ft.) during the upper Gilbert chron and Gauss chron (4.7-2.5 Ma).

During the lower part of the Matuyama (between ~2.5-2.1 Ma) shelf/slope sedimentation continued as lateral progradation and infilling of accommodation space. This interval also contains a marine hardground in Unda and an onlapping sequence near Clino, again consisting of pelagic-rich sediments. Although no tight age constraints exist between the two lithologic features, it may also represent a rapid drop in sea level and deposition of an onlapping lowstand sequence.

Late Pliocene: The latest Pliocene marks a turning point from rapid shelf/slope lateral progradation to a more platform-margin depositional environment. Extremely thick (~150 m, 500 ft.) accumulation of shelf/slope sediment occurred at Clino during this time interval, while at Unda the shelf/slope was transformed to a shallow margin and reef system (Figure 4). As accommodation space was filled at Clino, a transition to shallow-water facies occurred, with reef facies occupying the latest Pliocene time interval.

Pleistocene: Sediments above the Olduvai subchron, representing the Pleistocene, record further shallowing and lateral reef progradation (Figure 4). At Unda, predominantly platform-top sediments were recovered, consisting of reef, patch reef, and peloidal/skeletal platform interior packstone and grainstones. This shallow platform sequence is punctuated by numerous subaerial-exposure related horizons. Further seaward, the lower Pleistocene in core Clino still had near-reef/backreef facies, consisting of massive corals and coral floatstone/rudstone. This reef margin facies gave way to more platform interior-type sediments during successive sea-level highstands. These backreef sediments consisted of mainly patch reef and skeletal sands.

By middle Pleistocene time the shelf/slope had been near completely infilled through progradation. An aggradational-style dominated carbonate deposition during the middle and late Pleistocene as intermittent sea-level highstands flooded the platform margin, separated by prolonged periods of subaerial exposure. Average slope angles on the western margin of GBB became progressively lower during this aggradational phase. The slope angle calculated at the Brunhes/Matuyama boundary is about 0.2°.

Synchroneity of Seismic Sequence Boundaries

Sequence boundaries (SB) identified in multi-channel seismic lines before drilling, and refined after coring and well-logging, were examined in a chronostratigraphic framework. The dynamics of this prograding platform margin are confirmed by combining the sequence boundaries and the chronostratigraphic datums (Figure 4).

SB 7 and 6 were penetrated in Unda but not Clino. SB6 is located close to the base of 3An in Unda and is projected just below the bottom of Clino, in close proximity to the project base of chron 3An in the late Miocene.

SB5 represents the hiatal/condensed sedimentation surface on the top of the reef in Unda and below the prominent disconformity at 536.5 mbmp (1760 fbmp). This sequence boundary is well constrained between the top of chron 3An and the base of chron 3n (5.3-4.7 Ma). This interval contains the Miocene/Pliocene boundary and likely represent a fall in eustatic sea level and sediment bypass on the slope near the location of Clino. The late early Pliocene and early late Pliocene were marked by high accumulation and shelf/slope progradation at both Unda and Clino. Progradation continued well into lower Matuyama (2r) time, and is capped by SB4.

SB4 lies within the middle of the progradational events on western GBB. This reflector is correlated with the submarine hardground in Unda and the pelagic-rich interval in Clino (Figure 4). As at SB5, these features are interpreted to indicate a sudden drop in sea level and temporary shut-down of shallow-water sediment production. The subsequent interval of accumulation is between 2.5 and 2.1 Ma, a period of extremely rapid sedimentation and lateral progradation of the platform. SB4 is near the middle part of this time interval in Unda, and near the base in Clino (Figure 4). Clearly, the locus of sediment production and deposition was rapidly migrating westward within this short period of time. Above SB4, the facies near Unda progressively shallowed, while rapid shelf/slope sedimentation continued at Clino, continually infilling the relatively large accommodation space. The platform topography between Unda and Clino was by this time becoming much more subdued.

SB3 is representative of a final, less dramatic progradational infilling episode at the end of the Pliocene. Progradation during this time period occurred through rapid, lateral reef growth. These prograding reef facies initiated sometime between 1.9 and 2.0 Ma and continued at Unda until the top of the Olduvai (~1.66 Ma), while at Clino reef facies continue well up into Matuyama time (1.66-0.83 Ma). Reef growth during this latter interval at Clino severed to further reduce topographic relief between the platform top at Unda and Clino.

During the Brunhes chron, SB2 and SB3 recorded near horizontal deposition of platform-top facies. These two reflectors can be traced eastward on the platform where they eventually shallow, and likely represent repetitive flooding episodes during the late Pleistocene. SB1 which is delineated near Clino and further west, merges with the reflector representing SB2 before reaching Unda. No additional age constraints could be placed on these reflectors.

Relevance of the BDP to Leg 166

A first-time study such as this, on the chronostratigraphy of prograding shelf/platform carbonates, provides the opportunity to assess platform development, constrain a record of sea-level changes, refine the timing of major lithologic events, and improve correlation of these events both regionally and globally. The significant findings related to the chronostratigraphy of the BDP are as follows.

High-resolution chronostratigraphy is obtainable in prograding-margin carbonate through a combined age-dating approach involving micropaleontology, strontium-isotope stratigraphy, and magnetostratigraphy. We have found that the conventional open-ocean biostratigraphic approach must be used with caution due to the possibility of time-erroneous first- and last-appearance datums. These biostratigraphic datums can be either premature LAD's or delayed FAD's resulting from the overwhelming dilution of shallow-platform derived sediment. Abundant age-diagnostic foraminiferal and nannofossil datums are often concentrated in pelagic-rich intervals formed when the source of platform sediment is temporarily shut down. Although low in abundance, microfossils found in the platform-rich prograding units usually appear to be good indicators of depositional age and still provide a most powerful tool for age determination. The preferred method of utilizing biostratigraphic data is to plot the complete age-range for each marker species, to fully comprehend the depositional processes and system under which the sediment accumulated, and to use caution as to the absolute-age interpretation of first and last occurrences.

Chronostratigraphic correlation between Unda and Clino provides a model for the dynamics of carbonate margin progradation and aggradation in relation to sea-level changes. Progradation along the western margin of GBB occurred in several successive pulses: during the late Miocene, late early Pliocene, and latest Pliocene. This last progradational event in the late Pliocene contained a transition from shelf to reef to platform, with a rapid westward migration of reefs near the Pliocene/Pleistocene boundary. Interestingly, progradation occurred during the early Pliocene sea-level highstand period as well as the latest Pliocene, a time period considered a "lowstand" on much of the shallow platform. The distinction between highstand and lowstand was much less distinct during much of the late Cenozoic as GBB had a gently dipping shelf/ramp morphology. The steep platform margin and associated abrupt on/off nature of sea-level highstand/lowstand seen today, and through much of the middle and late Pleistocene, are fairly recent developments. Pre-middle/upper Pleistocene basin/periplatform deposits around the Bahamas should be interpreted with this new understanding of platform topography.

A sea-level record is obtainable from information archived in well-dated platform interior, platform margin, shelf/slope, and basin sediments. Clino and Unda, in conjunction with other shallow core-borings in the Bahamas provide a first-step in deciphering the record, timing, and magnitude of sea-level change. In general, since the middle Miocene four third-order scale sea-level events are recorded in the western margin of GBB, not including the middle and late Pleistocene flooding events. The oldest sea-level event recorded was a middle Miocene (<12.6 Ma) highstand event which flooded an existing shallow platform and resulted in slope/open-shelf facies near Unda. This highstand flooding gave way to a prolonged upper middle Miocene condensed/hiatal interval, capped by shallow-water facies and a distinct discontinuity surface. This middle Miocene sequence of events occurred prior to the latest Miocene (chron 3An, 5.9 Ma). A subsequent late Miocene event deposited shallow-water reefal sediment near Unda, perhaps as part of a major rise in eustatic sea level. Similar upper late Miocene age deposits have been recovered and dated from much shallower portions of other Bahamian platforms. The early Pliocene consisted of a major sea-level rise that forced eastward backstepping of the shallow-water platform. The subsequent highstand resulted in major progradation of the western margin of GBB. The late Pliocene, again saw progradation of the margin and the westward shift of the clinoform depocenter. This late Pliocene highstand event was interrupted by a fall in sea level, temporarily reducing sediment production on the platform and resulting in a marine hardground on the proximal slope. At Clino, deposition of a pelagic-rich unit occurred during this drop in sea level, followed by extremely high sedimentation related to the westward shift of the upper-shelf zone of sediment production. This lowstand is correlative to the buildup of Northern Hemisphere glaciers and the worldwide drop in eustatic sea level. The late Pliocene/Pleistocene lowstand is consistently recorded in Bahamian platforms as well as around the world. The numerous subaerial-exposure horizons in the upper portion of both Unda and Clino provide a record of the frequent middle and late Pleistocene highstand flooding events.

Seismic reflectors and major sequence boundaries appear to by synchronous within our age-dating resolution. Especially well constrained is the late Miocene sequence boundary, the late Pliocene sequence boundary, and a Pliocene/Pleistocene sequence boundary. The late Miocene and late Pliocene sequence boundaries both represent periods of erosion and/or nondeposition on the slope, and can be tied to major changes in sea level.

Rates of sediment accumulation associated with clinoform deposition, shelf aggradation, and platform aggradation are now much better constrained. Rates of accumulation for prograding pulses were calculated to exceed 300 m/m.y. In proximal shelf/slope settings, a rate such as this is not unusual, as accumulation rates in late Pleistocene and Holocene sediments easily reach this value (Wilber et al., 1990). Reef accumulation rates in Unda during the late Miocene were calculated to be as high as 260 m/m.y. Although well within the accumulation rate of Cenozoic reefs, this high accumulation rate coupled with an actual thickness of ~61 m (200 ft.), suggests perhaps that it formed on a rising sea level. Average rates of Pleistocene platform aggradation on western GBB range from around 13 to 84 m/m.y., and are controlled by whether the highstand elevation is capable of flooding the precursor topography. Overall, the pattern of late Pliocene to late Pleistocene accumulation on western GBB is similar to all other age-dated Bahamian platforms (eastern GBB, LBB, and San Salvador Island), as well as an atoll record in the central Pacific, which strongly suggests eustatic sea-level control.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To study the amplitude and timing of the Neogene and Quaternary sea-level changes and their records in the carbonate depositional sequences to refine the timing of sequence boundaries and determine the facies of the stacked depositional sequences (especially the carbonate lowstand deposits).

2) To retrieve low-latitude isotope signals of the "Icehouse" World and examine the history of the Gulf Stream and its relationship to sea-level fluctuations.

3) To examine fluid flow in platform margins.

4) To study the biological evolution of shallow-water biota.

5) To establish a high-resolution climate and sedimentation record for the Quaternary.

Specific Objectives and Methodology

Neogene-Quaternary Sea-Level Fluctuations

The main objective of Leg 166 is to study the record of Neogene-Quaternary sea-level fluctuations in the prograding carbonates. Within this sea-level objective, the goals are to 1) determine the timing of the sequence boundaries and relative sea-level fluctuations, 2) determine the stratigraphic response of carbonates to sea-level changes of variable frequency by analyzing the facies of the stacked depositional sequences, 3) retrieve a low-latitude isotope signal of the "Icehouse" World in the Neogene and Quaternary and compare it with the stratigraphic record to potentially document a causal link between eustasy and sequence stratigraphic pattern, and 4) estimate magnitude and rate of sea-level changes using age and recovered facies for a precise subsidence analysis.

The target horizon is the base of the Neogene. A successful drilling of the deep-water sites by the *JOIDES Resolution* will generate a data set which can be compared with NJ/MAT of Leg 150 for a test of the synchroneity of sea-level changes.

Fluid Flow

There is increasing evidence that there is active fluid movement deep within carbonate platforms. This evidence has been derived from results from the BDP and also from ODP legs on the Queensland Plateau and in the Pacific (Elderfield et al., 1993; C. Paull, pers. comm.). Based on drilling on the western portion of the GBB, it is now known that the majority of the alteration from metastable carbonates to low-Mg calcite and dolomite occurred in a regime dominated by seawater rather than meteoric fluids. The evidence for this is principally the absence of any freshwater signatures below a depth of 100-150 m in the two holes drilled by the BDP (Melim et al., in press). This suggest the presence of massive circulation of seawater in the subsurface of the Bahamas. Further evidence for circulation was derived from the analysis of borehole fluids retrieved during the drilling. The chemical analysis of borehole fluids reveal that in some areas there is a rapid build-up of Sr resulting from the recrystallization of carbonate, yet in other areas, the Sr content is not increased (Figure 5). We believe that Sr profiles with no gradients indicate areas in which active circulation is taking place, while in other areas where Sr content is built up circulation is stagnant or not as active.

In summary, the samples collected during the BDP confirmed the existence of fluid movement but there is still insufficient information to resolve the fundamental question about the flow mechanism within the platform. The goal is to assess the processes responsible for fluid circulation in platforms by sampling slope sediments and analyzing their pore water chemistry.

What Processes?

There are basically three processes which can account for fluid circulation within the platform. First, and perhaps most important, there is a hydraulic head difference between Andros Island and the adjacent seaways. This causes circulation across the entire bank depending on the anisotropy ratio. This circulation is driven by the head difference, but only involves freshwater under Andros itself. In addition to the head differences between Andros and the Straits of Florida, there are also slight but nevertheless significant differences in the mean sea level between the platform and adjacent waters. This process has been proposed by Carballo et al. (1987) to be responsible for the pumping of sea water through supratidal sediments and reefs (Buddemeier and Oberdorfer, 1986). Whitaker and Smart (1990) suggested that this might be responsible for subsurface movement of fluids from the GBB under Andros Island. Although the extent of the difference is unknown on the western margin, it is probable that sea level on the platform is significantly higher than in the Straits of Florida. This would cause of difference in the head between these two bodies of water with a resultant downward and outward flow.

Second, there is a distinct salinity difference as a result of evaporation between the waters on the surface of GBB and the adjacent Straits of Florida. During the summer months when evaporation is the most intense the density difference may be between 5 and 10 g/kg. It has been suggested (Simms, 1984) that this density difference alone may be sufficient to cause downward convection through the platform up to depths of hundreds of meters.

A third mechanism which is possible is that of Kohout convection in which cold water is circulated through the flanks of the platform and is buoyed upward by the higher heat gradient within the platform compared to the adjacent oceans (Kohout, 1965, 1967). Simms (1984) concluded that such a flow should be present in all steep-margined platforms where there is a strong horizontal pore-water density gradient. The recharge of water for this process would take place at some depth on the flanks of the platform through parts of the platform which did not possess thick veneers of sediment.

It is also possible that hydraulic, temperature and density gradients may be of similar magnitudes in some portions of the platform, leading to circulation patterns that are influenced by a combination of fluid potentials. In addition the geometry of the fluid flow will be influenced by the permeability along depositional surfaces, thereby channeling fluid flow.

How Do we Recognize Fluid Flow?

Sites of recharge and discharge probably exist along the entire slope of the platform on various stratigraphic levels. In the Tongue of the Ocean we have observed discharge of water with different salinity along the cemented upper slope (upper 300 m) but never an associated benthic community. Further downslope, the cemented slope is overlain by uncemented sediment and, as a result, discharge occurs into these unconsolidated sediments. The idea is to sample some of these fluids using the sediment as a receptacle to capture the fluids. Thus, fluid flow can be recognized by deviation in the water chemistry and temperature from a steady state condition. In the absence of flow, the pore water chemistry and the temperature characteristics are controlled by diffusion and recrystallization. However, if water is moving out of a formation, the characteristics of the geochemical and geothermal gradients change attaining a concave upward appearance. Conversely, if water is moving into the formation the profiles become concave downwards.

By examining the profiles one can establish the presence of flow, and by examining the pore water chemistry one can establish with some certainty where the water is coming from. For example, water which has its origin on the GBB, is elevated in salinity and oxygen isotopic composition. In contrast water, derived from the Straits of Florida will have normal salinity and oxygen isotopic composition.

Paleoceanography

Since the middle Cretaceous, several major changes have occurred in climate, fauna, and ocean circulation. The seaways in the Bahamian archipelago have potentially the record of most of these events. Leg 166 will address aspects of the Neogene events, such as 1) retrieving a Quaternary high-resolution climate and sedimentological record; and 2) revealing the Gulf Stream history and its relationship to sea-level fluctuations. In addition, deepening one hole of the Bahamas Transect to the mid-Cretaceous sequence boundary could add very valuable data for regional Caribbean paleoceanography, as well as address important global problems. For example:

<u>The onset of Gulf Stream Current</u>: The Bahamas Transect is located on the periphery of the modern day Caribbean/ Gulf Stream current that influences global climate and ocean circulation. The timing of the onset of this circulation, however, is still not precisely determined. Leg 101 documented its existence from the Oligocene onwards (Austin et al., 1988) but it probably started sometimes in the Late Cretaceous. In addition, several tectonic events in the Caribbean might have influenced its vigor and flow pattern. For example, the break-up of the carbonate platform system on the Nicaraguan Rise in the middle to late Miocene might have strengthened the current (Buffler et el., 1994). The most distal hole of Leg 166 potentially has the record of these changes in current strength.

<u>The record of the Paleogene "Doubthouse" Earth</u>: The latest Paleocene- middle Eocene is an interval has at least two unconformity generating events. However, this time interval is glacial to some but non-glacial to others. A comparison of the $\delta^{18}O$ proxy of sea-level change of this interval with the isotope values of the overlying Neogene can test their similarity with both non-glacial and glacial events. Since these unconformities occur at a time of relatively frequent magnetic polarity changes they can be dated accurately and are suitable to evaluate synchroneity.

<u>The influence of the Cuban collision</u>: With the collision of Cuba with the North American Plate in the (?) Late Cretaceous/Early Cenozoic to late Eocene, the Bahamian archipelago became part of the foredeep rather than a passive continental margin. The onset of the collision and the timing of the subsequent collisional events are not well constrained. In the relatively distal location of the Bahamas Transect, these tectonic events are probably recorded in increased subsidence pulses due to loading, and seen in sedimentary record in variations in sediment thickness with an increase of mass gravity flows.

The K/T boundary: There is potentially a K/T boundary preserved in the Straits of Florida, although the boundary was not preserved at Site 627, north of Little Bahama Bank.

The mid-Cretaceous drowning of the mega-bank: Towards the end of the Early Cretaceous, a large mega-bank was established along the eastern and southern margin of the North American continent. This "mega-bank" segmented and partially drowned in the Albian to Cenomanian. Documenting the extent of the mega-bank, the cause, and timing of the disintegration of this mega-bank was one of the major objectives of Leg 101. The drilling was intended to resolve the controversy between scientists who interpreted the modern platform configuration as a reflection of the Early Jurassic rift topography (Mullins and Lynts, 1977) and those who viewed the modern archipelago as a remnant of a large mega-bank that drowned in the middle Cretaceous (Sheridan et al., 1981, Ladd and Sheridan, 1987; Schlager and Ginsburg, 1981). The debate continues in the wake of the drilling, because drilling failed to reach the mid-Cretaceous sequence boundary (MCSB) in the Straits of Florida and Northeast Providence Channel. Drilling the MCSB along the Bahamas Transect will add important information to the controversy, and achieve a goal that was intended during Leg 101.

DRILLING PLAN/STRATEGY

Neogene-Quaternary Sea-Level Fluctuations

Shallow Sites

For a complete understanding of the sedimentary response and to achieve high-resolution age-dating, a transect is needed from the shallow platform (proximal) to the adjacent deep water (distal). The two core borings, Unda and Clino, on the platform penetrated middle/late Miocene to Holocene sequences and provide part of the record in the proximal part. Three shallow borings on islands give an additional record of the upper part of the Neogene, mostly the latest Miocene to Recent (McNeill et al., 1988). A new site on the platform is planned to the base of the Neogene to retrieve the sedimentary record of the base of the Neogene in the proximal part of the sequences. The target depth will be determined by carrying the seismic reflector dated as the base of the Neogene into platform.

Deep-Water Sites

The deep-water sites are planned to be drilled during Leg 166 (Table 1; Figure 1). A transect of four sites is proposed approximately oriented in the direction of the progradation (proposed site BT-1, -2, -3, and -4). An additional site, proposed site BT-5, will be located approximately 10 km north of the transect to analyze lateral continuity of sequence boundaries and facies variations in the prograding lobes. The most basinward drill site of the proposed transect is situated on the periphery of the Gulf Stream, permitting the determination of the influence of the Gulf Stream on the deposition of the sequences and possible changes of its intensity during the Neogene. In addition, the thick Quaternary sediment package on the leeward slope of GBB will provide a high-resolution record of the climate and short-term sea-level fluctuations in the Quaternary. Thus, the record of two major energy sources of climate, namely the orbital forcing and ocean circulation, and their variations can be evaluated along the proposed transect. Some of these sites serve also for the secondary objectives.

Fluid Flow Objectives

It is suggested that in areas where Holocene unconsolidated muddy sediments are onlapping older cemented rocks, fluids move into or out of the platform and may partially also move through the sediment. By coring the sediment and squeezing its waters, we can achieve an idea of the composition of these fluids. As one progresses away from the platform, the influence of advection would probably become less and the pore water chemistry would become dominated by diffusion.

Leg 166 will sample along two transects away from the platform edge, specifically to examine fluid flow (Table 1; Figure 1). The first transect will coincide with the sea-level transect and utilize some of the same sites. This profile has a gentle slope to it. The first site will be located at 250 m water depth and be situated as close to the slope break as possible. Penetration will be approximately 100 m. Other sites will be located at depths of 300 and 400 m. The second transect, also consisting of three holes, will be located away from a steep margin, where the Holocene sediment wedge is somewhat thinner. Penetration will be 50 to 100 m depending on unconsolidated sediment thickness at that location.

Paleoceanographic Objectives

A deep drill hole penetrating the MCSB is needed to address Leg 166 objectives (Table 1; Figure 1). The preferred location would be on the periphery of the Gulf Stream which would be ideal for answering questions in regards to the current evolution. Unfortunately, such a location is prone to have large hiati due to winnowing and thus is less suitable for all the other objectives. Thus, a location closer to the platform, i.e., the second to the last of the distal transect sites is chosen as a site for a deep hole. The target depth is approximately 1700 m and would probably require a reentry cone.

PROPOSED SITES

The proposed sites (Table 1; Figure 1) are located on the basinward part of the existing seismic line in order to have a direct correlation to the shallow-water drill sites, Unda and Clino.

Proposed site BT-1 is positioned approximately 850 m from the modern platform edge on the upper slope in approximately 250 m water depth; it will penetrate the thickest portion of the Quaternary wedge and the four youngest seismic sequences (lower Pliocene-Holocene) seen on the seismic. The objectives at BT-1 are to 1) date precisely the four penetrated sequence boundaries, 2) determine the facies within the different systems tracts, especially the nature of the onlapping units that are currently interpreted as lowstand deposits, 3) evaluate the fluid flow in this uppermost part of the slope, and 4) retrieve a high-resolution record of climate and sea-level fluctuations for the Quaternary and late Pliocene.

To achieve these objectives, we will double APC through the unconsolidated sediment and use one core for high-resolution stratigraphy, and one core for interstitial water analysis and overlap. Possible hard layers encountered will be penetrated with the XCB. Rotary drilling the hole would deepen it to approximately 500 m. The WSTP will be used at depth intervals of every 50 m to establish the presence of any geothermal gradients indicating fluid flow.

Proposed site BT-2, located 2.45 km further basinward than proposed site BT-1, is positioned on the lower slope portion of the sequences. The objectives at this site are to 1) obtain a sedimentary record and especially evaluate facies of lowstand vs. highstand deposits, 2) refine the age of the sequence boundaries, 3) produce a high-resolution isotope stratigraphy of the Neogene to Holocene, and 4) reveal possible fluid flow through this portion of the margin. To achieve these goals, we will adopt a similar procedure as described for proposed site BT-1.

Proposed site BT-3 is positioned on an undisturbed portion of the lower slope of western GBB at 525 m water depth. At this site the core will penetrate mostly the lower slope portions of the prograding sequences. Therefore, we anticipate a higher content of microfossils in the thinner foresets. The main objective of this site in regards to sea level is to combine the sedimentary record with the $\delta^{18}O$ isotope record of the Neogene to Recent. The second major objective is to reach the MCSB to 1) assess the cause of the platform demise in the mid-Cretaceous, 2) potentially sample the K/T boundary, 3) acquire a low-latitude record of the Paleogene "Doubthouse" and its transition into the Neogene "Icehouse", and 4) determine the onset of Florida Current. On the seismic lines no current deposits are obvious; thus the detection of the onset of the Florida Current is somewhat speculative.

Proposed site BT-4, approximately 11.7 km from the modern platform margin, is the basinward end of the Bahamas Transect. It is positioned east of mounded and discontinuous reflectors that indicate redeposition from the Gulf Stream. This position at the periphery of the Gulf Stream will allow us to address the two main objectives, namely to l) examine the facies of the basinal deposits within the prograding sequences, and 2) assess and date deposition and erosional gaps associated with the Gulf Stream.

Proposed site BT-5 is located approximately 10 km north of proposed site BT-3. Its main objective is to document possible lateral facies variations and test the synchronous timing of the sequence boundaries . This site should yield enough microfossils to measure the foraminiferal $\delta^{18}O$ isotope record. It is also an alternative site for the proposed deep hole to penetrate the MCSB.

To address the fluid flow objectives, Leg 166 will sample along two transects away from the platform edge. The first transect will coincide with the sea-level transect and utilize some of the same holes, i.e., proposed site BT-1 is equivalent to proposed site F-1 and proposed site BT-2 is equivalent to proposed site F-2.

Proposed site F-3 is located between proposed sites BT-3 and -2 and constitutes the basin end site for the fluid-flow transect at this location. Its main goal is to retrieve pore-water chemistry as an indication for the fluid flow through the margin.

Proposed sites F-4, F-5, and F-6 are dedicated to the fluid flow objectives. They are arranged in a transect with the shallowest hole at an approximate water depth of 250 m. Each successive site will be located approximately 1500 m down slope. Penetration will be 50 to 100 m, depending on unconsolidated sediment thickness at that location. Besides the fluid flow objectives, a high-resolution record of the Quaternary can be retrieved from the APC cores.

REFERENCES

Austin, J.A.,Jr., Schlager, W., Palmer, et al., 1986. *Proc. ODP, Init. Repts.*, 101: College Station, TX (Ocean Drilling Program).

Buddemeier, R.W., and Oberdorfer, J.A., 1986. Internal hydrology and geochemistry of coral reefs and atoll islands: Key to diagenetic variations. *In* Schroeder, J.H., and Purser, B.H., *Reef Diagenesis*: Berlin (Springer-Verlag), 91-111.

Buffler, R.T., et al., 1994. Evolution of Late Cretaceous-Cenozoic seaway: multiple ODP drilling objectives, Southeastern Gulf of Mexico/Southern Straits of Florida. ODP letter of intent.

Carballo, J.D., Land, L.S., and Miser, D.E., 1987. Holocene dolomitization of supratidal sediments by active tidal pumping, Sugarloaf Key, Florida. *J. Sediment. Petrol.*, 52:153-165.

Davies, P.J., McKenzie, J.A., Palmer-Julson, A., et al., 1991. *Proc. ODP, Init. Repts.*, 133: College Station, TX (Ocean Drilling Program).

Droxler, A.W., and Schlager, W., 1985. Glacial versus interglacial sedimentation rates and turbidite frequency in the Bahamas. *Geology*, 13:799-802.

Eberli, G.P., and Ginsburg, R.N., 1989. Cenozoic progradation of NW Great Bahama Bank - A record of lateral platform growth and sea-level fluctuations. *In* Crevello, P.D., et al. (eds.), *Controls on carbonate platform and basin evolution.* Spec. Publ. - SEPM, 44:339-355.

Elderfield, H., German, C., Palmer, M., Murton, B., Chin, C., Greaves, M., Gurvich, E., James, R., Klinkhammer, G., Ludford, E., Mills, R., Rudnicki, M., Thomson, J., and Williams, A., 1993. Preliminary geochemical results from the Broken Spur hydrothermal field, 29°N, Mid-Atlantic Ridge. *Eos*, 74:99 (Abstract).

Halley, R.B., and Matthews, R.K., 1987. Carbonate depositional environments modern and ancient - Part 6, Diagenesis 2. Colorado School of Mines Quarterly, 82:17-40.

Haq, B.U., Hardenboll, J., and Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. *In* Wilgus, C.K., et al. (eds.), *Sea-level changes; an integrated approach.* Spec. Publ. - SEPM, 42:72-108.

Kendall, C.G.St.C., and Schlager, W., 1981. Carbonates and relative changes in sea level. *Mar. Geol.*, 44:181-212.

Kohout, F.A., 1965. A hypothesis concerning cyclic flow of salt water related to geothermal heating in Floridan aquifer. *Trans. N.Y. Acad. Sci., Ser. II*, 28/2:878-883.

Kohout, F.A., 1967. Ground-water flow and the geothermal regime of the Floridian plateau. *Trans. Gulf Coast Ass. Geol. Soc.*, 17:339-354.

Ladd, J.W., and Sheridan, R.E., 1987. Seismic stratigraphy of the Bahamas. *AAPG Bull.*, 71:719-736.

McNeill, D.F., 1989. Magnetostratigraphic dating and magnetization of Cenozoic platform carbonates from the Bahamas [Ph.D. dissert.]. University of Miami, Coral Gables, FL.

McNeill, D.F., Ginsburg, R.N., Chang, S-B.R., and Kirschwink, J.L., 1988. Magnetostratigraphic dating of shallow-water carbonates from San Salvador, Bahamas. *Geology*, 16:8-12.

Melillo, A.J., 1988. Neogene planktonic foraminifer biostratigraphy, ODP Leg 101, Bahamas. *In* Austin, J.A., Jr., Schlager, W., et al., *Proc. ODP, Sci. Results*, 101: College Station, TX (Ocean Drilling Program), 3-46.

Melim, L.A., Swart, P.K., and Maliva, R.G., in press. Diagenesis of carbonates from the Bahamas Drilling Project, western margin Great Bahama Bank: meteoric versus marine burial diagenesis. Spec. Publ. - SEPM.

Mullins, H.T., 1983. Comment on eustatic control of turbidites and winnowed turbidites. *Geology*, 11:57-58.

Mullins, H.T., and Lynts, G.W., 1977. Origin of the northwestern Bahama platform: review and reinterpretation. *Am. Ass. Oetr. Geol.*, 88:1447-1461.

Posamentier, H.W., and Vail, P.R., 1988. Eustatic controls on clastic deposition; II, Sequence and systems tract models. *In* Wilgus, C.K., et al. (eds.), *Sea-level changes: An integrated approach.* Spec. Publ. - SEPM, 42:125-154.

Sarg, J.F., 1988. Carbonate sequence stratigraphy. *In* Wilgus, C.K., et al. (eds.), *Sea-level changes: An integrated approach.* Spec. Publ. - SEPM, 42:155-188.

Schlager, W., 1981. The paradox of drowned reefs and carbonate platforms. *Geol. Soc. Am. Bull.*, 92:197-211.

Schlager, W., 1991. Depositional bias and environmental change - important factors in sequence stratigraphy. *Sediment. Geol.*, 70:109-130.

Schlager, W., and Ginsburg, R.N., 1981. Bahama carbonate platforms - the deep and the past. *Mar. Geol.*, 44:1-24.

Sheridan, R.E., Crosby, J.T., Bryan, G.M., and Stoffa, P.L., 1981. Stratigraphy and structure of southern Blake Plateau, northern Florida Straits, and northern Bahama platform from multichannel seismic reflection data. *AAPG Bull.*, 65:2571-2593.

Simms, M., 1984. Dolomitization by groundwater flow systems in carbonate platforms. *Trans. Gulf Coast Assoc. Geol. Soc.*, 34:411-420.

Swart, P.K., and Guzikowski, M., 1988. Interstitial-water chemistry and diagenesis of periplatform sediments from the Bahamas, ODP Leg 101. *In* Austin, J.A., Jr., Schlager, W., et al., *Proc. ODP, Sci. Results*, 101: College Station, TX (Ocean Drilling Program), 305-314.

Whitaker, F.F., and Smart, P.L., 1990. Active circulation of saline ground water in carbonate platforms: Evidence from Great Bahama Bank. *Geology*, 18:200-203.

Wilber, R.J., Milliman, J.D., and Halley, R.B., 1990. Accumulation of Holocene bank-top sediment on the western margin of Great Bahama Bank. *Geology*, 18:970-974.

Williams, D.F., Trainor, D.M., Guilderson, T., Gamble, R., and Corbin, J., 1988. Calcium carbonate sedimentation on the northwestern Gulf of Mexico margin; a new tool for chemical stratigraphy and depositional modelling. *In* Weide, A., et al. (eds.), Field Trip Guide Book - Gulf Coast Ass. Geol. Societies, 38:395-397.

Figure 1. Location map of the Bahamas Transect.

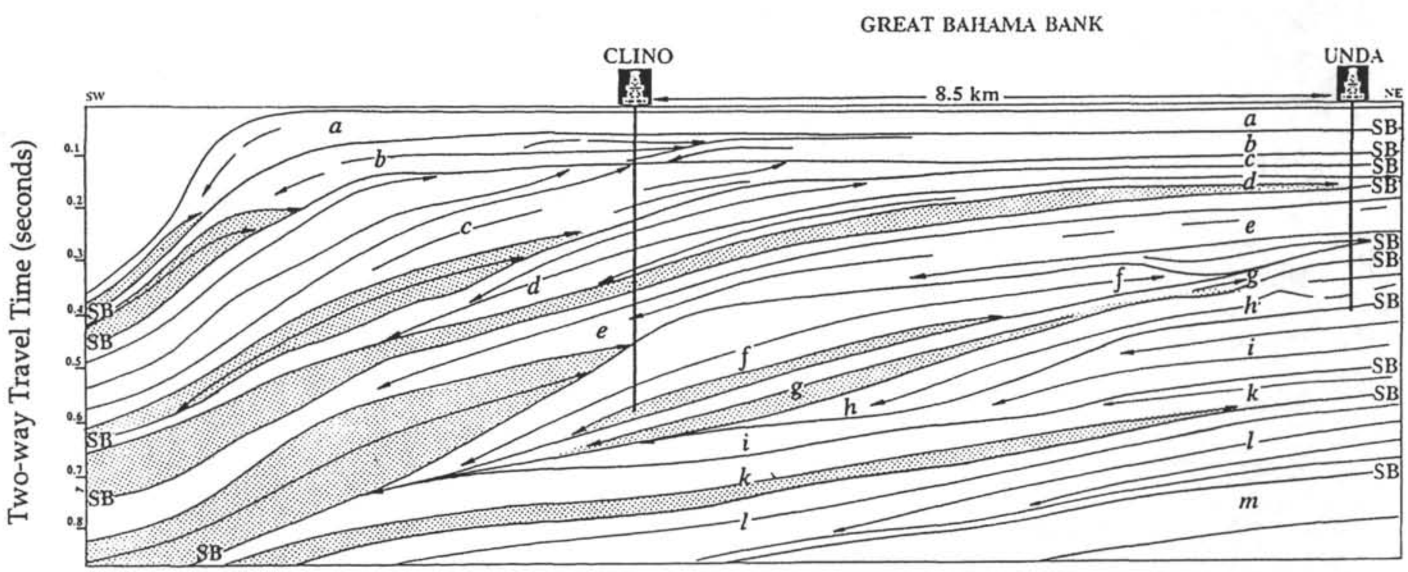


Figure 2. Line drawing of the prograding sequences at the western margin of the GBB with drilling locations. Sequences *h-a* are late Miocene to Recent in age. Miocene/Pliocene boundary is on top of sequence *f*. Sequence boundaries are indicated by truncations (sequences *h, g, f*) and/or onlap patterns (sequences *e-a*). Stippled areas are onlapping packages; white areas are prograding downlapping units.

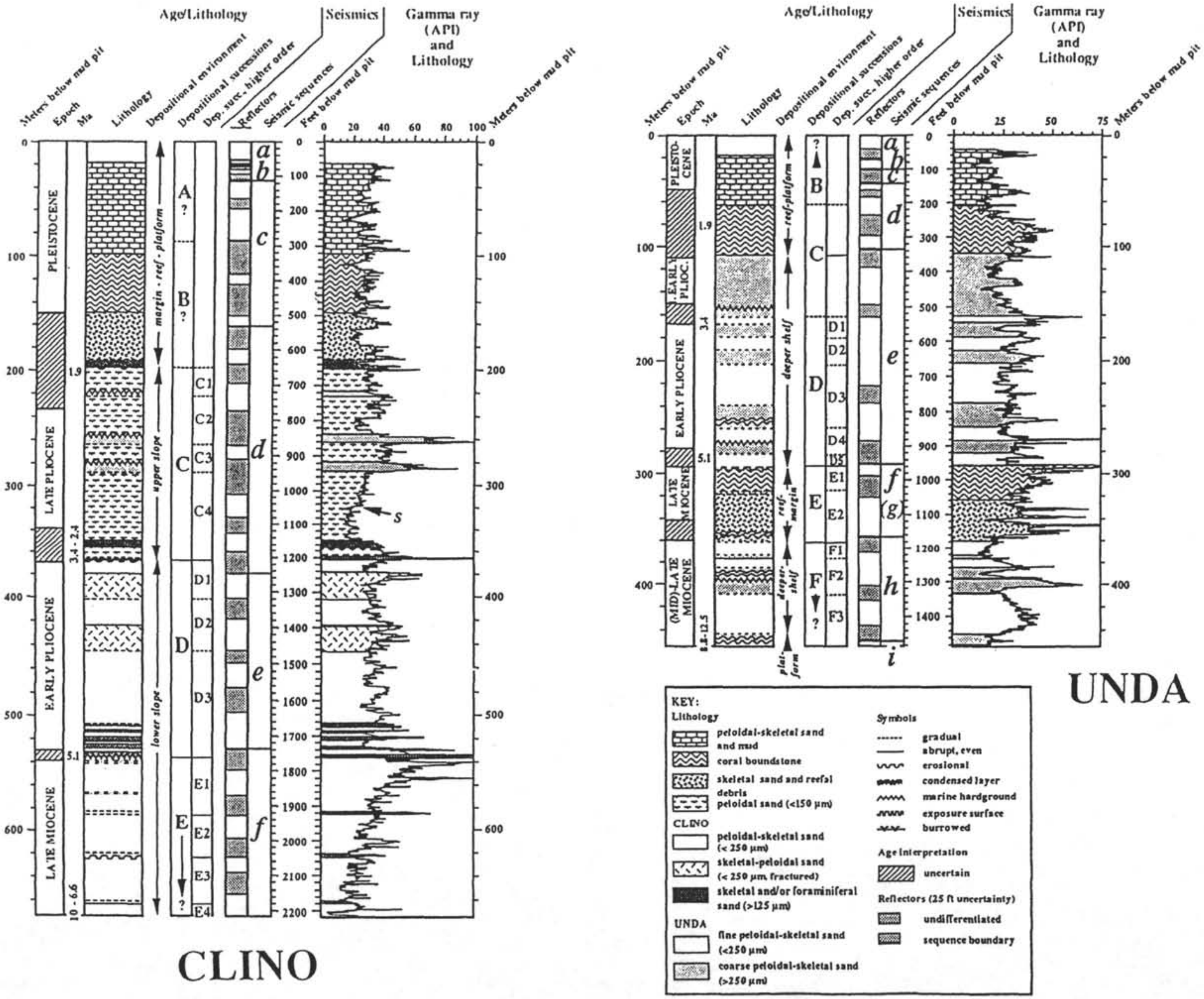


Figure 3. Correlation of ages, sedimentary successions, seismic reflectors and sequences, and gamma ray signature of Clino and Unda.

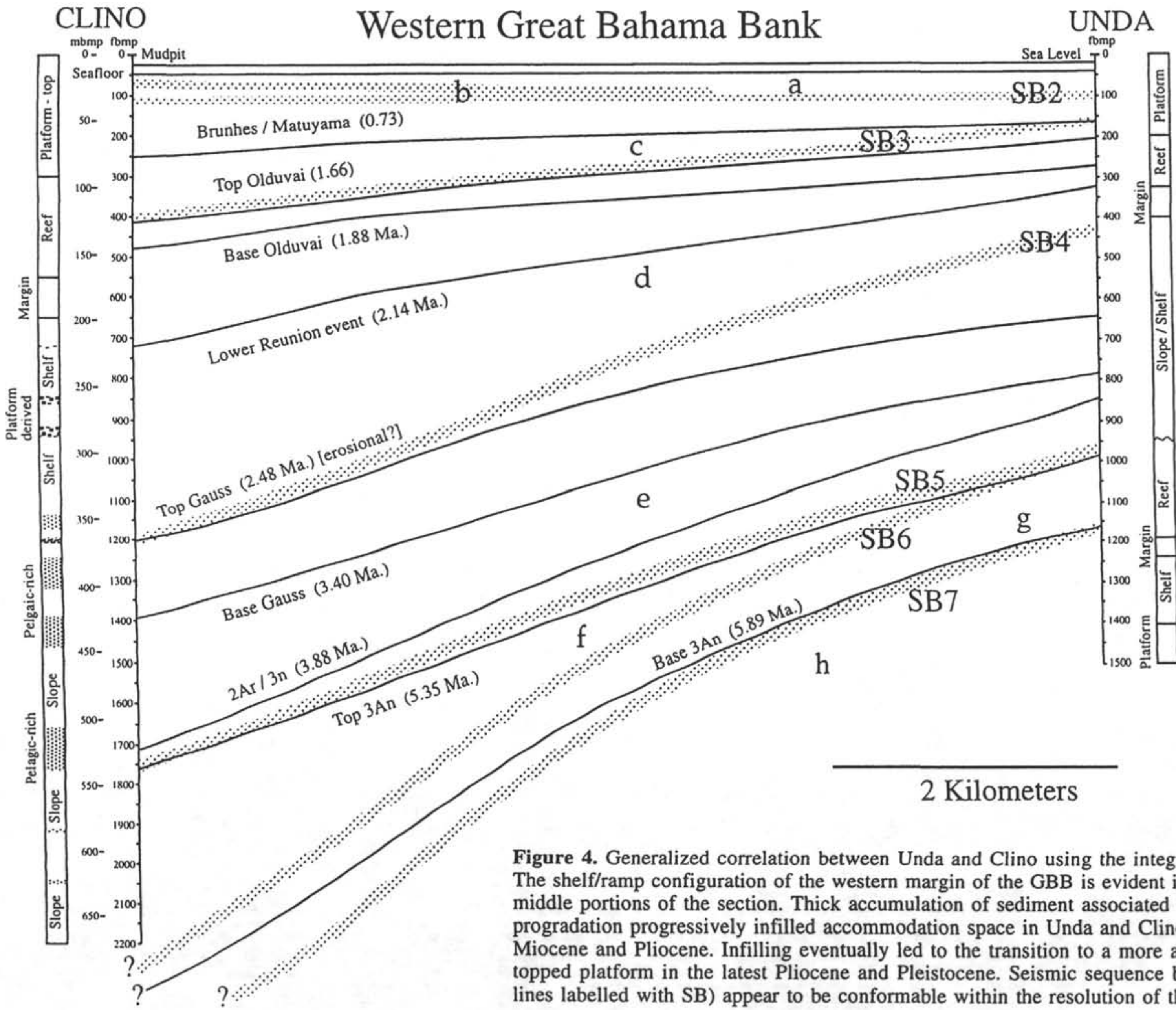


Figure 4. Generalized correlation between Unda and Clino using the integrated age model. The shelf/ramp configuration of the western margin of the GBB is evident in the lower and middle portions of the section. Thick accumulation of sediment associated with margin progradation progressively infilled accommodation space in Unda and Clino during the late Miocene and Pliocene. Infilling eventually led to the transition to a more aggradational, flat-topped platform in the latest Pliocene and Pleistocene. Seismic sequence boundaries (shaded lines labelled with SB) appear to be conformable within the resolution of the time lines.

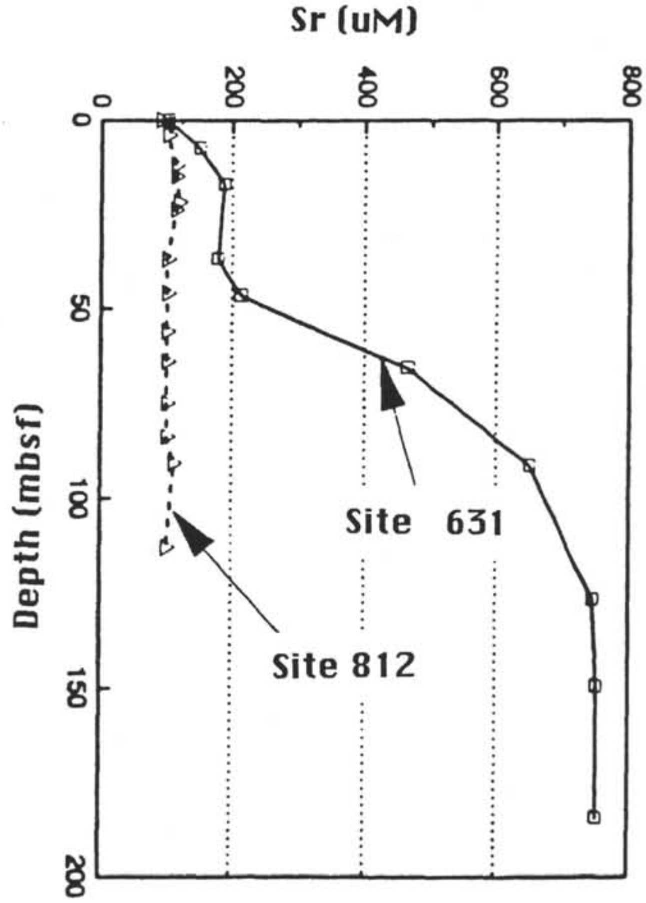


Figure 5. Comparison of the Sr gradient at Site 631 (Leg 101 - Bahamas) and Site 812 (Leg 133 - Queensland Plateau). Note the strong gradient at Site 631, indicating an absence of fluid movement at this site (Swart and Guzikowski, 1988). In contrast, Site 812 has almost no Sr gradient in spite of a large amount of recrystallization (Davies, McKenzie, Palmer-Julson, et al., 1991). Geothermal measurements confirmed the movement of cold bottom water into the formation.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: BT-1/F-1	**PRIORITY**:	**POSITION**: 24°33'N, 79°10'W
WATER DEPTH: 250 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: ± 1300 m
SEISMIC COVERAGE: Western Line SP 2098 (approx.). High-resolution MCS & SCS lines June/July 1994.		

Objectives: To determine the facies in the carbonate sequences, precisely date the sequence boundaries, retrieve a record of Quaternary climate and sea-level fluctuations, and assess the mechanisms of fluid flow in the platform.

Drilling Program: Double APC, XCB, and RCB.

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

Nature of Rock Anticipated: Calcareous mud, sand, and rudite.

SITE: BT-2/F-2	**PRIORITY**:	**POSITION**: 24°31'N, 79°14'W
WATER DEPTH: 338 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 930 m
SEISMIC COVERAGE: Western Line SP 2144 (approx.). High-resolution MCS & SCS lines June/July 1994.		

Objectives: To document the sedimentary record of the carbonate sequences and their response to sea-level fluctuations and to document the facies of the lowstand deposits, determine the ages of the sequence boundaries, and assess the mechanisms of fluid flow in the platform.

Drilling Program: Double APC, XCB, and RCB.

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

Nature of Rock Anticipated: Calcareous mud, sand, and rudite.

SITE: BT-3	**PRIORITY**:	**POSITION**: 24°30'N, 79°18.5'W
WATER DEPTH: 525 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 1650 m
SEISMIC COVERAGE: Western Line SP 2260 (approx.). High-resolution MCS & SCS lines June/July 1994.		

Objectives: To retrieve the $\delta^{18}O$ record of the Neogene to Recent, date the sequence boundaries, retrieve the Paleogene sedimentary and isotopic record, and drill to the mid-Cretaceous sequence boundary.

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

Logging and Downhole Operations: Quad combo, and (FMS, GHMT, and GLT if time permits).

Nature of Rock Anticipated: Calcareous mud and rudite, chalk, and shallow-water carbonates..

SITE: BT-4	**PRIORITY**:	**POSITION**: 24°28'N, 79°21.5'W
WATER DEPTH: 600 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 820 m
SEISMIC COVERAGE: Western Line SP 2350 (approx.). High-resolution MCS & SCS lines June/July 1994.		

Objectives: To document the basinal facies of the prograding sequences, and to assess and date the deposition and erosional gaps produced by the Gulf Stream.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: Quad combo, and (FMS, GHMT, and GLT if time permits).

Nature of Rock Anticipated: Calcareous mud and rudite.

SITE: BT-5	**PRIORITY**:	**POSITION**: 24°35.5'N, 79°15.9'W
WATER DEPTH: 550 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 900 m*
SEISMIC COVERAGE: High-resolution MCS & SCS lines June/July 1994.		

* 1700 m if used as an alternate site to BT-3.

Objectives: To retrieve the $\delta^{18}O$ record of the Neogene to Recent, assess the lateral variability of facies and sequence boundaries, and drill to the mid-Cretaceous sequence boundary.

Drilling Program: APC, XCB, RCB, (and reentry if used as an alternate site).

Logging and Downhole Operations: Quad combo, and (FMS, GHMT, and GLT if time permits).

Nature of Rock Anticipated: Calcareous mud and rudite.

SITE: F-3	**PRIORITY**:	**POSITION**: 24°33.5'N, 79°15.25'W
WATER DEPTH: 400 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: High-resolution MCS & SCS lines June/July 1994.		

Objectives: To assess the mechanism of fluid flow through the platform and retrieve a record of the Quaternary climate.

Drilling Program: Double APC.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated: Calcareous mud and rudite.

SITE: F-4	**PRIORITY**:	**POSITION**: 23°35'N, 79°03'W
WATER DEPTH: 250 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE: High-resolution MCS & SCS lines June/July 1994.		

Objectives: To assess the mechanism of fluid flow through the platform and retrieve a record of the Quaternary sea level and climate.

Drilling Program: Double or triple APC.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated: Calcareous mud and rudite.

SITE: F-5	**PRIORITY**:	**POSITION**: 24°33.4'N, 79°15.1'W
WATER DEPTH: 350 m	**SEDIMENT THICKNESS**: 6 km	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: High-resolution MCS & SCS lines June/July 1994.		

Objectives: To assess the mechanism of fluid flow through the platform and retrieve a record of the Quaternary sea level and climate.

Drilling Program: Double or triple APC.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated: Calcareous mud and rudite.

SITE: F-6	**PRIORITY**:	**POSITION**: 24°33.2'N, 79°15'W
WATER DEPTH: 450 m	**SEDIMENT THICKNESS**: ± 6 km	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: High-resolution MCS & SCS lines June/July 1994.		

Objectives: To assess the mechanism of fluid flow through the platform and retrieve a record of the Quaternary sea level and climate.

Drilling Program: Double or triple APC.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated: Calcareous mud and rudite.

LEG 167
California Margin

LEG 167

OCEAN DRILLING IN THE CALIFORNIA MARGIN AND SOUTHERN CALIFORNIA BORDERLAND

Modified from Proposals 396-Rev2 , 422-Rev, and 386-ADD/ADD2/ADD3 Submitted By

Mitchell Lyle, Lowell.D. Stott, John Barron

To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

Fluctuations in flow of the California Current, one of the world's important eastern boundary currents, are highly sensitive to climatic change, yet little is known about Neogene fluctuations in current strength. Coastal upwelling, associated with the current, is driven in the Holocene by persistent summer northerly winds and is thus also sensitive to and an indicator of climatic change.

Leg 167, a series of transects across the California Current, along the California continental margin, and within the California Borderland, aims to determine 1) Neogene fluctuations in current strength in response to climate and tectonic reorganizations of the Pacific Basin and its effects on heat and salt transport in the Pacific Ocean, 2) the history of fluctuations in coastal upwelling in relation to changes in current strength, 3) the response of primary productivity to Neogene climate change, 4) changes in the calcite compensation depth, 5) how both terrestrial and marine organic carbon are preserved in continental margin and hemipelagic sediments, and the change of deposition rates as a function of distance from shore, 6) the relationship between organic carbon preservation and primary productivity, sedimentation rate, and bottom water oxygen content, 7) how Neogene climate changes and the related growth of continental ice sheets have interacted with the carbon cycle, 8) the high-resolution history of organic carbon burial as it relates to climate change, and 9) the impact of climate change on the history of deep water communication, anoxia, and processes that produced laminations in the Santa Monica Basin. Drilling in the Eel River Basin will examine gas hydrate formation and the origin of a bottom-simulating reflector.

Secondary objectives include study of the Plio-Pleistocene deformation of the Gorda Plate, the northward movement of the Mendocino Triple Junction, basement composition and rotation rates of possible terranes along coastal California, geomagnetic secular variation and the nature and timing of small-scale geomagnetic excursions.

INTRODUCTION

The modern California Current System is probably the best studied of the world's eastern boundary currents, and because of these modern measurements it is possible to hindcast the past behavior of this eastern boundary current system with much greater confidence than for any other in the world. It is probably the best place in the world to understand how eastern boundary currents have responded to climate change.[1]

A change in the strength (mass transport) or salinity of the California Current, either because of changes in vapor transport to the North Pacific or because of restricted communication pathways may have contributed to changes in global circulation during the Pleistocene. Given the rates at which circulation changes may have occurred (within hundreds of years or less according to evidence from modeling studies and other proxy data from the Atlantic) the California Borderland Basins may provide the best location to recover high-resolution Pleistocene marine records suitable to resolve relatively rapid changes in circulation and ocean chemistry in the North Pacific.

The oxygen deficient basins along the margin of California are also large sinks for organic carbon produced within the water column by marine plankton and carbon flushed from the continents. Process-oriented studies of the global carbon cycles require resolution of the complex transformations of carbon (organic and carbonate) within the water column and on the seafloor.

STUDY AREA

Dynamics of the California Current

The California Current annually carries about 10 Sv of cold, low salinity, north Pacific water into the eastern tropical Pacific Ocean (Sverdrup et al., 1942; Hickey, 1979). It is the major transport

[1] Studies from this area include the California Cooperative Fisheries Program (CalCOFI) of seasonal measurements of hydrography and biology, major physical oceanography experiments such as CUEA (Coastal Upwelling Experiment and Analysis), CODE (COastal Dynamics Experiment), and the West Coast Satellite Time Series and Coastal Transition Zone program (Brink and Cowles, 1991, and references therein), and long and short term studies of biogeochemical flux such as the VERTEX study (Knauer et al.,1979; Knauer and Martin, 1981), MULTITRACERS (Dymond and Lyle, in press; Lyle et al, in press); Low Level Waste Disposal Project (Dymond and Lyle, in press, Fischer et al.,1983), long term sediment trap deployments off Monterey (C. Pilskaln, pers. comm.), and short term sediment trap deployments in the California Borderlands region (Dymond et al., 1981; Sautter and Thunell, in press).

mechanism for low salinity surface waters from the north Pacific to be mixed into the remainder of the Pacific Ocean.

Long-term hydrographic studies and more focussed process studies have shown that the California Current is subject to both seasonal and interannual cycles. The pattern of winds along the coast controls seasonal variations. Changes in the dynamic topography of the North Pacific Gyre produce interannual variability in the current. California Current structure thus reflects both the local winds along the west coast of the United States and basin-wide events within the north and equatorial Pacific Ocean. The California Current combines diffuse flow, which extends many hundreds of kilometers from the coast, with local high-velocity zones of southward flow that separate nutrient-rich upwelled waters from the relatively barren offshore waters (e.g., Huyer et al., 1991). The core of the offshore California Current flow is located approximately 250-350 km from the coast at the border of Oregon and California and is about 300 km from the coast at Point Conception (Hickey, 1979; Lynn and Simpson, 1987).

The importance of both local and remote forcing in California Current flow has been emphasized by modeling efforts. Pares-Sierra and O'Brien (1989) found that the local wind field in the Northeast Pacific is adequate to drive the annual cycle of the current and to create the general features of its structure. They could only model interannual variations of the California Current by coupling the local model with one driven by equatorial winds. Kelvin waves generated during El Niño events in the equatorial Pacific propagate up the western coast of North America and strongly affect the California Current.

The modeling suggests that in the much longer climatic cycles that are observable by paleoceanographic studies, the location and strength both of trade winds and of westerlies should probably have a major impact on mean transport in the California Current. Numerical climate simulations of the last glacial maximum (~18 ka) using the NCAR Community Climate Model (CCM) indicate a weakened Pacific high in the perpetual July simulation (COHMAP, 1988). At 9 ka, when perihelion occurred in summer and the earth's axial tilt was greater than it is today, the CCM simulates a slightly enhanced high pressure cell (Kutzbach, 1987). The outer Borderland Basins lie beneath the axis of the California Current and are thus ideally situated to study long-term (last one million years) changes in upwelling intensity and productivity at relatively high resolution (10^2 years).

Coastal California Upwelling

Upwelling along coastal California is driven by "equatorward" winds that roughly parallel the coast (Huyer, 1983). Ekman transport of surface waters by these winds causes transport of surface waters away from the coastline and upwelling of nutrient-rich waters from below. The upwelling waters are restocked by shallow flow inward toward the shelf beneath the surface ocean layer. The winds are seasonally to the south in northern California but always blow toward the equator south of San Francisco. In addition, upwelling-favorable winds are strongest in the north during the seasonal upwelling period. This wind pattern, today, causes the strongest coastal upwelling in July to be located between Cape Blanco and San Francisco in the north, but in the winter months causes the strongest upwelling to be located south of San Diego (Huyer, 1983). This seasonal cycle of winds and upwelling is a direct result of the seasonal migration of the North Pacific High pressure regime. The North Pacific High migrates between its southerly limit at 28°N in February and its most northerly limit, 38°N, in July (Huyer, 1983). Thus by monitoring the strength, and if possible, the seasonality of coastal upwelling along coastal California in paleoceanographic studies, we will be able to track the latitudinal position and strength of the North Pacific High as climate changes.

The Southern California Bight, which extends from Point Conception (34°N) to Cape Colnett (31°N), has a somewhat more complicated hydrographic setting. The Bight consists of a series of basins and ridges, and a coastline that trends northwest-southeast. As a result of this coastline orientation, the California Current lies farther offshore in the Bight than it does along northern California or Baja. The Southern California Countercurrent (SCC) flows northward along the coast of the Bight and is comprised of eddies spun off by the California Current and warmer and saltier water originating south of the Bight. At Point Conception, most of the SCC water rejoins the southward flowing California Current. The interaction of the Southern California Countercurrent and the California Current result in a cyclonic flow pattern around the Bight. A more detailed description of the physical oceanography of the Southern California Bight is provided in Eppley (1986). Offshore Ekman transport is lower in the Bight than along the regions immediately to the north and south due to the more offshore position of the California Current (Figure 1). However, significant upwelling does occur in the bight due to local wind stress curl. Between 30° and 40°N there is a positive wind stress curl that induces upwelling and this in turn reinforces the coastal upwelling (Nelson, 1977). In the California Bight, this curl induced upwelling is greatest during the spring (Figure 1).

We envision major changes in the axis of the California Current and the California Eddy System south of 40°N during glacials depending on the position of the North Pacific high pressure cell. Experiments by Kutzbach (1987) indicated a southward displacement of the North Pacific high pressure cell from 40°N today to around 30°N, adjacent to the California Borderland Province during the Last Glacial Maximum (Figure 2). This change in wind forcing at 30°N would have been coupled with exposure of land masses now covered by water around the Channel Islands. Consequently, the Cortez Ridge may have acted as Point Conception does today in diverting the California Current westward away from the coast and causing strong upwelling in its wake. This would depend, however, on the longitude of the high pressure cell. The Kutzbach (1987) July simulation indicates an eastward shift in the position of the cell with its center at around 130° at 18 ka. If this simulation is correct it would imply that wind stress over the borderlands may have actually diminished and that prevailing summer winds would have been more from east than from the north. Hence, Ekman transport and seasonal upwelling would also have been reduced rather than enhanced by the southward shift in the high pressure cell. It is important to resolve this uncertainty because it relates to the strength of the California Current and hence, the net mass transport of low salinity waters from the North Pacific towards the equator. It is also not clear whether a strong eddy system would have developed south of Cortez Basin, causing a cyclonic circulation to develop off the California Current system within the Southern California Bight. Paleoreconstructions of surface circulation patterns and upwelling intensity south of Point Conception and within the California Bight, in particular, are needed to address this issue.

There is preliminary evidence to support the notion that circulation within the California Bight was significantly different during low stands of sea level. Interpreting the data in the context of the above is not possible without information from the entire California margin. For example, planktonic foraminiferal isotopic data from San Nicolas Basin, lying on the landward side of Cortez Ridge, record a glacial/interglacial $\delta^{18}O$ change of between 2.7‰ and 3.0‰. Since the ice volume effect is 1.3‰ (Fairbanks, 1989), the waters overlying San Nicolas Basin were either colder and/or more salty during the last glacial than they are today. If the residual 1.7‰ was due to temperature alone this would imply surface waters were approximately 8°C colder than they are today. This result is enigmatic since CLIMAP (1984) estimated that glacial temperatures along Southern California were no more than 2°C colder than present. In support of the isotopically-derived 8°C change is the fact that the glacial planktonic foraminiferal assemblages are dominated by left-coiling *Neogloboquadrina pachyderma,* a species characteristic of present-day spring-time conditions in the subpolar region of the northeast Pacific (Reynolds and Thunell, 1986). Similar isotopic values are also recorded in Tanner Basin which lies seaward of San Nicolas Basin and west of Cortez Ridge. In light of the CLIMAP results why should there have been such a large glacial/interglacial $\delta^{18}O$ change in these two adjacent basins? We believe there are two possible explanations both involving changes in surface circulation patterns during glacial conditions. One interpretation of these results would have involved changes in the strength of upwelling within the basins. There may have been stronger upwelling over San Nicolas and Tanner Basin during glacial intervals. Enhanced upwelling would bring colder sub-surface waters to the surface and cause *G. bulloides* $\delta^{18}O$ values to increase. Enhanced upwelling in the region of the Borderland Basins may be a logical consequence of the southward shift in the North Pacific high pressure cell indicated in the model results of Kutzbach (1987).

If the CLIMAP estimates are approximately correct, however, the isotopic results from Tanner and San Nicolas Basin could reflect a change in surface water salinities compared to today (^{18}O of waters is correlated to salinity through evaporation/precipitation; Craig and Gordon, 1965). The surface waters of the California Current would have been saltier, either due to higher net evaporation over the basins or because salinities in the North Pacific also increased during the last glacial. This is consistent with Herguera et al.'s (1991) suggestion that salinities in the North Pacific increased enough during the last glacial to produce intermediate waters.

Late Pleistocene Paleoceanographic Studies

Gorsline and colleagues (Gorsline et al., 1968; Gorsline and Barnes, 1972; Gorsline and Prensky, 1975) have published a number of studies dealing with glacial-interglacial changes in sedimentation in the outer Borderland Basins. In these basins, sediments from the last glacial are characteristic of polar-subpolar climates. In contrast, Holocene sediments from the outer basins have lower carbonate accumulation rates and a warmer foraminiferal fauna. Based on these observations, Gorsline and Prensky (1975) concluded that upwelling was more intense and productivity higher during the last glacial relative to the Holocene. This hypothesis will be tested during Leg 167. Background studies needed to calibrate the paleoceanographic records are already in progress. The Multitracers Study (Collier et al., 1989) has used sediment traps and plankton tows to calibrate paleoceanographic tracers of primary productivity and water masses in the northern sector of the California Current. The tracers have then been measured in the sediments to describe the evolution of this region during deglaciation (Welling, 1990; Dymond and Lyle, in press; Karlin et al., in press; Sancetta et al., in press; Dymond et al., in press; Lyle et al., in press) and will provide the basic means for calibrating the northern sector studies in this program. Studies in the southern study area by Thunell and his colleagues (e.g., Sautter and Thunell, in press) and by several Scripps Institution of Oceanography research projects are providing similar information around the southern transect.

The deglaciation studies indicate how the combination of modern studies and paleoceanographic work can be a powerful tool to interpret environmental change. Sancetta et al (in press) show that spring bloom diatom species were much more abundant at 18 ka than in Holocene sediments. In contrast, diatom species associated with summer upwelling almost triple in abundance from glacial to Holocene sediments. Similarly, redwood pollen, a tree species that prefers regions of summer coastal fog, appears only after 11 ka (Sancetta et al., in press). This is another indicator of coastal upwelling, since coastal summer fogs are characteristic of regions where upwelling brings cold water to the surface ocean. The two data sets indicate to us that persistent summer upwelling only appeared after ice retreat, in the Holocene, off northern California and Oregon.

Radiolarian studies from the Multitracers sites (Moore, 1973; Pisias and Welling, unpubl.) calibrated to sediment trap, plankton tow, and surface sediment compositions show that the peak in subarctic conditions in the region was at 15 ka., coincident with the maximum in the Cordilleran ice sheets. The glacial-interglacial transition as recorded by the transition from subarctic conditions to conditions more typical of the Holocene was completed well before 11 ka, which again is similar to the near complete withdrawal of ice from the Pacific Northwest (Booth, 1987).

Finally, peak carbonate burial in the northeast Pacific did not occur at 18 ka, but reached a maximum at about 15 ka, coincident with maximum subarctic conditions, and then dropped abruptly to a plateau at about 11 ka (Karlin et al., in press; Lyle et al., in press). A further drop in carbonate contents occurred at 7 ka, and carbonate contents have remained low since then. The total change in calcium carbonate CCD in the northeastern Pacific is about 2 km since the last glacial maximum, much greater than any other location in the Pacific Ocean. We still do not understand whether the carbonate peak is associated with high calcium carbonate production relative to that of organic carbon in subarctic surface waters, or to associated changes in deep-water corrosiveness to calcite.

We have interpreted these features to indicate that the deglaciation caused a major northward shift in the transition zone between subarctic water masses and water masses more commonly associated with the California Current. The shift in radiolarian faunal boundaries spanned almost 10° of latitude (Pisias, unpubl.). Associated with this shift was the appearance of persistent summer upwelling off the southern Oregon coast, which had been poorly developed during glacial times. All of these patterns are consistent with an ocean that responded to the shifting wind patterns associated with the deglaciation.

Kutzbach (1987) has suggested that a major feature of the deglacial change is a northward migration of the North Pacific High, which should have produced both local- and remotely-forced changes in the California Current System. The model suggests that the center of the high was offshore Cape Conception (35°N) in July at the last glacial maximum and at approximately 40°N now.

It is probable that both the average trade-wind strength and the average strength of the westerlies should have a major impact on mean transport in the California Current. Interestingly, the paleoceanographic studies indicate a response to climate change remotely forced from the region of the California Current. Since part of the response of the California Current to climate change seems to be externally forced, studying the evolution of the California Current will produce important information about the interactions of the wind-field over much of the Pacific Ocean. In addition, because coastal upwelling in the region responds to the local wind field, we will be able to infer wind patterns from changes in paleoproductivity .

Studies of laminated sediments in the Santa Barbara Basin demonstrate that from 8 ka to the present there were only minor changes in the importance of radiolarian assemblages associated with the California Current (Pisias, 1978). Most of the changes in the radiolarian assemblages were with fauna found in subtropical water masses. The inferred sea surface temperature changes and recent oceanographic data all suggest that low latitude processes had significant impact on the California Current offshore Southern California (Pisias, 1978). It has not yet proved possible to collect a longer sediment record from the Santa Barbara Basin in order to examine the Pleistocene record. Repeated attempts to piston core the basin have been stopped by turbidites at around 11 ka.

Records that cross the Pleistocene/Holocene boundary have been recovered from Tanner Basin, one of the outermost basins of the California Continental Borderlands province (Gorsline et al., 1968; Kheradpir, 1970; Morin, 1971; Kahn et al., 1981) Their studies have shown that there are significant carbonate variations and faunal changes since the last glacial maximum. It is unclear, however, whether the carbonate curves represents variable dilution by terrigenous material or changes in carbonate burial flux (Kheradpir, 1970). Oxygen isotope studies and faunal analyses have suggested that sea surface temperatures have warmed by about 5°C since 18 ka (Kahn et al., 1981). Further oxygen isotope work is now being done in the basin by Alan Mix (pers. comm.), and sediment trap studies being carried out by Robert Thunell (pers. comm.) will define the modern seasonal flux cycle of microfossils and major sedimentary components to help calibrate the paleoceanographic record. A synthesis of previous sediment trap results for Panama Basin, San Pedro Basin and Gulf of Alaska (Station PAPA) is presented in Sautter and Thunell (1991). Our results indicate that plankton respond rapidly at the species level to sudden hydrographic changes and that patterns of seasonal succession reflect the establishment of distinctly different environmental settings. Rapid increases and decreases, on time scales of a week or less, in foraminiferal flux are an indication of how rapidly this plankton group responds to changes in surface water conditions. Micropaleontological, organic geochemical and stable isotopic studies of material collected during our previous sediment trap experiment in San Pedro Basin and current trapping project in Santa Barbara Basin will provide a good basis for interpreting the climate records contained in the Borderland sediments.

Neogene Paleoceanographic Studies

A series of DSDP cores and uplifted basins along the North American continental margin have been studied by Ingle (1973, 1981) to outline pre-Pleistocene paleoceanography of the margin. Marked variations in planktonic foraminiferal assemblages have been observed since the early Miocene (see also Barron and Keller, 1983; Barron, 1986). Subtropical faunas, which today are confined to the southernmost part of California, have expanded several times northward, at times as far north as northern California. It is unknown at the present time whether these changes represent changes in upwelling strength, changes in basinal circulation, or a combination of the two end-member processes. Study of core transects will help to evolve a proper understanding of the dynamics of the north Pacific Ocean. Newly drilled material will also permit study of most of the Neogene section at a time resolution impossible to do on DSDP sedimentary material or on land. Much of the material on land has also been subjected to significant burial diagenesis before it was uplifted and exhumed. It is also difficult to get a high-resolution time scale for many of the exposed basins. Drilling offshore will provide stratigraphic ties between the exposed basins on land and the marine sedimentary record.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To examine the Neogene fluctuations in the strength of the California Current in response to climate and tectonic reorganizations of the Pacific Basin and the effects of these fluctuations on heat and salt transport in the Pacific Ocean, upwelling along coastal California, and primary productivity.

2) To study changes in the calcite compensation depth in the northeast Pacific.

3) To determine a) how both terrestrial and marine organic carbon are preserved in continental margin and hemipelagic sediments, and how deposition rates change as a function of distance from shore, b) the relationship between organic carbon preservation and primary productivity, sedimentation rate, and bottom water oxygen content, c) how Neogene climate changes and the

related growth of continental ice sheets in both northern and southern hemispheres changed the burial of calcium carbonate, marine organic carbon, and terrestrial organic carbon in the northeast Pacific, and d) the high-resolution history of organic carbon burial as it relates to climate change, using ultra-high-resolution Pleistocene records in the santa barbara Basin to more typical 10-100 cm/k.y. hemipelagic records.

4) To study the formation of gas hydrates and the origin of a prominent bottom-simulating reflector in the Eel River Basin

5) To study of the Plio-Pleistocene deformation of the Gorda Plate, the northward movement of the Mendocino Triple Junction, and basement composition and rotation rates of possible terranes along coastal California..

6) To examine geomagnetic secular variations and the nature and timing of small-scale geo-magnetic excursions.

Specific Objectives and Methodology

Plio-Pleistocene Climate and Oceanography since Northern Hemisphere Glaciation

How do the ice ages affect the wind patterns of the North Pacific, and how do these wind patterns affect the physical variables important to thermohaline circulation (i.e., the oceanic heat and salt balance)? From modern analogy, we can ascertain that changes in California Current flow and coastal upwelling are strongly linked to the wind field over the north Pacific Ocean. By monitoring California Current flow further in the past, we will learn vital information about north Pacific wind fields needed to constrain detailed global paleoceanographic and climatic models. By standard paleoceanographic techniques we can also monitor paleotemperature and can model salinity.

The Plio-Pleistocene sections proposed to be drilled off the California margin will also study the longer term evolution of climate in the region. For example, in the late Pleistocene and Holocene, the north Pacific is not saline enough to form deep waters. During the last 5 m.y., however, uplift of the Cascade Ranges, Sierra Nevada, and Colorado Plateau may have significantly decreased the export of fresh water out of the north Pacific and may have shut off earlier deep water formation. If the Atlantic Ocean is an analogy, this should have been extremely important for the cooling of high latitude North America. Monitoring of the California Current is one of the best ways to study deep water formation in the north Pacific, because formation of north Pacific deep waters should weaken California Current flow and warm subarctic waters.

Drilling will also provide oceanic reference sections for modeling late Neogene climates of western North America. The arid western regions of the United States contain abundant, typically glacial, late Neogene lacustrine deposits. The fluctuating lake levels in the Great Basin may be caused by either changes in regional precipitation, or temperature-mediated evaporation. A better understanding North Pacific oceanography and climate will greatly help our understanding of the associated continental climate regimes.

Surface Water Geochemistry and Circulation History

By drilling in the California Borderland Province, we will recover Pleistocene records suitable for resolving the paleoceanography south of Point Conception, specifically to investigate glacial/ interglacial changes in the geochemistry of the California Current and to investigate whether the exposure of Cortez Ridge along the outer margin of the California Borderland Province during low stands of sea level caused the axis of the California Current to shift seaward, producing a hydrographic setting near 30°N similar to that of Point Conception today. The consequence of this, in conjunction with a shift in the North Pacific High Pressure Cell (Kutzbach, 1987), would have been a southward shift in the latitude of strongest upwelling and marine productivity associated with this current system from 40°N to about 30°N, adjacent to the Borderlands.There is reason to believe that surface circulation south of Point conception, and specifically within the California Bight was significantly altered by glacial climatic and sea level changes. Hence, one of the primary objectives for ODP drilling in the California Borderland is to determine how the circulation system operated and how this influenced upwelling and organic productivity under glacial conditions.

On shorter time scales, the Santa Monica and Santa Barbara laminations contain microfossil remains of plankton living at the time each laminae was being deposited. Calcareous microfossils, particularly planktonic foraminifera, are a conspicuous component of this material. The planktonic foraminifera will be used to reconstruct paleo-sea surface temperatures and infer changes in nutrient cycling using faunal/floral, stable isotopic, and trace element techniques. Sediment trapping studies in San Pedro Basin and Santa Barbara Basin provide the basis for interpreting the fossil assemblages found in the inner basins. This type of analysis is currently being used to reconstruct biannual sea surface temperatures records for the past 1000 years (Stott, in prep.). The historic record of spring sea surface temperatures and temperatures estimated from the $\delta^{18}O$ of planktonic foraminifera *(Neogloboquadrina pachyderma*-dextral) extracted from ^{210}Pb-dated laminae from Santa Monica Basin show a strong similarity suggesting this technique can be used to study the patterns of temperature variability beyond the historic records.

One of the most promising lines of research made possible by recovering the laminated sequences is the reconstruction of short-term climate cyclicity and the character of climate variations which are not possible from bioturbated sequences. For example, by using spectral analysis Hagadom and Stott (in prep.) have found a strong repetitive pattern in $\delta^{18}O$ values of planktonic foraminifera extracted from individual laminae extending from 1988 to 1700 in a Santa Monica box core sequence. In this record there is a strong spectral peak at about 15 years. This pattern is also apparent in the shorter historic record of sea surface temperatures.This may indicate a pattern of sea surface temperature variability responding to a decadal-scale forcing function. At this time there is no clear indication what that forcing function is. However, one important objectives in obtaining longer ODP core sequences in the inner basins is to determine whether this has been a persistent pattern, extending through larger climate changes like the Little Ice Age, and back to the Last Glacial Maximum. This would provide a comprehensive record against which climate models could be tested at time scales not normally available from conventional geologic records. Interestingly, there is no strong spectral peak at 5 to 7 years in the fossil isotopic record that would point to a clear El Niño forcing. If the record of El Niño influence is present it is either obscured at the sample resolution available from the Santa Monica laminae (2 year resolution/laminae) or these events have not been sufficiently cyclic in the Borderlands. A higher resolution record from Santa Barbara Basin (1 year resolution) will help answer this question.

Deep Water History

The California Borderland basins underlie the highly productive waters of the California Current System (Eppley, 1986). The inner basins (Santa Barbara and Santa Monica) are characterized by high sedimentation rates (10-200 cm/k.y.) of mostly hemipelagic origin. Santa Monica and Santa Barbara Basins have maximum depths of 925 m and 575 m respectively, and are dysaerobic to anoxic over much of their basin floors. Anoxia results from restricted deep water convection over the shallow sills that surround the basins (Gorsline and Teng, 1989). At the present time there is no benthic bioturbation in the center of Santa Monica Basin. X-radiographs of box core sections taken from the center of the basin reveal distinct laminations in the top 30 centimeters of sediment. This lamination pattern is similar to that of Santa Barbara Basin. However, the thickness and frequency of lamination differs significantly between the two basins. Sedimentation rates are approximately twice as high in Santa Barbara Basin compared to Santa Monica. The laminae in Santa Barbara Basin are true varves and are thought to originate from seasonal variations in the sediment particles supplied to the basin. In the winter, detrital silts and clays are carried by stream runoff, and biogenic particles, mainly diatoms, are produced during spring and summer blooms.

In Santa Monica Basin the average frequency of lamination is approximately 5-7 years, closely related to El Niño frequency (Christensen, 1991; Gorsline, in prep.). The laminations show up in X-radiographs as density contrasts. The cause of these density contrasts is not known although various ideas have been set forth, including, differences in % organics, % clays, and/or % biogenic material, (Grant, 1991). The laminations are non-continuous, extending back only to the middle of the Little Ice Age (Christensen, 1991). There is evidence from a single piston core that prior to the Little Ice Age the basin alternated between anoxic and oxic conditions at least back to ~10 ka. There is a good possibility, therefore, that alternating anoxic/oxic conditions and laminations have occurred in Santa Monica Basin during the Pleistocene in response to specific environmental and climate variations. Understanding the forcing mechanism that produce these alternating conditions in relation to climate changes is a primary objective of ongoing research by a number of research groups. A long sediment record that can be obtained by the Ocean Drilling Program is an essential need in these studies.

Berelson et al. (1987) and Hickey (1991) have shown that San Pedro Basin (the basin immediately south of Santa Monica Basin) has been flushed periodically by oxygen enriched waters. The most recent documented flushing occurred in 1982-1984 during the last major ENSO event. This was followed by an extended period of stagnation between 1984-1987. During the stagnation period the bottom of San Pedro Basin became essentially anoxic. In contrast to Santa Monica and Santa

Barbara basins there is no evidence of laminations in this basin, in the top several meters of the sediment column (Lund, pers. comm.). Hence, the oxygen concentrations have always remained high enough to support a benthic community capable of at least periodically homogenizing the sediment column. However, the process of periodic deep water oxygenation documented for San Pedro Basins may provide a clue to the process that produces laminations in Santa Monica Basin and Santa Barbara Basins.

Reimers et al. (1990) have proposed that seasonal renewal of deep water in Santa Barbara Basin is partially responsible for the varved character of deep basin sediments. During periods of stagnation, bacterial growth on the sediment surface is enhanced and this leaves an organic rich layer on the surface. In Santa Monica Basin, however, the renewal of oxygen during ENSO events is not sufficient to allow bioturbating organisms to re-inhabit the basin floor.

Santa Monica may be an example of an intermediate-condition between that of San Pedro and Santa Barbara Basins. In Santa Monica, the deep waters may also be periodically renewed as in San Pedro. However, during the past 300 yr. there has either been too little time and/or too little oxygen renewal to allow benthic communities to repopulate and bioturbate the sediment column. Because the lamination frequency is longer in Santa Monica compared Santa Barbara Basin the periodic renewal of deep waters supplies enough oxygen to inhibit the onset of bacterial growth in Santa Monica Basin. At slightly higher oxygen concentrations or with shorter stagnation periods the basin may become repopulated by bioturbating organisms. This appears to be the case for the time interval spanning the Little Ice Age. If this scenario is correct, the pattern and history of laminations and the chemical signatures of the laminae in Santa Monica and Santa Barbara Basins will provide important insight to the oceanographic processes linked to climate forcing (e.g., ENSO).

A downcore comparison of geochemical records from Santa Monica and in Santa Barbara Basins would allow reconstruction of the strength, duration, and frequency of interbasinal deep water communication patterns and oxygen renewal during various climatic cycles. Long sediment records from Santa Monica Basin and Santa Barbara Basin that extend back at least to the Last Glacial Maximum are a necessary component to a comprehensive reconstruction of deep water processes and circulation within the Borderlands. The hydrographic setting we envision during low stands of sea level would have caused further restrictions to deep water oxygen renewal. The recovery of long core sequences is necessary to determine if this is correct. If so, we expect to see a progressive reduction in deep water oxygen levels from the southern end (Cortez Basin) towards the north, passing through San Nicolas, Santa Cruz, Santa Monica and Santa Barbara Basins. This can be resolved using geochemical tracers and deep water faunal patterns as has been done for the modern (e.g., Douglas et al., 1979).

Pre-Late Pliocene

The objectives for pre-late Pliocene drilling are more reconnaissance in nature, partly to collect high-resolution northeast Pacific sedimentary sections for comparison with other Neogene sections recovered during Atlantic, Indian, and equatorial Pacific drilling. There are also a series of specific Miocene and Pliocene problems, such as continental evolution (e.g., the uplift of the Sierra Nevada Mountain Range), and comparison to marine deposits now uplifted and part of the continent. In particular, it will be important to tie offshore studies to the Miocene Monterey Formation, one of the best studied Neogene marine sections in the world. Specific objectives include:

Early Pliocene (~4.5 Ma): Was the early Pliocene decline in diatomaceous sedimentation documented in onshore and offshore sections of Southern California (Barron, 1986; Barron and Baldauf, in press) due to a slackening of the California Current and climatic warming (Ingle, 1973) or to a "silica shift" to deposition in the Antarctic (Barron, 1986; Barron and Baldauf, in press).

Late Miocene Carbon Shift (6.2 Ma): The top of the Monterey Formation is marked by an increase in terrigenous deposition which appears to be roughly synchronous and coincident with the late Miocene Carbon Shift (Barron, 1986). Both events may record an increase in transport of terrigenous organic carbon to the continental slope and deep sea. The east-west transect will be crucial for dating the resumption of increased terrigenous deposition at the top of Monterey-equivalent rocks and will help to determine if the events are synchronous and whether the increased terrigenous deposition was due to tectonics or to sea level changes.

Late Miocene High Latitude Cooling (~10-8 Ma): Late Miocene high-latitude cooling seemingly resulted in intensification of the California Current, as evidenced by displacement of subarctic and cool temperate faunas and floras to the south (Ingle, 1973), and also seems to have resulted in higher upwelling and deposition of relatively pure diatomaceous sediments in the upper part of the Monterey Formation (Barron, 1986; Barron and Baldauf, in press). The timing of the cooling in various sections of the transects and how productivity was affected can be established by drilling.

<u>Monterey Carbon Excursion</u> (17.8-13 Ma): Vincent and Berger (1985) relate a pronounced shift in the $\delta^{13}C$ of foraminifers between about 17.5 and 13.5 Ma to the rapid extraction of organic carbon from the ocean-atmosphere system and burial in marginal basins. This period coincides with the deposition of phosphate-rich sediments in the lower part of the Monterey Formation. Keller and Barron (1983) and Barron and Baldauf (in press) relate the onset of diatom-rich sedimentation in the Monterey Formation and elsewhere in the North Pacific to a "silica shift" from the North Atlantic to the North Pacific. Drilling sites on the continental margin are likely to encounter the base of "Monterey-like" deposition and to recover sections coincident with the Monterey Carbon Excursion and can be used to further evaluate this hypothesis.

Sedimentation History

The sedimentation patterns within the Borderlands are largely controlled by the climate, topography (above and below sea level) and the size and exposure of various terrigenous sources (adjacent topography and rivers). During the Pleistocene the sedimentation patterns would have been significantly altered by climate changes, sea level changes and vegetation differences. The sedimentation patterns throughout the basins provide important information about the environmental history of the region.

During the last three to four centuries, sedimentation in the center of Santa Monica Basin has been dominated by fine-grained hemipelagic sediments (Malouta et al., 1981). The top 10 to 20 cm of sediment in the deep (>870 m), central portion of Santa Monica Basin are green, clayey silts with uniformly low sand contents of 2 to 4% by weight and mean grain sizes from 3 to 8 μm (Gorsline and Emery, 1959; Gorsline, 1980; Malouta et al., 1981). Surficial sediments in the center of the basin contain an average of 7 to 8% carbonate and as much as 6% organic carbon by weight. Based on seismic interpretations, Gorsline and Teng (1989) indicate that this type of sedimentation pattern has characterized sedimentation in the basin throughout the Holocene. Terrigenous input is the dominant component, contributing 75 to 80% of the sediment deposited in the basin during the Holocene (Schwalbach and Gorsline, 1985). The remaining portion is biogenic, consisting of fossil carbonate, silica and organic carbon. Interestingly, the thickness of light and dark laminations that appear in the Santa Monica X-radiographs appear to correlate with the record of rainfall and river runoff (Figure 3). The pattern of lamination in down core sediments extending through the Pleistocene should provide important insight about the pattern of rainfall and runoff during large-scale climate changes.

Interpretation of pre-Holocene sedimentation patterns using seismic sections suggest that deposition in the central portion of Santa Monica basin has been primarily hemipelagic throughout the Pliocene-Pleistocene (Gorsline and Teng, 1989). These form flat-lying reflections of varying amplitude and continuity. The Plio-Pleistocene sequences have been subdivided into two units (Pl and P2) on the basis of a distinct basin-edge unconformity. Seismic facies interpretation indicate that PI is mostly shelf to deep basinal deposits and P2 is dominated by mass flow and hemipelagic deposits. At deeper horizons, the classical Miocene Monterey sequence do not appear to be preserved except as erosional remnants scattered around the basin margin. It may be totally missing in the center of the basin. The Plio-Pleistocene units appear to be lying on unstratified, discontinuous, hummocky basement reflectors. The basement rocks are the classical Franciscan complex. Coring into these deeper reflectors would confirm these interpretations and provide a calibration for further seismic interpretation throughout the borderlands.

Carbon Cycling and Organic Geochemistry

The Leg 167 transects, one near sources of major fluvial input (and thus near major point sources of terrestrial organic carbon input) and one off a relatively arid coastline, will help to define the typical rates of terrestrial organic carbon burial in hemipelagic sediments and can help to define how far terrestrial organic carbon travels from continental margins. Linking data about organic carbon burial to the paleoceanographic studies will provide major new information about how organic carbon burial responds to climate change, in some drill sites with yearly resolution. The laminated sediments of the Santa Barbara Basin preserve an ultrahigh-resolution record that can be used to study frequency of El Niños in the past and possible nonlinear responses of upwelling intensity to climate change (Lange et al., 1987; Kennedy and Brassell, 1991). Organic biomarkers

(Brassell et al., 1986; Prahl et al., 1989) can be used to determine the deposition rates of terrestrial organic carbon, to determine sea surface temperatures, and to determine the types of phytoplankton that are associated with marine productivity events.

The transects proposed along the California margin will also study how organic carbon is preserved in the sediments, an important but poorly understood geochemical process. The margin contains anaerobic basins, aerobic basins under high productivity, and a gradient of productivity offshore. There is also high preservation of organic matter near shore (30% or more of total organic carbon rain through the water column within 250 km of the coast; Jahnke, 1990; Dymond and Lyle, in press) and a sharp gradient to lower preservation beyond that distance. Drilling in the California margin will examine whether high productivity causes both anoxia and higher organic carbon burial (Pedersen and Calvert, 1990; Calvert and Pedersen, in press; Pedersen et al., in press) or whether slight differences in anaerobic versus aerobic decomposition rates lead to major enrichments in organic carbon (Canfield, 1989). The tie between sedimentation rate and organic carbon preservation (Heath et al., 1977; Müller and Suess, 1979; Henrichs and Reeburgh, 1987) and organic carbon preservation will also be studied by comparing paleoproductivity, sedimentation rate, and organic carbon preservation in older sediments drilled along the transect. Study of the carbon burial along this margin will also permit us to make oxygen balances for North Pacific deep waters. Jahnke and Jackson (1987) have shown that as much 50% of the all deep benthic oxygen consumption occurs along the eastern margins of ocean basins. Thus, carbon deposition along this margin may significantly affect the composition of sediments and ocean waters in the interior of the Pacific basin.

Wendorf and Pratt (in prep.) have recently documented anomalous %TOC/%TRS (Total organic carbon/Total Reduced Sulfur) in Santa Monica core samples. Coupling their findings with other geochemical data available from previous Borderland studies (e.g., Crisp et al., 1979; Jahnke, 1990; Jorgensen, 1983; Finney and Huh, 1988; Savrda et al., 1984), these workers note that sulfate reduction is not taking place in this anoxic basin to a depth of 20 cm in the sediment column. In other Borderland Basins, including Santa Barbara Basin, sulfate reduction occurs within the upper 20 cm (Leslie et al., 1990). Hence, Santa Monica appears to be unique among the Borderland Basins. Sulfate reduction may not occur in this basin until much deeper, possibly meters, below the sediment/water interface (Leslie et al., 1990). Wendorf and Pratt (in prep.) suggest the unique nature of the sulfur cycle in Santa Monica Basin compared to the other Borderland basins may be due to a difference in the reactivity of the organic matter reaching the bottom of this basin and possibly because there is a net flux of nitrate into the sediments (Jahnke, 1990).

Gas Hydrates

At least one Leg 167 site has known gas hydrates and a strong relatively deep BSR (proposed site CA-1 in the Eel River Basin; Field and Kvenvolden, 1985; Brooks et al., 1991). We plan to drill through this reflector and sample for composition, log for physical properties information, and for measurement of the temperature profile to document the range of conditions for formation of these environmentally important clathrates. The outcropping Eel River Basin gas hydrates recovered in piston cores appear to be composed of biogenic methane (Brooks et al., 1991). The temperature at the depth where the BSR is located will prove to be an important calibration point for the P-T stability field of these end member gas hydrates. In addition, with this calibration, one will be able to use seismic stratigraphy to map fluid flow out of a continental margin with significant components of both compression and transverse motion along it.

Tectonic Studies

Rotation and Deformation of the Gorda "Plate"

The assumption of rigid plate behavior breaks down in continental buffer zones (e.g., the western United States), oceanic island arcs with back-arc spreading (e.g., Mariana Trough and Arc), and for small remnants of the Farallon Plate along western North America (e.g., The Gorda Deformation Zone). Investigation of nonrigid plate behavior in continental crust is complicated by the heterogeneity of continental crust and resulting complex fault motions. Investigation of nonrigid plate behavior in arc and back-arc environments is complicated by volcanic overprinting.

Deformation in the region of the Gorda Ridge is more modest; it has modified but not obscured the magnetic anomaly pattern. The observations of clockwise fanning of Pacific/Gorda magnetic anomalies and of 20% shorter magnetic anomalies within the Gorda Deformation Zone than on the corresponding portion of the Pacific Plate would seem to imply subduction at the Mendocino

Transform. However, gravity profiles across the Mendocino Transform can be easily modelled without recourse to subduction (Wilson, 1989), and two focal mechanisms of earthquakes along the transform show simple strike-slip parallel to the fault. The alternative to Mendocino subduction is left-lateral strike-slip reactivation of isochron-parallel normal faults formed at the spreading center (Silver, 1971; and most subsequent authors). The extent (if any) of conjugate northwest-trending faulting is hotly debated. Five alternative models have been proposed for deformation in the Gorda Deformation Zone (Stoddard, 1987). Four of the models are shown in Figure 4; a fifth, by Wilson (1986, 1989) combines aspects of two of these end members. No model successfully accounts for the remarkable continuity of simple magnetic anomalies southward from undeformed Juan de Fuca Plate, through the magnetic bight transition to the Gorda Deformation Zone, and south to the Mendocino Transform.

Oriented piston coring of the hemipelagic sediments along an approximate isochron will collect a continuous record of tectonic rotation at the proposed sites, up to the point of refusal of the APC due to stiffening sediments. APC coring should penetrate at least to 1.6 Ma (100 mbsf) at proposed site CA-3, the site with the highest sedimentation rate, and more likely sediments as old as 3.7 Ma, at proposed site CA-4 (200 mbsf penetration). Thus we can expect to see continuous records of perhaps up to 40° rotation, at a resolution higher than and independent of rotations inferred from magnetic anomaly fabric (e.g., Riddihough, 1980).

How does young oceanic crust respond to forces that require nonrigid plate behavior? ODP Leg 116 (Bengal Fan) investigated the buckling and thrusting of old oceanic crust in response to compression approximately perpendicular to the crustal fabric. The proposed sites east of the Gorda Ridge will investigate the changing responses of young oceanic crust to compression in a geometry that permits reactivation of original normal faults with strike-slip or thrust components, or a combination of both. Such reactivation may also be typical on microplates during ocean spreading center reorganizations (Engeln et al., 1988). The two sites will provide important primary information on the timing and rates of rotation of the eastern flank of the Gorda Ridge and will detect differential rotation along strike, which are predicted by several models and will be immensely useful to define the paleoceanographic gradients away from the coast.

Translation and Rotation of the California Margin

Several distinct allocthons make up the margin of California, due to the distribution of shear between the Pacific and North American plates and to the instability of the Mendocino Triple Junction (McKenzie and Morgan, 1969; Dickinson and Snyder, 1979; Atwater, 1989; Figure 5). One of the mechanisms that the triple junction can migrate northward is by an inland shift of fault motion into North America, and seems to be shown by young continental fault structures found today around the Cape Mendocino Triple Junction (Atwater, 1989, and references therein). If this mechanism occurred, the oldest continental crust transferred to the Pacific Plate need not be at the modern location of the triple junction. Instead, the oldest crust should be found somewhere to the southwest.

The first order tectonic objective of the drilling along the California margin is to document the age, movement, and rotation of sedimentary basins on the continental margin. We seek to drill relatively undistorted basins, and will use the paleomagnetic information, combined with biostratigraphic ages to document translation, rotation, and tilting of the margin. We will also drill at least two of the margin holes to basement in order to identify basement and to recover sufficient sections of basement for dating and structural studies. Paleomagnetic information from the other sedimentary sequences along the California margin will help constrain motion along the margin, although they in themselves may not provide definitive information.

Paleomagnetism

The major source of information on processes occurring in the core comes from spatial and temporal changes in the geomagnetic field, termed paleosecular variation (PSV). The periods of historical observation and most lake sedimentary records are not of sufficient length to characterize the probable time scales of geodynamo processes. Significant progress has been made in the last few years in establishing the basic character of secular variation over the last 10 ka in glacial lake sediments and archaeological sites in America (e.g., Lund and Bannerjee, 1985; Sprowl and Bannerjee, 1985; Verosub et al., 1986; Hanna and Verosub, 1989) and Europe (e.g., Turner, 1983). These studies have found coherent patterns of secular variation on a regional scale with periodicities ranging from about 1200-2400 years (Lund and Olsen, 1987). The features may drift westward (Karlin, 1984) and "poleward-like" sunspots (Hagee and Olsen, 1989), but convincing global correlations remain elusive, partly because of the scarcity of high quality, well dated records. For certain intervals from about 10-40 ka, paleomagnetic records from dry lake deposits and DSDP Site 480 in the Gulf of California raise the tantalizing possibility that secular variation may contain recurring waveforms that migrate and evolve with time (e.g., Negrini et al., 1984, 1988; Levi and Karlin, 1989). However, these records are limited in time and areal extent and there is a strong need to assess the character and coherence of these patterns at this and other periods of time.

Very little is known of secular variation patterns on time scales of tens to hundreds of thousands of years. Studies of Lake Biwa (Kawai et al., 1972), Site 480 (Levi and Karlin, 1989) and the Blake Plateau (Denham, 1976) provide what little we know of paleosecular variation for the last 200 ka. The existence or global nature of geomagnetic excursions noted in these sediments have yet to be verified. Recently, Schneider and Kent (1986, 1990) reported persistent nondipolar features in pelagic equatorial piston cores. If substantiated, such long term nonaxial dipole behavior has important ramifications not just to understanding core dynamo processes, but also for evaluating the limits of paleomagnetism in plate tectonic reconstructions.

At present, there are no reliable long-term high-resolution paleomagnetic records from mid- and high-latitude sites. All of the sites along the California Margin, including those on the Gorda Ridge, are promising candidates for obtaining continuous geomagnetic field recordings. The high-resolution records from the proposed sites will address several very important questions concerning the behavior of the geomagnetic field during the Plio-Pleistocene, in particular 1) the timing and structure of geomagnetic excursions and reversals over the last 3-4 m.y., 2) the rate, direction, and permanency of non-polar drift, 3) the periodicities of secular variation over different time intervals and their spectral content variation, if any, through time, 4) the presence, if any, of characteristic waveforms in PSV patterns and whether their signature remains constant or evolves with time.

DRILLING PLAN/STRATEGY

Leg 167 consists of a series of transects across the California Current, along the California continental margin, and within the California Continental Borderland.

Three of the transects will extend across the California Current, one at about 40°N (the Gorda transect), one at about 35°N (the Conception transect), and one at about 30°N (the Baja transect). At each transect, changes in productivity and water properties (SST, nutrients, salinity) will be investigated as well as burial rates of carbonate and organic carbon. By comparing changes in properties across California Current flow (within each transect) to changes along flow paths, we can infer rates of upwelling and rates of advection for the California Current. Paired continental and pelagic sites will help us to understand deep and intermediate water properties within the region. A depth transect of sites within the Gorda Transect will enable reconstruction of the northeastern Pacific CCD.

Another transect will run from offshore into the California Borderlands Basins to investigate the evolution of intermediate waters that underlie the California Current and their effect upon paleoproductivity and organic carbon preservation along the continental margin. Modern intermediate flow is from the south, carrying poorly-oxygenated nutrient-rich tropical Pacific water northward into the region. There are indications that this circulation may reorganize, however, with climate change. This transect will also document the evolution of the Southern California Countercurrent.

The last transect is a north-south coastal transect, designed to study the evolution of productivity along the coast. Climate models suggest that the changing north-south upwelling patterns will be highly sensitive to changes in atmospheric circulation, and that these patterns will strongly constrain future versions of atmospheric and oceanic circulation models.

PROPOSED SITES

Along the margins, sites were chosen in areas of sediment accumulation isolated from major channels and sediment source regions. In the California Borderlands, sites were located in isolated basins or distal fan sections to provide both high sedimentation rates for high-resolution paleoceanographic studies and few turbidites or slumps to hinder interpretation of the sedimentary record. Offshore, pelagic sites were chosen on or near topographic highs to avoid the nearly ubiquitous fan and channel deposits along the continental margins.

Twenty potential drill sites have been identified (Figure 6, Table 1). Proposed site CA-3, the shallow pelagic site for CCD studies in the Gorda Transect, proposed site BA-1, an outer Borderland site to document the evolution of intermediate waters that flow into the Borderlands region, and redrilling of Site 893 to completely recover a section of the upper 200 m of sediments in the Santa Barbara basin are all considered alternate sites. Additional alternate sites include proposed site CA-13, the outermost site in the Conception Transect, proposed site BA-5 in the Descanso Plains, a potential hemipelagic window in a major sediment fan environment, and proposed site CA-7, off Point Arena.

REFERENCES

Atwater, T., 1989. Plate tectonic history of the northeast Pacific and western North America. *In* Winterer, E.L., Hussong, D.M., and Decker, R.W. (eds.) *The Eastern Pacific Ocean and Hawaii.* DNAG (Volume N): Geol. Soc. Am., 21-73.

Barron, J.A., 1986. Paleoceanographic and tectonic controls on deposition of the Miocene Monterey Formation and related siliceous rocks in California. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, 53:105-119.

Barron, J.A., and Baldauf, J.G., in press. Development of biosiliceous sedimentation in the North Pacific during the Miocene and early Pliocene. *Proc. 3rd Int. Working Group Meeting of IGCP Project 246* (University of Tokyo Press).

Barron, J.A., and Keller, G., 1983. Paleotemperature oscillations in the middle and late Miocene of the northeastern Pacific. *Micropaleontology*, 29:577-581.

Berelson, W.M., Hammond, D.E., and Johnson, K.S., 1987. Benthic fluxes and the cycling of biogenic silica and carbon in two Southern California borderland basins. *Geochim. Cosmochim. Acta*, 51:1345-1363.

Bolt, B.A., Lomnitz, C., and McEvilly, T.V., 1968. Seismological evidence on the tectonics of Central and Northern California and the Mendocino Escarpment. *Bull. Seis. Soc. Am.*, 58:1725-1767.

Booth, D.B., 1987. Timing and processes of deglaciation along the southern margin of the Cordilleran ice sheet. *In* Ruddiman, W.F., and Wright H.E., Jr. (eds.), *North American and adjacent oceans during the last deglaciation*: Boulder, CO (Geol. Soc. Am.), K-3: 71-90.

Brassell, S.C., Eglinton, G., Marlowe, I.T., Pflaumann, U., and Sarntheim, M., 1986. Molecular stratigraphy: a new tool for climatic assessment. *Nature*, 320:29-133.

Brooks, J.M., Field, M.E., and Kennicutt, M.C., II, 1991. Observations of gas hydrates in marine sediments, offshore northern California. *Mar. Geol.*, 96:103-109.

Calvert, S.E., and Pedersen, T.F., in press. Organic carbon accumulation and preservation in marine sediments: How important is anoxia? *In* Whelan, J., and Farrington, J. (eds.) *Productivity, accumulation and preservation of organic matter in recent and ancient sediments*: Columbia University Press.

Canfield, D.E., 1989. Sulfate reduction and oxic respiration in marine sediments: implications for organic carbon preservation in euxinic environments. *Deep-Sea Res.*, 30:121-138.

Christensen, C.J., 1991. An analysis of sedimentation rates and cyclicity in the laminated sediments of Santa Monica Basin, California Continental Borderland [M.S. thesis]. Univ. Southern California, Los Angeles, CA.

CLIMAP Project Members, 1984. The last interglacial ocean. *Quat. Res.*, 21:123-224.

COHMAP Members, 1988. Climatic changes of the last 18,000 years: observations and model simulations. *Science*, 241:1043-1052.

Collier, R.W., Dymond, J., Pisias, N., and Lyle, M., 1989. Effects of seasonal oceanographic cycles on the paleoceanographic record: Initial results from the MULTITRACERS Experiment. *Eos*, 70:365.

Craig, H and Gordon, L.I., 1965. Isotopic oceanography - Deuterium and oxygen 18 variations in the ocean and the marine atmosphere. *Rhode Island University, Narragansett, Marine Lab. Occ. Publ.*, 3-1965:277-374.

Crisp, P.T., Brenner, S., Venkatesan, M.I., Ruth, E., and Kaplan, I.R., 1979. Organic chemical characterization of sediment-trap particulates from San Nicolas, Santa Barbara, Santa Monica, and San Pedro Basins, California. *Geochim. Cosmochim. Acta*, 43:1791-1801.

Denham, C.R., 1976. Blake polarity episode in two cores from the Greater Antilles Outer Ridge. *Earth Planet. Sci. Letters*, 29:422-434.

Dickinson, W.R., and Snyder, W.S., 1979. Geometry of triple junctions related to San Andreas transform. *J. Geophys. Res.*, 84:561-572.

Douglas, R.G., Cotton, M.L., and Wall, L., 1979. Distributional and variability analysis of benthic foraminifera in the Southern California Bight. *Bureau of Land Management* (Volume II, Report 21).

Dymond, J., and Lyle, M., in press. Particle fluxes in the ocean and implications for sources and preservation of ocean sediments. *In* Hay, W.W. (ed.) *Geomaterial Fluxes, Glacial to Recent*: Washington, D.C. (National Research Council, National Academy of Science)

Dymond, J., Suess, E., and Lyle, M., in press. Barium in deep sea sediments: a geochemical indicator of paleoproductivity. *Paleoceanography.*

EEZSCAN84 Scientific Staff, 1986. Atlas of the exclusive economic zone, western conterminous United States. *U.S. Geol. Surv. Misc. Invest. Ser.*, I-1792.

Engeln, J.F., Stein, S., Werner, J., and Gordon, R.G., 1988. Microplate and shear zone models for oceanic spreading center reorganizations. *J. Geophys. Res,* 93:2839-2856.

Eppley, R.W., 1986. *Plankton dynamics of the Southern California Bight. Lecture notes on coastal and estuarine studies*: Berlin (Springer-Verlag).

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature,* 342:637-642.

Field, M.E., and Kvenvolden, K.A., 1985. Gas hydrates on the Northern California continental margin. *Geology*, 13:517-520.

Finney, B., and Huh, C.A., 1989. History of metal pollution in the Southern California Bight: An Update. *Environ. Sci. Technol.*, 23:294-303.

Gorsline, D.S., 1980. Depositional patterns of hemipelagic Holocene sediment in borderland basins on an active margin. *In* Field, M.E., Bouma, A.H., Colburn, I.P., Douglas, R.G., and Ingle, J.C. (eds.) *Quaternary environments of the Pacific coast.* SEPM Pacific Section Symposium, 4:185-200.

Gorsline, D., and Barnes, P., 1972. Carbonate variations as climatic indicators in contemporary California flysch basin. *Proc. 24th Int. Geol. Congr.*, 6:270-277.

Gorsline, D.S., Drake, D., and Barnes, P., 1968. Holocene sedimentation in Tanner Basin, California Borderland. *Geol. Soc. Am. Bull.*, 79:659-674.

Gorsline, D.S., and Emery, K.O., 1959. Turbidity-current deposits in San Pedro and Santa Monica Basins off Southern California. *Geol. Soc. Am. Bull.*, 70:279-290.

Gorsline, D. S., and Prensky, S., 1975. Paleoclimatic inferences for late Pleistocene and Holocene from California continental Borderland basins. *In* Suggate, R., and Cresswell (eds.) *Quaternary Studies.* The Royal Society of New Zealand, 147-154.

Gorsline, D.S., and Teng, L.S.-Y., 1989. The California Continental Borderland. *In* Winterer, E.L., Hussong, D.M., and Decker, R.W. (eds.) *The Eastern Pacific Ocean and Hawaii.* DNAG (Volume N): Geol. Soc. Am., 471-487.

Grant, C.W., 1991. Distribution of bacterial mats (*Beggiatoa* sp.) in Santa Barbara Basin, California: a modern analog for organic-rich facies of the Monterey Formation [MS thesis]. California State Univ., Long Beach, CA.

Hagee, V.L., and Olson, P., 1989. An analysis of paleomagnetic secular variation in the Holocene. *Phys. Earth Planet. Inter.*, 56:266-284.

Hanna, R.L., and Verosub, K.L., 1989. A review of lacustrine paleomagnetic records from western North America: 0-40,000 years B.P. *Phys. Earth Planet. Inter.*, 56:76-95.

Heath, G.R., Moore, T.C., Jr., and Dauphin, J.P., 1977. Organic carbon in deep-sea sediments. *In* N.R. Anderson, N.R., and Malahoff, A. (eds.) *The fate of fossil fuel CO_2 in the oceans*: New York (Plenum Publ. Co.), 605-625.

Henrichs, S.A., and Reeburgh, W.S., 1987. Anaerobic mineralization of marine sediment organic matter: rates and the role of anaerobic processes in the oceanic carbon economy. *J. Geomicrobiol.*, 5:191-237.

Herguera, J. C., Stott, L.D., and Berger, W.H., 1991. Glacial deep-water properties in the west equatorial Pacific: bathyal thermocline near a depth of 2000 m. *Mar. Geol.*, 100:201-206.

Hickey, B.M., 1979. The California Current system – hypotheses and facts. *Prog. Oceanogr.*, 8:191-279.

Hickey, B.M., 1991. Variability in two deep coastal basins (Santa Monica and San Pedro) off Southern California. *J. Geophys. Res.*, 96:16689-16708.

Huyer, A., 1983. Coastal upwelling in the California Current system. *Prog. Oceanogr.*, 12:259-284.

Huyer, A., Kosro, P.M., Fleischbein, J., Ramp, S.R., Stanton, T., Washburn, L., Chavez, F.P., Cowles, T.J., Pierce, S.D., and Smith, R.L., 1991. Currents and water masses of the coastal transition zone off Northern California, June to August 1988. *J. Geophys. Res.*, 96:14809-14831.

Ingle, J.C., 1973. Summary comments on Neogene biostratigraphy, physical stratigraphy, and paleoceanography in the marginal northeastern Pacific Ocean. *In* Kulm, L.C., von Huene, R., et al., *Init. Repts. DSDP*, 18: Washington (U.S. Govt. Printing Office), 949-961.

Ingle, J.C., 1981. Origin of Neogene diatomites around the north Pacific rim. *In* Garrison, R., and Douglas, R.G. (eds.) *The Monterey Formation and related rocks of California.* SEPM Pacific Section: Los Angeles, 159-179.

Jahnke, R. A., 1990. Early diagenesis and recycling of biogenic debris at the seafloor, Santa Monica Basin, California. *J. Mar. Res.*, 48:413-436.

Jahnke, R., and Jackson, G.A., 1987. Role of sea floor organisms in oxygen consumption in the deep North Pacific Ocean. *Nature*, 329:621-623.

Jorgensen, B.B., 1983. Processes at the sediment water interface. *In* Bolin, B., and Cook, R.B. (eds.) *The major biogeochemical cycles and their interactions:* SCOPE, 477-509.

Kahn, M.I., Oba, T., and Ku, T.L., 1981. Paleotemperatures and the glacially induced changes in the oxygen-isotope composition of sea water during late Pleistocene and Holocene time in Tanner basin, California. *Geology*, 9:485-490.

Karlin, R., 1984. Paleomagnetism, rock magnetism, and diagenesis in hemipelagic sediments from the N.E. Pacific Ocean and Gulf of California [Ph.D dissert.]. Oregon State Univ., Corvallis, OR.

Karlin, R., Lyle, M., and Zahn,R., in press. Carbonate variations in the NE Pacific during the late Quaternary. *Paleoceanography*.

Kawai, N., Yaskawa, K., Nakajima, T., Torii, M., and Horie, S., 1972. Oscillating geomagnetic field with a recurring reversal discovered from Lake Biwa. *Proc. Japan Acad.*, 86:412-420.

Keller, G., and Barron, J.A., 1983. Paleoceanographic implications of Miocene deep-sea hiatuses. *Geol. Soc. Am. Bull.*, 94:590-613.

Kennedy, J.A., and Brassell, S.C., 1991. Molecular stratigraphic record of 20th Century climatic variability. *Eos*, 72:273.

Kheradpir, A., 1970. Foraminiferal trends in the Quaternary of Tanner Basin, California. *Micropaleontology*, 16:102-116.

Knapp, J.S., 1982. Seismicity, crustal structure, and tectonics near the northern termination of the San Andreas fault [Ph.D. dissert.]. Univ. Washington, Seattle, WA.

Kutzbach, J.E., 1987. Model simulations of the climatic patterns during the deglaciation of North America. *In* Ruddiman, W.F., and Wright, H.E., Jr. (eds.) *North America and adjacent oceans during the last deglaciation*. DNAG Geology of North America (Volume K-3): Geol. Soc. Am., 425-447.

Lange, C.B., Berger, W.H., Burke, S.K., Casey, R.E., Schimmelman, A., Soutar, A., and Weinheimer, A.L., 1987. El Niño in Santa Barbara Basin: Diatom, radiolarian, and foraminiferan responses to the "1983 El Niño event". *Mar. Geol.*, 78:153-160.

Leslie, B.W., Lund, S.P., and Hammond, D.E., 1990. Rock Magnetic evidence for the dissolution and authigenic growth of magnetic minerals within anoxic marine sediments of the California Borderland. *J. Geophys. Res.*, 95:4437-4452.

Levi, S., and Karlin, R., 1989. A sixty thousand year geomagnetic record in the Gulf of California: DSDP Site 480. *Earth Planet. Sci. Lett.*, 92:219-233.

Lund, S.P., and Bannerjee, S.K., 1985. Late Quaternary paleomagnetic field secular variation from two Minnesota lakes. *J. Geophys. Res.*, 90:803-825.

Lund, S.P., and Olson, P., 1987. Historic and paleomagnetic secular variation and the Earth's core dynamo process. *Rev. Geophys.*, 25:917-928.

Luyendyk, B.P., Kammerling, M.J., and Terres, R., 1980. Geometric model for Neogene crustal rotations in Southern California. *Geol. Soc. Am. Bull.*, 91:211-217.

Lyle, M., Zahn, R., Prahl, F., Dymond, J., Collier, R., Pisias, N., and Suess, E., in press. Paleoproductivity and carbon burial across the California Current: The MULTITRACERS transect, 42°N. *Paleoceanography*.

Lynn, R.J., and Simpson, J.J., 1987. The California Current system: the seasonal variability of its physical characteristics. *J. Geophys. Res.*, C12:12,947-12,967.

Malouta, D.N., Gorsline, D.S., and Thornton, S.E., 1981. Processes and rates of recent (Holocene) basin filling in an active transform margin: Santa Monica Basin, California Continental Borderland. *J. Sediment. Petrol.*, 51:1077-1095.

McKenzie, D.P., and Morgan, W.J., 1969. The evolution of triple junctions. *Nature*, 224:125-133.

Moore, T.C., Jr., 1973. Late Pleistocene-Holocene oceanographic changes in the northeastern Pacific. *Quat. Res.*, 3:99-109.

Morin, R.W., 1972. Late Quaternary biostratigraphy of cores from beneath the California Current. *Micropaleontology*, 17:475-491.

Müller, P.J., and Suess, E., 1979. Productivity, sedimentation rate, and sedimentary organic matter in the oceans I. Organic carbon preservation. *Deep-Sea Res.*, 26A:1347-1362.

Negrini, R.M., Davis, J.O., and Verosub, K.L., 1984. Mono Lake geomagnetic excursion found at Summer Lake, Oregon. *Geology*, 12:643-646.

Negrini, R.M., Verosub, K.L., and J.O. Davis, J.O., 1988. The middle to late Pleistocene geomagnetic field recorded in fine-grained sediments from Summer Lake, OR, and Double Hot Springs, NV, USA. *Earth Planet. Sci. Lett.*, 87:173-192.

Nelson, C.S., 1977. Wind stress and wind stress curl over the California Current. *NOAA Tech. Report*, NMFS SSRF-714 (U.S. Dept. of Commerce).

Pares-Sierra, A., and O'Brien, J.J., 1989. The seasonal and interannual variability of the California Current system: a numerical model. *J. Geophys. Res.*, C3:3159-3181.

Pedersen, T.F., and Calvert, S.E., 1990. Anoxia versus productivity: what controls the formation of organic-carbon-rich sediments and sedimentary rocks? *AAPG Bull.*, 74:454-466.

Pedersen, T.F., Shimmield, G.B., and Price, N.B., in press. Lack of enhanced preservation of organic matter in sediments under the oxygen minimum on the Oman Margin. *Geochim. Cosmochim. Acta.*

Pisias, N.G., 1978. Paleoceanography of the Santa Barbara Basin during the last 8,000 years. *Quat. Res.*, 10:366-384.

Prahl, F., Muehlhausen, L., and Lyle, M., 1989. An organic geochemical assessment of oceanographic conditions at MANOP Site C over the past 26,000 years. *Paleoceanography*, 4:495-510.

Reimers, C.E., Lange, C.B., Tabak, M., and Bernhard, J.M. 1990. Seasonal spillover and varve formation in the Santa Barbara Basin, California. *Limnol. Oceanogr.*, 35:1577-1585.

Reynolds, L., and Thunell, R., 1986. Seasonal production and morphologic variation of *Neogloboquadrina pachyderma* in the northeast Pacific. *Micropaleontology,* 32:1-18.

Riddihough, R.P., 1980. Gorda Plate motions from magnetic anomaly analysis. *Earth Planet. Sci. Lett.*, 51:163-170.

Sancetta, C., Lyle, M., Heusser, L., Zahn, R., and Bradbury, J.P., in press. Late Glacial to Holocene changes in upwelling and seasonal production of the northern California Current system. *Quat. Res.*

Sautter, L., and Thunell, R., 1991. Planktonic foraminiferal responses to upwelling and seasonal hydrographic conditions: sediment trap results from San Pedro Basin, Southern California Bight. *J. Foraminiferal Res.*, 21:347-363.

Sautter, L.R., and Thunell, R., in press. Seasonal variability in the oxygen and carbon isotopic composition of planktonic foraminifera from an upwelling environment: sediment trap results from the San Pedro Basin, Southern California Bight. *Paleoceanography*.

Savrda, C.E., Bottjer, D.J., and Gorsline, D.S., 1984. Developments of a comprehensive oxygen-deficient marine biofacies model; Evidence from Santa Monica, San Pedro, and Santa Barbara Basins, California Continental Borderland. *AAPG Bull.*, 68:1179-1192.

Schneider, D.A., and Kent, D.V., 1986. Influence of non-dipole field on determination of Plio-Pleistocene true polar wander. *Geophys. Res. Lett.*, 13:471-474.

Schneider, D.A., and Kent, D.V., 1990. The time-averaged paleomagnetic field. *Rev. Geophys.*, 28:71-96.

Schwalbach, J.R., and Gorsline, D.S., 1985. Holocene sediment budgets for the basins of the California Continental Borderland. *J. Sediment. Petrol.*, 55:829-840.

Silver, E.A., 1971. Tectonics of the Mendocino Triple Junction. *Geol. Soc. Am. Bull.*, 82:2965-2978.

Sprowl, D.E., and Bannerjee, S.K., 1985. High-resolution paleomagnetic record of geomagnetic field fluctuations from varved sediments of Elk Lake, Minnesota. *Geology*, 13:531-533.

Stoddard, P.R., 1987. A kinematic model for the evolution of the Gorda Plate. *J. Geophys. Res.*, 92:11524-11532.

Sverdrup, H.U., Johnson, M.W., and Fleming, R.H., 1942. *The Oceans*: Englewood Cliffs, N.J. (Prentice Hall), 712-730.

Thunell, R., and Sautter, L., 1992. Planktonic foraminiferal faunal and stable isotopic indices of upwelling: a sediment trap study in San Pedro Basin Southern California Bight. *In* Summerhayes, C., Prell, W., and Emeis, K. (eds.)*Upwelling systems: Evolution since the early Miocene.* Geol. Soc. Am. Spec. Publ., 64:77-91.

Turner, G.M.,1983. Paleomagnetic results from recent European sediments. *In* Creer, K.M., Tucholka, P., and Barton, C.E. (eds.) *Geomagnetism of baked clays and recent sediments*:Amsterdam (Elsevier), 202-211.

Verosub, K.L., Mehringer, P.J., and Waterstadt, P., 1986. Holocene secular variation in western North America: paleomagnetic record from Fish Lake, Harney County, Oregon. *J. Geophys. Res.*, 91:3609-3623.

Vincent, E., and Berger, W.H., 1985. Carbon dioxide and polar cooling in the Miocene: the Monterey hypothesis. *In* Sundquist, E.T., and Broecker, W.S. (eds.) *The carbon cycle and atmospheric CO_2: natural variations Archean to Present*: Washington, D.C. (AGU), 455-486.
Welling, L., 1990. Radiolarian microfauna in the northern California Current system: spatial and temporal variability and implications for paleoceanographic reconstructions [M.Sc. thesis]. Oregon State University, Corvallis, OR.
Wilson, D.S., 1986. A kinematic model for the Gorda deformation zone as a diffuse southern boundary of the Juan de Fuca Plate. *J. Geophys. Res.*, 91:10259-10270.
Wilson, D.S., 1989. Deformation of the so-called Gorda Plate. *J. Geophys. Res.*, 94:3065-3075.

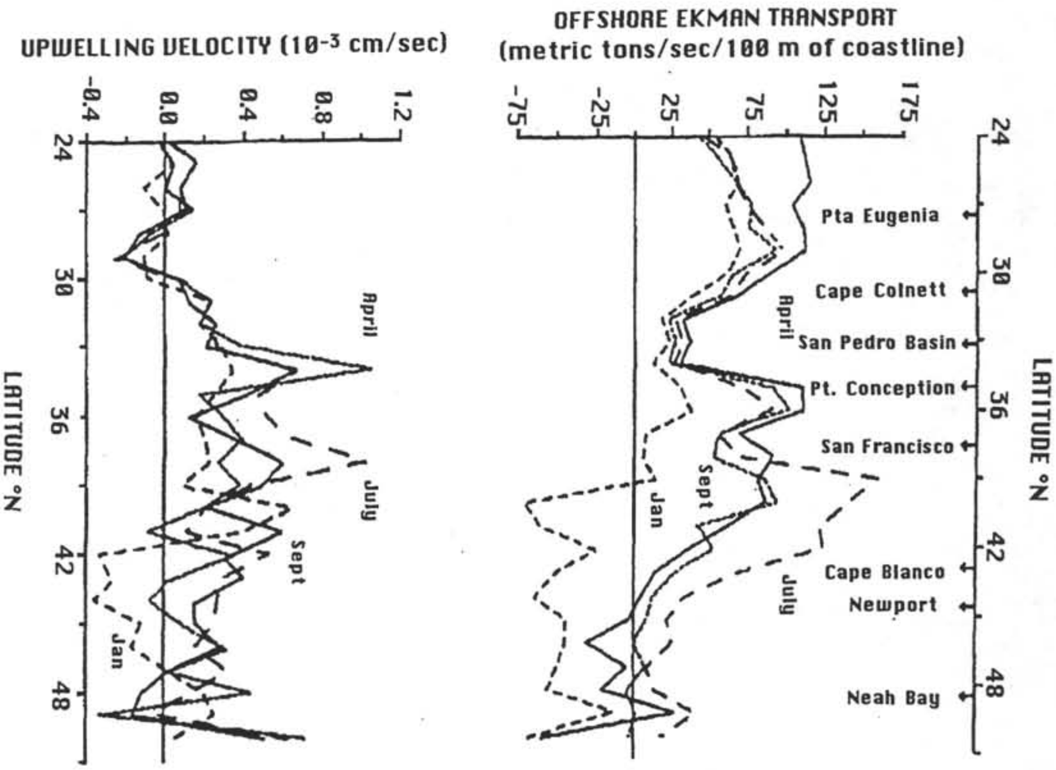


Figure 1: Offshore Ekman transport along the margin of California. Data was calculated from long-term mean wind stress data. From Thunell and Sautter (1992).

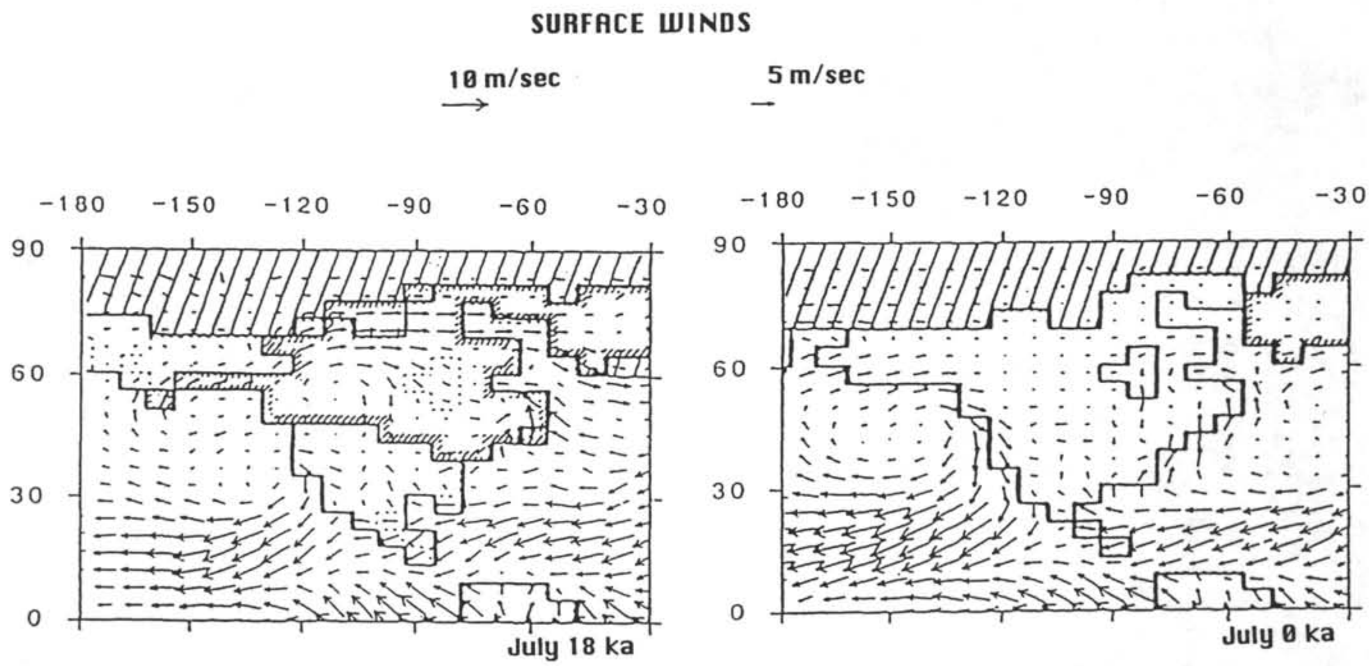


Figure 2. Surface winds generated from a global climate model for July, today, and at the last glacial maximum. Note the center of the North Pacific High at about 40°N at 10 ka and at about 30°N at 18 ka. From Kutzbach (1987).

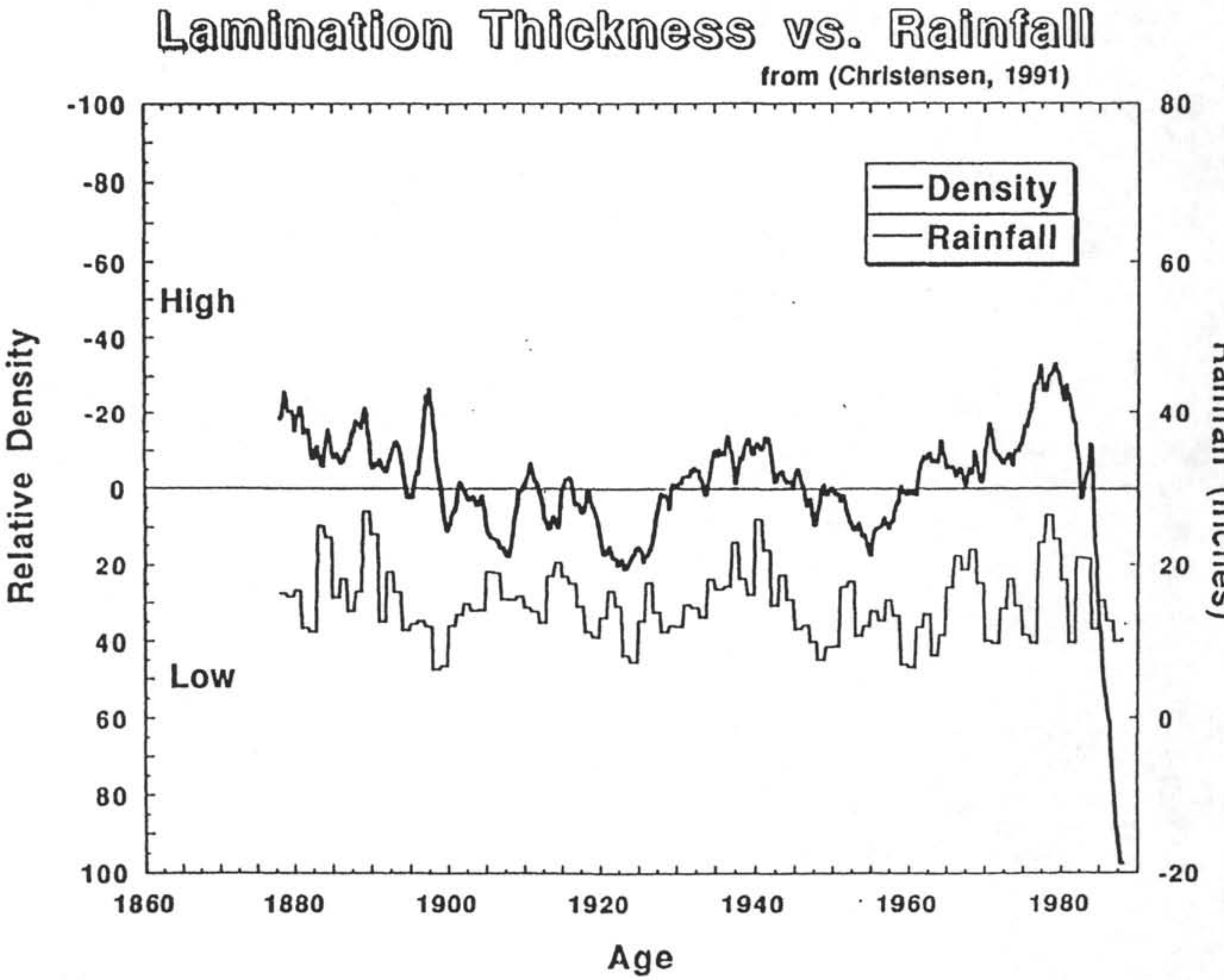


Figure 3. Plot of rainfall in the Los Angeles region (data compiled from the Los Angeles Times) together with the digital density patterns of light and dark lamina in box core DOE 26 from Santa Monica Basin. The correlation between rainfall and the lamination record suggests that the lamination record can provide information about climate variability that can be used in climate reconstruction (Gorsline, in prep.).

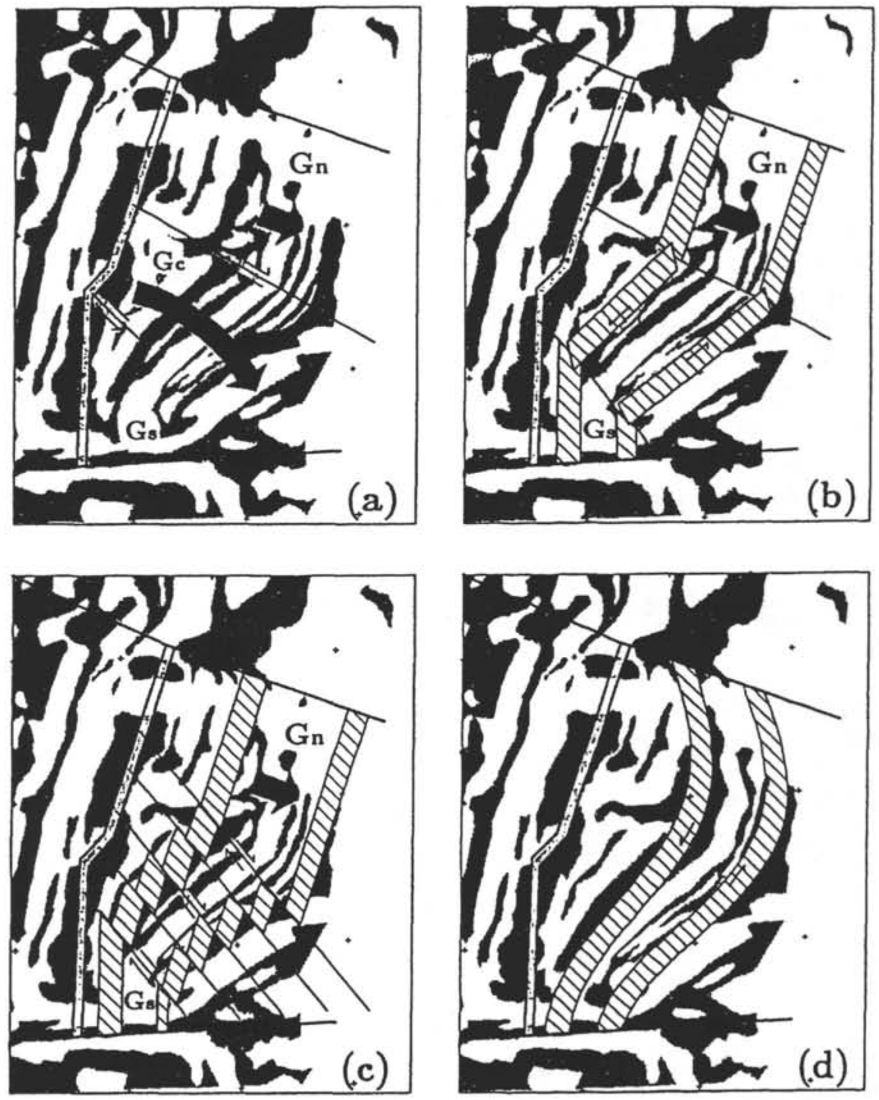


Figure 4. Tectonic models for evolution of the Gorda Deformation Zone (from Stoddard, 1987).

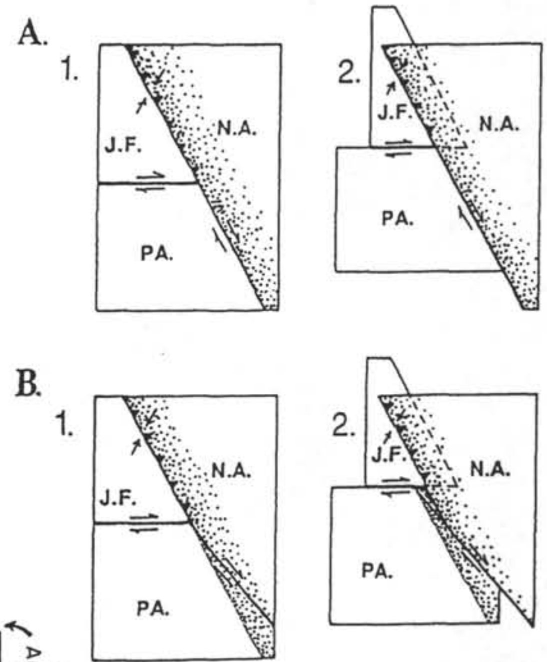
A) Riddihough (1980) treats the Gorda Deformation Zone as 2 rigid plates (Central and South) in order to reconstruct a tectonic history. The Gorda Deformation Zone is separated from the Juan de Fuca Plate along a fault zone running NW/SE from about 42.5°N at the Gorda Ridge. This model would suggest that all points along an isochron should have rotated through the same arc in each segment. In the case of a 4 Ma isochron, which we intend to drill, this arc is about 40° in a clockwise direction. The model also requires that the Gorda Deformation Zone would have to subduct beneath the Mendocino Fracture Zone in order to conserve area. The timing of rotation is relatively constant on the southernmost part of the Microplate, with no evidence of rotation younger than 1 Ma. Riddihough's Central Gorda Plate experienced the same rotation history of that to the south in the older part of the record, but differs strongly between 3 and 1 Ma.

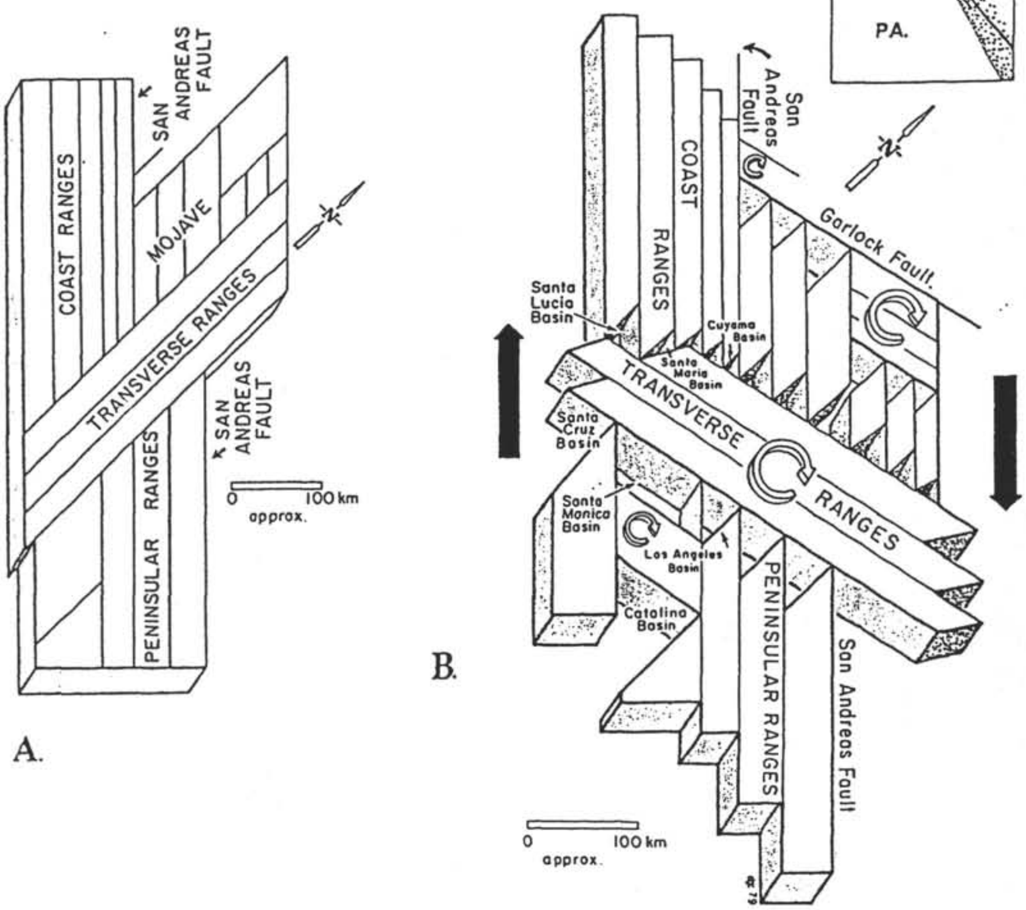
B) Knapp (1982) developed a left-lateral shear model for the Gorda Deformation Zone, in which the northern and southern parts of the Gorda Ridge flank have not rotated, and all rotation is confined within the central portion. This model predicts that only the central portion of the Gorda Ridge will have experienced rotation, and that some chaotic movement should be expected in the northern magnetic bight. The timing of the rotation depends solely on the timing of stress upon the plate. This model does not eliminate the need for subduction (or obduction) of the southern Gorda Microplate beneath the Mendocino Fracture Zone.

C) A third model proposed is the right lateral shear model of Bolt et al. (1968). This model satisfies the deformation of the plate by right-lateral deformation from the region of the Cape Mendocino Triple Junction to the Gorda Ridge. It has fallen into disfavor because at least one large earthquake near the California coast has been shown to be a left-lateral strike slip event. Furthermore, GLORIA imaging of the region shows no significant fabric with a NW-SE trend (EEZSCAN84, 1986). In any event, this model predicts little or no rotation of individual blocks, if shear is confined to discrete faults.

D) Stoddard (1987) has proposed a flexural-slip model that is similar to the older Knapp (1982) deformation model. Instead of rigid plates, however, he assumes that the plate can act elastically. In his model, the north-south stress experienced by the plate causes sinusoidal buckling. Because of the geometry of the area, the amplitude of the buckle increases to the east, causing left-lateral shear between adjacent blocks. This model predicts that the degree of rotation of an isochron should vary along its length, from counterclockwise in the north to strongly clockwise in the central region, to weak clockwise rotation in the south. The timing or rotation again is dependent upon when stress was applied to the southern Gorda region. This model also requires some obduction along the Mendocino Fracture Zone.

Figure 5. Right: From Atwater (1989). Idealized geometry of the Mendocino Triple Junction, a fault-fault-trench (F-F-T) triple junction. PA. = Pacific Plate; J.F. = Juan de Fuca Plate; N.A. = North American Plate. A: Stable configuration for an F-F-T junction. The trench and one fault are collinear. As plate motions proceed, the junction maintains its geometry ad boundary types. B: Approximation of the present Mendocino junction. The San Andreas fault and the Cascadia trench are not collinear. When the plates move, the triangular gap that appears at the junction (triangle) must be accommodated by the surrounding regions. This junction is unstable.





Above: From Luyendyk et al., 1980. A rotation model for Southern California tectonic history. Faults used in the model are: Coast Ranges west from San Andreas = Cuyama, Rinconada, Nacimiento, Hosgri, and Santa Lucia Bank. Peninsula Ranges west from San Andreas = San Jacinto, Elsinore, Newport-Inglewood, and East Santa Cruz-San Clemente. Transverse Ranges = Big Pine-Pinto Mountain, Santa Ynez-Blue Cut, Simi(?)-Hayfield, and Malibu Coast-Santa Monica-Salton Creek. In the Mojave region, the rotated block is bounded by the Garlock, Calico, and Manix-Cady faults. A. Inferred initial fracture pattern and pre-rotation geometry for Oligocene time in Southern California. B. Miocene-Pliocene time (?) geometry after the clockwise rotation event which probably occurred in mainly Miocene time. Sinistral and dextral slip has occurred and deltoid basins have opened at the joins of the rotated and unrotated blocks.

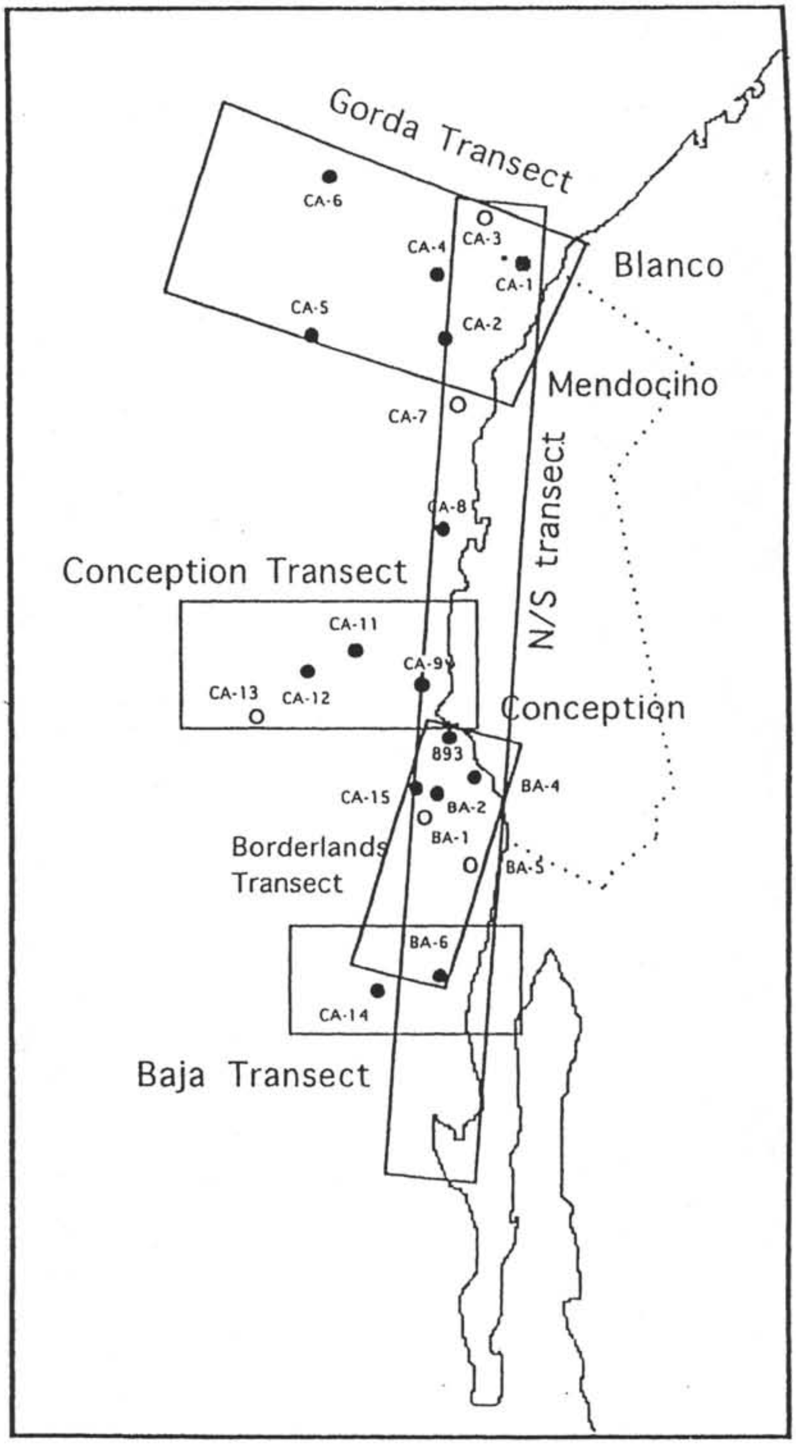


Figure 6. Location of proposed sites and transects for Leg 167.

TABLE 1

PROPOSED SITE INFORMATION AND DRILLING STRATEGY

SITE: BA-1	**PRIORITY**: 2	**POSITION**: 32°15'N, 118°28'W
WATER DEPTH: 1835 m	**SEDIMENT THICKNESS**: >600 m	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: SCS & MCS L4-90-SC line 109, crossline L4-90-SC line 112.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Borderlands Transect), and sedimentation in East Cortez Basin, and the Neogene history of intermediate water flow along the margin.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Miocene-Recent silts and clays.

SITE: BA-2	**PRIORITY**: 1	**POSITION**: 32°57'N, 118°55'W
WATER DEPTH: 1715 m	**SEDIMENT THICKNESS**: >1500 m	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: MCS & SCS L4-90-SC line 109, crossline L4-90-SC line 124.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Borderlands Transect), and the Neogene history of intermediate water flow along the margin.

Drilling Program: (Triple) APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pliocene-Recent silts and clays.

SITE: BA-4	**PRIORITY**: 1	**POSITION**: 33°47'N, 118°49'W
WATER DEPTH: 895 m	**SEDIMENT THICKNESS**: >1200 m	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: MCS & SCS L4-90-SC line 125		

Objectives: To study the Pleistocene record of the Southern California Eddy and paleoproductivity and upwelling (Borderlands Transect), the Pleistocene history of intermediate water flow (inner Borderlands), and the history of C_{org} burial and preservation.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pliocene-Recent silts and clays.

SITE: BA-5	**PRIORITY**: 2	**POSITION**: 32°03'N, 117°17.8'W
WATER DEPTH: 1300 m	**SEDIMENT THICKNESS**: >600 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: CFAULTS-1 and CFAULTS-2 cruises (SCS).		

Objectives: To study the Pleistocene record of the California Current and paleoproductivity and upwelling (Borderlands Transect), the Pleistocene history of intermediate water flow along the margin, the clastic sedimentation history (inner California Borderlands), and to date the PEL seismic stratigraphic horizon

Drilling Program: (Triple) APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Pliocene-Recent silts and clays.

SITE: BA-6	**PRIORITY**: 1	**POSITION**: 30°20'N, 117°00'W
WATER DEPTH: 2600 m	**SEDIMENT THICKNESS**: >600 m	**TOTAL PENETRATION**: 300 m
SEISMIC COVERAGE: 1970's USC analog data (SCS).		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Baja Transect), and sedimentation in San Quintín Basin, and the Neogene history of intermediate water flow along the margin.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Miocene-Recent silts and clays.

SITE: CA-1	**PRIORITY**: 1	**POSITION**: 41°40'N, 124°50'W
WATER DEPTH: 918 m	**SEDIMENT THICKNESS**: 440 m	**TOTAL PENETRATION**: 500 m
SEISMIC COVERAGE: 0130 GMT line CA1-14, 6/20/94.		

Objectives: To study the Plio-Pleistocene record of the California Current and the Neogene record of paleoproductivity and upwelling (Gorda Transect), the Neogene sediment record in the Eel River Basin, and to investigate gas hydrate composition and formation.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, GHMT, and BHTV.

Nature of Rock Anticipated: Pliocene-Recent silts and clays; Miocene and younger sediments of the subduction complex.

SITE: CA-2	**PRIORITY**: 1	**POSITION**: 40°05.5'N, 125°22.5'W
WATER DEPTH: 2040 m	**SEDIMENT THICKNESS**: 730 m	**TOTAL PENETRATION**: 320 m
SEISMIC COVERAGE: 0805 GMT line CA2-13, 6/23/94.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Gorda Transect).

Drilling Program: Trtiple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Early Miocene-Recent silts and clays.

SITE: CA-3	**PRIORITY**: 2	**POSITION**: 42°20'N, 125°51'W
WATER DEPTH: 2460 m	**SEDIMENT THICKNESS**: 195 m	**TOTAL PENETRATION**: 195 m
SEISMIC COVERAGE: SCS F3-84-9C JD 189-1615 hrs.		

Objectives: To study the Plio-Pleistocene record of the California Current and paleoproductivity and upwelling (Gorda Transect), the Plio-Pleistocene history of the CCD in the northeast Pacific, and the history of deformation on the Gorda Plate.

Drilling Program: (Triple) APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, GHMT, and BHTV.

Nature of Rock Anticipated: Pliocene-Recent hemipelagic clays; MORB and anomaly 2R (3 Ma).

SITE: CA-4	**PRIORITY**: 1	**POSITION**: 41°01.2'N, 126°26.6'W
WATER DEPTH: 3115 m	**SEDIMENT THICKNESS**: 260 m	**TOTAL PENETRATION**: 220 m
SEISMIC COVERAGE: 1146 GMT line CA4-14, 6/21/94.		

Objectives: To study the Plio-Pleistocene record of the California Current and paleoproductivity and upwelling (Gorda Transect), the Plio-Pleistocene history of the CCD in the northeast Pacific, and the history of deformation on the Gorda Plate.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Late Miocene-Recent hemipelagic clays; MORB and anomaly 3R (5.1 Ma).

SITE: CA-5	**PRIORITY**: 1	**POSITION**: 39°06'N, 127°45'W
WATER DEPTH: 4220 m	**SEDIMENT THICKNESS**: 416 m	**TOTAL PENETRATION**: 416 m
SEISMIC COVERAGE: SCS F3-84-NC JD171 0250 hrs.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Gorda Transect) and the Neogene history of the CCD in the northeast Pacific.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Late Oligocene-Recent hemipelagic clays; MORB and anomaly 9/10 (29.6 Ma).

SITE: CA-6	**PRIORITY**: 1	**POSITION**: 40°59'N, 130°07'W
WATER DEPTH: 3273 m	**SEDIMENT THICKNESS**: 115 m	**TOTAL PENETRATION**: 115 m
SEISMIC COVERAGE: ARGO-1 site survey for DSDP Leg 5 (SCS).		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Gorda Transect) and the Neogene history of the CCD in the northeast Pacific.

Drilling Program: Triple APC.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated: Late Miocene-Recent hemipelagic clays; MORB and anomaly 4R (7.7 Ma).

SITE: CA-7	**PRIORITY**: 2	**POSITION**: 39°23'N, 124°15'W
WATER DEPTH: 1245 m	**SEDIMENT THICKNESS**: >700 m	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE: 0230 GMT line CA7-07, 6/16/94.		

Objectives: To study the Plio-Pleistocene record of the California Current and paleoproductivity and upwelling (N/S Transect).

Drilling Program: (Triple) APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Plio-Pleistocene hemipelagic clays and mid-lower Miocene sedimentary rocks.

SITE: CA-8	**PRIORITY**: 1	**POSITION**: 36°59'N, 123°15'W
WATER DEPTH: 2590 m	**SEDIMENT THICKNESS**: >1000 m	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE: SCS F2-84-SC and MCS L90-SC.		

Objectives: To study the Plio-Pleistocene record of the California Current and paleoproductivity and upwelling (N/S Transect).

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Plio-Pleistocene hemipelagic clays and mid-lower Miocene sedimentary rocks.

SITE: CA-9	**PRIORITY**: 1	**POSITION**: 34°32.7'N, 121°06'W
WATER DEPTH: 873 m	**SEDIMENT THICKNESS**: >700 m	**TOTAL PENETRATION**: 500 m
SEISMIC COVERAGE: L5-79-SC line 25, crossline L4-90-SC line 103 (SCS).		

Objectives: To study the Plio-Pleistocene record of the California Current and paleoproductivity and upwelling (Conception Transect), and the Neogene sediment record in the Santa Lucia Basin.

Drilling Program: Trtiple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated: Miocene-Recent silts and clays; lower Miocene or Franciscan (?).

SITE: Site 893	**PRIORITY**: 2	**POSITION**: 34°17.25'N, 120°02.19'W
WATER DEPTH: 576.5 m	**SEDIMENT THICKNESS**: >1000 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: ODP Leg 146, Site 893.		

Objectives: To study the Pleistocene record of the California Current and paleoproductivity and upwelling (N/S Transect) and the evolution of the Southern California Countercurrent.

Drilling Program: APC.

Logging and Downhole Operations: Geophysical.

Nature of Rock Anticipated: Pleistocene hemipelagic sediments and mid-lower Miocene sedimentary rocks.

SITE: CA-11A	**PRIORITY**: 1	**POSITION**: 34°33'N, 122°03'W
WATER DEPTH: 3750 m	**SEDIMENT THICKNESS**: 330 m	**TOTAL PENETRATION**: 330 m
SEISMIC COVERAGE: SCS F2-84-SC.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Conception Transect).

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated:Miocene-Recent silts and clays; MORB and anomaly 6C (24 Ma).

SITE: CA-12A	**PRIORITY**: 1	**POSITION**: 34°00'N, 123°00'W
WATER DEPTH: 4160 m	**SEDIMENT THICKNESS**: 280 m	**TOTAL PENETRATION**: 280 m
SEISMIC COVERAGE: SCS F2-84-SC.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Conception Transect).

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated:Miocene-Recent silts and clays; MORB and anomaly 7B (26 Ma).

SITE: CA-13	**PRIORITY**: 2	**POSITION**: 32°54'N, 123°20'W
WATER DEPTH: 4165 m	**SEDIMENT THICKNESS**: 145 m	**TOTAL PENETRATION**: 145 m
SEISMIC COVERAGE: SCS F2-84-SC.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Conception Transect).

Drilling Program: (Triple) APC and XCB.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated:Miocene-Recent silts and clays; MORB and anomaly 7 (25.8 Ma).

SITE: CA-14 (Site 470)	**PRIORITY**: 1	**POSITION**: 28°54.5'N, 117°31.1'W
WATER DEPTH: 3555 m	**SEDIMENT THICKNESS**: 165 m	**TOTAL PENETRATION**: 165 m
SEISMIC COVERAGE: DSDP Leg 63, Site 470.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Baja Transect).

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: Standard logs, FMS, and GHMT.

Nature of Rock Anticipated:Miocene-Recent silts and clays; MORB, middle Miocene.

SITE: CA-15	**PRIORITY**: 1	**POSITION**: 32°40'N, 119°29'W
WATER DEPTH: 1315 m	**SEDIMENT THICKNESS**: >600 m	**TOTAL PENETRATION**: 400 m
SEISMIC COVERAGE: SCS L4-90-SC line 124 & MCS L1-78-SC line 15, crossline L4-79-SC line 901.		

Objectives: To study the Neogene record of the California Current and paleoproductivity and upwelling (Borderlands Transect), and sedimentation in Tanner Basin, and the Neogene history of intermediate water flow along the margin.

Drilling Program: Triple APC and XCB.

Logging and Downhole Operations: No logging.

Nature of Rock Anticipated:Miocene-Recent silts and clays; Miocene sedimentary rocks.

LEG 168

Juan de Fuca Hydrothermal Circulation

LEG 168

HYDROTHERMAL CIRCULATION IN OCEANIC CRUST: EASTERN FLANK OF THE JUAN DE FUCA RIDGE

Modified from Proposal 440 and 400-Add Submitted By

Earl Davis, Michael Mottl, Kristin Rohr, Keir Becker,
Andrew Fisher, Geoffrey Wheat, and Heiner Villinger

To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

Simple examples of several common hydrothermal flow regimes have been found on the eastern flank of the Juan de Fuca Ridge. Three of these regimes are the focus of Leg 168, including areas where 1) there is a sharp transition from sediment-free to sediment-covered igneous crust, where heat flow, crustal temperatures, basement fluid compositions, and upper-crustal seismic velocities all show large systematic changes associated with the transition from open to closed hydrothermal circulation, 2) particularly flat basement and uniform sediment cover has allowed the relatively subtle thermal signature of cellular convective fluid circulation to be detected with seafloor heat-flow measurements, and 3) fluid flow within the igneous crust and through the seafloor is forced by basement relief.

Each of the cases represent situations that occur commonly in all ocean basins, but because of the unusual simplicity of the occurrences in this area, they provide ideal targets for drilling. Leg 168, which focuses mainly on the physics and fluid chemistry of ridge-flank fluid circulation, consists of three arrays of relatively shallow holes to provide direct information about lateral gradients in basement fluid composition, formation pressures, and temperatures, and strong constraints on formation-scale permeability and the vigor of circulation. Studies will rely on existing, well-proven tools and techniques, as well as two improved tools to make the measurements of undisturbed formation pressure and temperature more reliable. In choosing sites for the holes, consideration was also given to the goal of understanding how hydrothermal circulation affects the chemical, mineralogical, and physical alteration of the upper crust.

INTRODUCTION

Despite the lack of topographically-induced head, many hydrologic regimes in sediments and igneous crustal rocks beneath the seafloor are very active. Driving forces for fluid flow originate from rapid sediment accumulation and associated consolidation in sedimentary basins, subaerial topographic head across coastlines of continental margins, tectonic thickening and associated consolidation in subduction zone accretionary prisms, and thermal buoyancy in ridge-crest and ridge-flank settings. The consequences of fluid flow within the igneous and sedimentary parts of the oceanic crust and between the crust and the water column are profound. Fluid circulation in the igneous crust dominates the heat budget at ridge crests, to the extent that at some spreading rates it may not be possible for magma chambers to be maintained in steady state (e.g., Lister, 1983). High-temperature hydrothermal fluids are extremely effective at dissolving and transporting large quantities of base metals from the igneous crust to the seafloor and forming large polymetallic sulfide deposits (Hekinian et al., 1980; Koski et al., 1984; Rona et al., 1986; Davis, et al., 1987; Davis, Becker, et al., 1992; Davis, Chapman, et al., 1992). Long-term circulation of lower-temperature crustal fluids is believed to be responsible for the general alteration and mechanical consolidation of the upper igneous crust (Alt et al., 1986; Houtz and Ewing, 1976; Jacobson, 1992; Purdy, 1987). Fluid pressures generated in subduction zone accretionary prisms modify the mechanical behavior of the deforming sediment section (e.g., Bangs et al., 1990; Davis et al., 1983; Moore, Mascale, et al., 1988), and the resultant fluid flow may be responsible for methane migration, the formation of methane hydrates, and for diagenetic changes in the sediments (Gieskes et al., 1990; Hyndman and Davis, 1992). In all environments, the integrated effect of fluid exchange between the crust and water column has a strong influence on global geochemical cycles.

While the most spectacular manifestation of crustal fluid circulation is found along mid-ocean ridge axes in the form of high-temperature (ca. 350°C) springs that deposit sulfide minerals, most of the flux of both heat and seawater occurs through the mid-ocean ridge flanks. Modelling of heat flow indicates that advective heat loss through ridge flanks is more than triple that at ridge axes. Because this heat is lost at lower temperatures, the seawater flux through the flanks is more than ten times that at the axes. Advection cools the crust out to a mean age of 65 Ma (Sclater et al., 1980), over more than one third of the ocean floor (Anderson et al., 1979). This process is important for alteration of the oceanic crust, and for the accompanying changes in its chemistry, mineralogy, and physical properties, including seismic velocity (Jacobson, 1992; Purdy, 1987). Because of the wide range of crustal age and conditions on ridge flanks, however, and because of the limited amount of work done there to date, we know little about these processes in detail. Major questions remain about the way in which fluid flow is driven through the crust and seafloor, about the magnitudes of chemical exchange of numerous elements between the crust and water column, and about the factors that are most important in influencing water/rock interaction and thus in controlling fluid chemistry and the chemical and physical alteration of the crust.

Over the past decade, several sites of hydrothermal circulation on mid-ocean ridge flanks have been investigated. These include the Galapagos mounds, the southern flank of the Costa Rica Rift, the equatorial East Pacific Rise flanks, the western flank of the East Pacific Rise near 20°S, the western flank of the Mid-Atlantic Ridge, and the flanks of the Mariana Trough spreading axis. These sites represent a wide range in crustal age, basement topography, and sediment thickness. They have demonstrated a correspondingly wide range in hydrothermal conditions and processes. They have demonstrated further that we are still in an early, descriptive stage in studying hydrothermal phenomena on mid-ocean ridge flanks. Eventually, by characterizing the range of crustal conditions, the areal coverage of each set of conditions, and the accompanying alteration and geochemical fluxes, we should be able to estimate much more accurately the global impact of ridge-flank hydrothermal circulation.

The eastern flank of the Juan de Fuca Ridge has become one of the most thoroughly studied ridge flanks over the past five years. Representative examples of several hydrothermal environments have been found and studied in detail, and the crustal seismic structure has been imaged particularly well. Leg 168 is designed to provide critical hydrologic, geophysical, and geochemical observations in three "type-examples" of sub-seafloor fluid-flow systems that occur in remarkably simple form in this area, and to provide samples and direct observations that will reveal the nature of crustal evolution that has been documented by seismic data. Leg 168 will take advantage of recent technological advances made by ODP, as well as anticipated improvements to two tools that will greatly improve the efficiency of operations and enhance the chances of success of the program, and of detailed surface-ship and submersible site-survey information.

STUDY AREA

Regional Setting

The major plate-tectonic elements bounding the Juan de Fuca Plate are shown in Figure 1. The Juan de Fuca Ridge system is a remnant of the East Pacific Rise, and extends from 40°30'N off Cape Mendocino to 51°30'N off Queen Charlotte Sound. Seafloor spreading rates vary from about 25 mm/yr along the Gorda Ridge in the south to about 55 mm/yr along the Juan de Fuca Ridge. Along the continental margin to the east, the Juan de Fuca Plate and plate fragments are subducted beneath or overridden by North America at rates that vary from about 20 to 45 mm/yr. To the north and south of the Juan de Fuca Plate system, the Pacific Plate abuts North America directly, and moves in a direction generally parallel to the continental margin along the San Andreas and Queen Charlotte transform fault systems.

High rates of uplift in the coast ranges, particularly in the insular and coast ranges of British Columbia, combined with accelerated glacial erosion and sediment transport to the deep ocean during the Pleistocene, have caused much of the Juan de Fuca Plate to be buried by flat-lying turbidite sediments. Sediments supplied primarily from Queen Charlotte Sound and the Strait of Juan de Fuca have been transported to the south, and are ponded in what is referred to as Cascadia Basin, which is bounded on the east by the North American continental margin, and on the west by the elevated relief of the Juan de Fuca Ridge. In places sediments cover crust less than 1 Ma old. Sediment thickness generally increases with crustal age. In extreme cases along the continental margin, where crustal ages are typically 5-10 Ma, the combination of thermal and tectonic subsidence of the oceanic lithosphere has permitted several kilometers of sediment to accumulate.

The sediments that blanket the eastern flank of the ridge provide a conveniently soft layer in which heat-flow measurements can be made, and a relatively low-permeability, porous "filter" from which pore fluids can be extracted. The combination of detailed heat-flow and pore-fluid geochemical measurements sited along closely-spaced seismic reflection profiles have provided strong constraints on the directions and rates of fluid flow through the seafloor, and on the thermal structure, patterns of fluid flow, and pore-fluid composition in the upper igneous crust (e.g., Davis et al., 1989; Davis, Chapman, et al., 1992; Mottl and Wheat, in press; Wheat and Mottl, in press).

Of particular interest are the remarkably simple examples of three general "classes" of crustal fluid flow that have been found on the ridge flank and have become the focus of several detailed studies. These three "type" examples are the proposed targets for drilling. They comprise 1) a transition zone between sediment-free (permitting open hydrothermal circulation) and sediment-covered (hydrologically sealed) crust, 2) an area where a uniform cover of sediments over unusually flat-lying basement has permitted the pattern of cellular hydrothermal circulation in the upper igneous crust to be imaged with detailed heat-flow measurements, and 3) an area where rugged basement topography and large variations in sediment thickness have caused fluid flow from the upper igneous crust through the seafloor and into the water column to be focused for long periods of time. Each of these extremely simple and well characterized examples of common and important sub-seafloor hydrologic regimes is particularly well suited to the proposed quantitative studies. While the crust in which they occur is unusually young, similar situations can be found on virtually all ridge flanks, and the lessons to be learned will be extremely valuable for understanding the fundamental nature and consequences of crustal fluid flow as it occurs throughout the world's oceans.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To determine the lateral variations in composition and physical properties of upper oceanic crust associated with the transition from an open to a closed hydrothermal regime.

2) To examine the nature and consequences of crustal hydrothermal circulation in the absence of basement topography.

3) To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Specific Objectives and Methodology

Transition from Open to Sediment-Sealed Hydrothermal Circulation

About 20 km east of the axis of the Endeavour segment of the Juan de Fuca Ridge, the elevated relief of the ridge crest plunges beneath the western edge of Cascadia Basin. This area represents a fundamental hydrothermal transition zone; west of the edge of the abyssal plain turbidites, basement is covered by a relatively thin (few meters), discontinuous veneer of hemipelagic sediment through which fluids can pass with little hydrologic impedance, whereas to the east, the igneous crust is blanketed continuously by turbidite sediments which create a hydrologic barrier. Heat flow and estimated upper crustal temperatures, seismic velocities in the upper crust, and estimates of basement pore-fluid compositions all show clear lateral gradients that probably are associated with the transition from open to sealed hydrothermal circulation (Figure 2). Heat flow and estimated basement temperatures increase systematically to the east, away from the area of exposed basement. At a distance of 20 km from the outcrop, the average heat flow approaches the level appropriate for the underlying lithosphere. Estimated temperatures in the upper igneous crust increase from less than 10°C near where basement rocks outcrop to about 40-50°C, 20 km to the east. Basement pore-fluid compositions estimated from sediment pore-fluid studies (Wheat and Mottl, in press) change from close to that of seawater near the outcrop, to being strongly depleted in magnesium and enriched in calcium at a location 20 km to the east. Inferred chlorinities of the basement fluids are considerably higher than seawater at the location 20 km east of the basement outcrop. At least part of the increased value must be due to ongoing hydration reactions in the crust. This is consistent with the heat flow and seismic data, which show rapid changes in the vicinity. Seismic interval velocities determined for the upper crustal seismic layer 2A increase from values that range from 3000-3500 m/s to values exceeding 5000 m/s over the same spatial interval of about 20 km. While these are RMS velocities in a layer known to have strong velocity gradients, they probably indicate a significant increase in velocities throughout layer 2A. Such an increase is thought to occur on all ridge flanks and to indicate a decrease in porosity from alteration, although this is the only location studied to date where such an increase has been associated with a measured change in hydrothermal regime.

Drilling in this area will address numerous fundamental questions about lateral fluid and heat transport, and about the physical and chemical alteration of the crust that results from water-rock interaction. Specific questions include: How does chemical and thermal exchange over distances of 10-20 km beneath a sediment cover take place? If there is a net horizontal transport of fluid, what is the rate? What is the source and magnitude of the pressure gradient that drives the flow? How does the change in fluid chemistry and temperature with distance from sediment-free areas affect the nature of rock alteration? What is the dominant factor responsible for the increase in upper crustal velocity? Is there an accompanying decrease in permeability? And at what rate does the alteration take place? If it is found that crustal alteration is rapid, and is primarily a function of temperature and fluid chemistry, then the results of studying this simple hydrothermal transition zone can be generalized to all ocean basins. That this is the case is strongly suggested by the coincidence of the heat-flow, geochemical, and seismic transitions shown in Figure 2, by the high and stable values of upper crustal seismic velocities observed to the east of the hydrothermal transition zone, and by the return to more normal (just above seawater) basement-fluid chlorinities observed in an area not far east of the transition zone.

Cellular Convection in the Upper Oceanic Crust

Probably one of the most widespread processes responsible for heat transfer and the movement of fluids through the oceanic crust is porous medium convection. While common, this process has turned out to be inherently difficult to study. In most seafloor environments, the thermal anomalies associated with simple convective circulation appear to be much more subtle than the anomalies associated with sediment thickness variations (e.g., Davis et al., 1989; Davis, Chapman, et al., 1992) and/or with fluid flow that is forced by topography and permeability variations (e.g., Fisher et al., 1990); few examples of cellular convection in the upper oceanic crust have been documented (e.g., the Galapagos Mounds area: Green et al., 1981; Becker and Von Herzen, 1983). One clear example occurs within the area described above just east of the Endeavour Ridge segment, where the surface of the igneous crust is particularly flat. Local relief is less than about 20 m over a distance of 10 km, and the sediment cover is uniform at about 200 m (Figure 3b). A suite of heat-flow measurements spaced nominally 100 m apart along a 5-km-long line crossing the area defines a coherent pattern of variation. The profile exhibits a series of four peaks and troughs with an average half-wavelength of 600 m; heat flow varies between about 240 and 280 mW/m^2. The variations are too large to be explained by any conductive effects, but are surprisingly small if associated with porous-medium fluid convection in the uppermost crust. Temperatures estimated for the sediment-basement interface suggest that convection is driven by temperature differences of less than 10°C. A parallel line of measurements made with somewhat greater measurement spacing confirms the pattern. Although not as well defined, the locations of the peaks and troughs along the second profile suggest that the pattern of circulation is not aligned with ridge-parallel structural trends.

In this same area, a multi-channel seismic reflection study (Rohr and Schmidt, in press) has revealed a clear upper-crustal reflection from the base of layer 2A that is believed to be either from the boundary between upper crustal extrusive rocks and intrusive dikes beneath, or from a metamorphic front. Two-way travel time thickness of layer 2A varies from about 0.4 to 0.2 s; with velocities determined from the wide-angle reflection data, the layer thickness is found to be fairly uniform, averaging about 600 m (Figure 2). Results from DSDP Hole 504B suggest that the seismic boundary represents a fundamental hydrologic transition, with permeabilities in the upper extrusive part of the crust being several orders of magnitude higher than those in the altered or intrusive crust beneath (Anderson et al., 1985; Becker, 1990). The thickness of the upper crustal layer is commensurate with the thickness of the layer that hosts hydrothermal circulation as inferred from the half-wavelength of the heat-flow anomalies, assuming that the hydrothermal cells imaged by the heat-flow variations are of roughly unit aspect ratio (e.g., Lister, 1990).

Using the simplest configuration for the circulation, Davis, Chapman, and Forster (in prep.) have estimated the sensitivity of lateral temperature and pressure variations in the permeable upper crust to the bulk permeability of the layer that hosts circulation. The results are based on a 2-D numerical model of porous-medium circulation that simulates convection in a 600-m-thick layer of permeable basalts, which rests on an impermeable (purely conductive) basaltic medium, and is covered by a 200-m-thick layer of low-permeability (nearly purely conductive) sediment. The dependence of lateral temperature variation (shown in the plot as heat-flow variation) and pressure variation on permeability defined by the model results are shown in Figure 4. Also shown in the plot of temperature variation vs. permeability is the relationship predicted by assuming that the maximum horizontal temperature difference along the top of the convecting layer is equal to the average temperature drop across the layer. This simplifying assumption is invalid at permeabilities near the critical value for convection (there are no horizontal temperature variations at the onset of convection by definition), but it becomes reasonable when the circulation is vigorous. The numerical results and limiting-case calculations converge above a permeability of about $3x10^{-13}$ m^2.

The general character of the heat-flow vs. permeability relationship is as one might expect; Heat flow variation is zero below the onset of convection. Just above critical convective conditions, the amplitude of variation rises rapidly, then falls as the convection increases in vigor and efficiency. The observed heat-flow variation in the Juan de Fuca flank case (shown as a horizontal dashed line in Figure 4) is consistent with either of two possible conditions, one characterized by sluggish circulation at a slightly super-critical Rayleigh number, or one in which vigorous convection is present in a layer whose average permeability is roughly 10^{-12} m^2.

Drilling at this site will allow two important goals to be reached. Firstly, the sections that are in an upflow zone and a downflow zone of a single, well imaged convection cell can be sampled. Studies of fluids and solids from these regions will allow numerous questions about hydrothermal circulation to be addressed, such as; How stable are convection cells in the crust? Are upflow and downflow zones locked into the crust by virtue of the thermal capacity of the rock matrix, or do they migrate under the influence of changing proximity to the ridge crest, changing permeability structure, or regional forced flow? How are the chemical, mineralogical, and physical properties of the rock changed in the different parts of the circulation system? How thin are the boundary layers of flow?

Secondly, careful measurements of pressures and temperatures will permit the model presented above to be tested, and the ambiguity regarding the vigor of circulation to be resolved. The objective is important for the following reason. Permeability in the upper oceanic crust has been measured in boreholes at four locations; Hole 504B on the flank of the Costa Rica Rift (Anderson and Zoback, 1982; Becker et al., 1983; Anderson et al., 1985; Becker et al., 1989), Hole 395A on the flank of the Mid-Atlantic Ridge (Hickman et al., 1984; Becker, 1990), Hole 735B (Becker, 1991), and Holes 857D and 858G in Middle Valley (Becker et al., 1994). Average permeabilities in the sections of the upper few hundred meters of crust spanned by the permeability tests range from about 10^{-14} to 10^{-13} m^2. Measurements in Middle Valley demonstrated that fault zones, although spatially infrequent, may play a major role in influencing permeability. The probable large degree of heterogeneity of the crust makes characterizing the average hydrologic properties difficult. By using the relationships defined in Figure 4, together with the accurate constraints on temperature and pressure variations that can be determined by drilling, it should be possible to determine the vigor of hydrothermal circulation directly, and to derive the hydrologic characteristics of the upper crust at an appropriate, full formational scale.

Forced Fluid Flow through Basement Highs

At a point roughly 90 km from the ridge axis, there is an abrupt transition from the region of relatively smooth basement, typified by the "Cellular Convection" drilling site discussed above, to a region where the basement surface is much more rugged. In this region, basement topography consists primarily of linear ridges and troughs produced by block-faulting and by variations in volcanic supply at the time the seafloor was created. Local relief between ridges and troughs of 300 to 500 m is common, and major ridges are separated typically by 3-7 km (e.g., Figure 5). All of this relief is now buried by the turbidites of Cascadia Basin. The tops of two ridges lie a few tens to about 100 m below the sediment surface. At three locations along these ridges, small volcanic edifices are present, and these rise above the sediment surface to form small, isolated basement outcrops (e.g., Figures 5 and 6).

It has long been suggested that topographic highs and local basement outcrops play a key role in seafloor hydrogeology by serving to focus flow from the igneous crust into the oceans. The simplicity of the local structure and the small size of the volcanic outcrops in the area of rugged basement topography on the Juan de Fuca Ridge east flank has made the area an ideal target for seafloor studies. Results of a series of systematic surveys have confirmed several things about fluid flow in the crust and discharge through the seafloor in this environment; 1) Fluid circulation within the upper oceanic crust has been sufficiently vigorous to maintain relatively uniform temperatures at the sediment/basement interface, despite variations of sediment thickness of over a factor of five; 2) Where sampled, basement fluid compositions also appear to be locally homogeneous; 3) Fluids leak through the sediment "seal" above buried basement ridges at geochemically detectable rates (<1 to tens of mm/yr) that are inversely proportional to the local sediment thickness; 4) Fluids flow through at least one of the basement outcrops (the smallest studied in greatest detail) at rates sufficient to generate detectable thermal, chemical, and light transmissivity anomalies in the water column above the edifice summit; 5) Discharge through the outcrop has been sufficiently long-lived to have allowed significant hydrothermal precipitates to accumulate; cores from the outcrop have recovered green clay, semi-lithified black ferromaganese crusts and layers, and reddish iron oxides in indurated sediment; 6) The thermal structures of all three basement outcrops are fundamentally the same, allowing us to conclude that upflow and discharge not only have been stable and long-lived, but also are a general consequence of the permeability- and temperature-structure of what we have referred to as "Permeable Penetrators".

The basement outcrop selected for study (Figure 6) is highly localized (there is very little outcrop left!), mature, and still active, and thus it makes an ideal target for drilling. Although it is an exaggerated example, it is representative of a general class of circulation that is present wherever the crustal topographic relief of mid-ocean ridge flanks is partially filled in by sedimentation. An example in an "early" phase is the region of North Pond on the Mid-Atlantic Ridge flank studied by Langseth et al. (1993). A relic, fully-buried example was probably intersected at Site 417 on the Mid-Atlantic Ridge flank (Donnelly et al., 1979). Other examples of the same general phenomenon occur on the Costa Rica Rift flank (holes in the vicinity of, and including, Hole 504B; e.g., Mottl, 1989), Middle Valley (the Dead Dog vent field sampled by drilling at Site 858, a very extreme case; Davis, Mottl, Fisher, et al., 1992), and along the buried ridges along strike from the "Permeable Penetrator" outcrops (Figure 5), where drilling is also planned.

Whereas the general characteristics of fluid flow in this environment are reasonably well constrained, proper quantification of the hydrologic regime and elucidation of the consequences of fluid flow require drilling. With the array of proposed holes, the following questions can be addressed: To what degree are basement fluids thermally and chemically homogenized by circulation in this environment? Is the upper crust still sufficiently permeable to host vigorous free convection, similar to that inferred to exist in the much younger "Cellular Convection" area, or are the uniform temperatures estimated for the sediment/basement interface the result of fluid flow that is forced by the topography of this boundary as suggested by Fisher et al. (1990)? To what degree has hydrothermal alteration of the crust proceeded at this site? How have physical properties, namely velocity and permeability, changed with alteration? What are the nature and magnitude of the forces that drive fluid flow through the sediment section above basement ridges, and through

"Permeable Penetrators" where basement is exposed at the seafloor? What is the source of the fluids that vent through the seafloor at the outcrops? Do they simply come from the inferred-to-be homogeneous basement "reservoir" regionally sealed beneath the sediments, or is there a component from a deeper source? How are sediments chemically and physically affected by fluid seepage? And what is the nature of recharge? Is seawater supplied to the crust solely by regional diffuse flow through the sediments away from basement highs, or do some fluids enter the crust via locally focused pathways?

DRILLING PLAN/STRATEGY

Transition from Open to Sediment-Sealed Hydrothermal Circulation

The location of the proposed sites is shown in Figure 1 and the drilling plan outlined in Table 1.

Proposed holes HT-1 through HT-3 will be single-bit holes, drilled 50 m into the upper part of layer 2A. The westernmost hole (HT-1) will be spudded into sediment, but sited as close as possible to the point of igneous outcrop in order to permit sampling of the igneous crust and pore fluids where chemical and physical conditions are representative of an open hydrothermal regime. The easternmost hole (HT-3) will be located roughly 30 km from the basement outcrop, allowing crustal rocks and fluids to be sampled at a point where the influence of open circulation is absent and where seismic velocities have risen to a stable, high value. Intermediate points through the transition will be provided by a third single-bit hole (HT-2), and by the suite of holes drilled to address the objectives outlined in the next section. One of these will be a deep reentry hole that may ultimately (in a second drilling leg) penetrate through seismic layer 2A.

Detailed pore-fluid sampling (primarily by sediment squeezing) will be done to constrain the direction and rate of fluid flow through the sediment section, and to determine the changes in composition of basement fluids at each hole location. Similarly, detailed temperature and pressure measurements will be made to determine the pressure gradients that are present that drive fluid flow horizontally through basement beneath the sediment section, and vertically through the sediments and seafloor.

Cellular Convection in the Upper Oceanic Crust

Two pairs of holes are planned to address these objectives. Holes of one pair (CC-1 and CC-2) will be located over upwelling and downwelling limbs of one convection cell as imaged by heat flow. These will be APC/XCB cored down to basement to allow detailed determinations of pore-fluid composition, and will include frequent measurements of temperature and pressure. The holes will be backfilled after completion. Holes of the second pair (CC-3 and CC-4) will also be located over upwelling and downwelling limbs, but of an adjacent convection cell to avoid the potential perturbations caused by the cored holes. Holes of this second pair will be cased, drilled 25 m into basement, and instrumented with CORKs to allow the lateral pressure gradient between the convective upflow and downflow limbs to be determined accurately. Either of these holes will be available for later deepening through the upper crustal seismic layer 2A, and further downhole studies. This paired-hole strategy meets the normal requirements for coring sections that are to be drilled for casing; it avoids the potential of hydrologic intercommunication and it allows the difficult determination of formation pressure to be approached in two independent ways.

Forced Fluid Flow through Basement Highs

Proposed holes PP-1, PP-2, and PP-3 form a transect across one of the buried basement ridges in the "Permeable Penetrators" area where slow seepage through the sediment section has been detected from pore-fluid geochemical profiles in gravity and piston cores (Figure 5; Davis, Chapman, et al., 1992; Wheat and Mottl, in press). PP-1 is located in a basement trough now filled by about 500 m of sediment; PP-2 is located part-way up the buried basement ridge, where the sediment cover is about 200 m thick, and vertical fluid flow is just detectable geochemically (< 1 mm/yr); PP-3 is located at the summit of the buried ridge, where the sediment cover is only about 50 m thick, and the rate of fluid seepage is several mm/yr. These holes will be cored continuously through the sediment section, and detailed pore-fluid sampling and frequent downhole temperature and pressure measurements will be completed.

Proposed holes PP-4 and PP-5 are in analogous positions to proposed holes PP-1 and PP-3, but located roughly 1 km along strike. These holes will be drilled as reentry holes; one or both may be deepened later into seismic layer 2A. During Leg 168, they will be treated the same as proposed holes CC-3 and CC-4; penetration will extend only 25 m into basement, and the holes will be left instrumented with CORKs.

Proposed hole PP-6 is a single, deep hole drilled directly into the exposed summit of the "Permeable Penetrator" shown in cross-section in Figure 6. Sampling in this hole will provide constraints on the history of upflow and discharge at this site, and on the consequent degree of alteration experienced by the igneous rocks in this situation. Fluid samples will provide unambiguous information about basement fluid compositions currently ascending from the crust, and allow these fluids to be compared to those sampled from basement several kilometers away at proposed holes PP-1 through PP-5, and at the younger Hydrothermal Transition Zone sites. Sampling and downhole measurements will provide critical information about the distribution of permeable pathways, the magnitude and source of pressure driving flow, and the velocity of upflow in this volcanic edifice. It is possible that this hole can be started in hemipelagic sediments and hydrothermal deposits without a guidebase.

Drilling and post-drilling observations in all of the holes will allow the fluid-flow system in this region of rough basement topography to be very well characterized and quantified. The approach taken is the same as that outlined for the "Cellular Convection" area; detailed downhole sampling and measurements and longterm CORK observations will provide critical information about the vigor of circulation and the permeability of the upper crust at a formation scale, through quantification of the temperature and pressure differences along the sediment/basement interface in the way outlined in the previous section. APC/XCB holes will be drilled just to basement, and backfilled after completion.

Deep Drilling during a Future Program

Accurate measurement of pressure at the top of igneous basement in instrumented holes precludes drilling deeply into the upper crust. Twenty-five-meter basement penetration is suggested; even less may be advisable, as the lateral differentials to be detected are relatively small (e.g., Figure 4), and the interval over which the pressure is sensed (the permeable part of the section below grouted casing) should be kept to a minimum. Modest basement penetration will also minimize drilling disturbances, allowing pressures and temperatures to recover to formation conditions in a relatively short period of time.

While many important objectives can be reached through (and some only through) this shallow drilling during Leg 168, many questions cannot be answered without penetration through the full thickness of layer 2B, which may become the objective of a possible future program. This future drilling would address two categories of questions. The first concerns the physical and chemical nature of the oceanic crust and how it changes through time; What is the cause of the seismic layer 2A/2B boundary reflection? Is alteration a key factor as is suggested by the results of drilling at Hole 504B? Does the seismic boundary move up through the crustal section with time? What is the cause of the observed increase in RMS seismic velocity of the upper crust? Are there large changes in porosity, or is most of the change in velocity caused by volumetrically minor cementation? To what degree does the upper crust become hydrated? What are the primary controls on crustal alteration? What are the relative importances of temperature, fluid chemistry, and time? And what are the hydrologic consequences of alteration? How much is permeability affected? The second category includes questions addressed in the first leg of drilling, although these would be approached in a somewhat different manner in a second leg; Is the notion of cellular convection in a porous medium valid? What is the the thermal structure of hydrothermal convection in the upper crust? What are the dimensions of flow boundary layers? Do the lateral temperature variations provide a reasonable estimate of vertical temperature differences across the convecting layer? How deep does circulation penetrate? What is the nature of permeability? What structures provide the greatest influence? How does the permeability measured on the scale of the borehole compare with that estimated for the formation in the manner outlined above? And how stable is the pattern of circulation? Are zones of upflow geochemically distinct from zones of downflow?

As in the case of Leg 168, the Juan de Fuca Ridge east flank provides an extremely good site for investigating the structure of the upper crust, the nature of hydrothermal circulation at depth, and the nature and causes of crustal evolution. The seismic structure of the crust of this ridge flank is simple and extremely well imaged. Changes in velocities are well defined and clearly related to changes in hydrothermal regime. Knowledge gained from Leg 168 will provide an even better context than that already known from deeper holes.

Improvements to the CORK Design

Installations should be completed in two trips. Operations would begin with the drilling- and grouting-in of a special bottom hole assembly (BHA) consisting of drill-in casing (DIC, up to 100-150 m in length) and a special-purpose reentry cone. The second trip would be done with another specialized BHA containing a perforated interval above the drill bit that is sealed during drilling by a sliding sleeve. Upon reaching total depth, this BHA would land on and seal into the upper section of DIC, and provide a landing seat and seal for the CORK data logger and thermistor assembly. After the logger is inserted by wireline, and a submersible landing platform is dropped into place, the drill pipe would be disconnected from the second BHA at the level of the reentry cone and logger. If there were uncertainties about the target depth for the perforated interval or the stability of the hole, the installation could be done with three trips, with the section below the DIC drilled (and cored) with a normal BHA prior to setting the length of and inserting the final perforated and instrumented BHA.

Improved Measurements of Pressure and Temperature while Drilling

This new approach will involve a tool similar to the currently employed WSTP (water sampler and temperature probe), but modified and optimized for measuring formation temperature and pressure more reliably. The fluid sampling function will be eliminated so that the probe diameter can be reduced over its full length. The smaller diameter and simplified geometry will reduce the amplitude of the pressure and temperature disturbances associated with penetration, and allow the use of cylindrical theory for deriving equilibrium pressure, temperature, and possibly permeability and consolidation coefficient, from the transient decays. The much lower hydraulic compliance of the tool will also allow pressures to approach in-situ values in a much shorter period of time than that characteristic of the Barnes tool, which must consume large volumes of pore fluid before approaching equilibrium. Because of the much greater simplicity of the T-P probe, it will be possible to cycle the tool efficiently. Low power requirements should allow service-free use of the tool on a continuous basis. Because of the importance of the measurements of pressure and temperature, the tool may at times be deployed between every core.

Construction will be carried out as a joint third-party tool development project by E. Davis and K. Becker.

In the upper sections of sediment where APC penetration is possible (down to a depth of roughly 80-100 m in unaltered sediment), the APC temperature tool will be used also on a regular basis. Use of this tool will add 10-15 minutes to each core with which it is deployed; use of the T-P probe will require a wire-line trip and decay period for each deployment.

REFERENCES

Alt, J.C., Honnorez, J., Laverne, C., and Emmermann, R., 1986. Hydrothermal alteration of a 1 km section through the upper oceanic crust, DSDP Hole 504B: Mineralogy, chemistry, and evolution of seawater-basalt interaction. *J. Geophys. Res.*, 91:10309-10355.

Anderson, R.N., Hobart, M.A., and Langseth, M.G., 1979. Geothermal convection through oceanic crust and sediments in the Indian Ocean. *Science*, 204:828-832.

Anderson, R.N., and Zoback, M.D., 1982. Permeability, underpressures, and convection in the oceanic crust near the Costa Rica Rift, eastern equatorial Pacific. *J. Geophys. Res.*, 87:2860-2868.

Anderson, R.N., Zoback, M.D., Hickman, S.H., and Newmark, R.L., 1985. Permeability versus depth in the upper oceanic crust: in situ measurements in DSDP Hole 504B, eastern equatorial Pacific. *J. Geophys. Res.*, 90:3659-3669.

Bangs, N.L.B., Westbrook, G.K., Ladd, J.W., and Buhl, P., 1990. Seismic velocities from the Barbados Ridge complex: Indicators of high pore fluid pressures in an accretionary complex. *J. Geophys. Res.*, 95:8767-8782.

Becker, K., 1990. Measurements of the permeability of the upper oceanic crust at Hole 395A, ODP Leg 109. *In* Detrick, R., Honnorez, J., Bryan, W.E., Juteau, T., et al., *Proc. ODP, Sci. Results*, 106/109: College Station, TX (Ocean Drilling Program), 213-222.

Becker, K., 1991. In situ bulk permeability of oceanic gabbros in Hole 735B, ODP Leg 118. *In* Robinson, P.T., Von Herzen, R.P., et al., *Proc. ODP, Sci. Results*, 118: College Station, TX (Ocean Drilling Program), 333-347.

Becker, K., et al., 1989. Drilling deep into young oceanic crust at Hole 504B, Costa Rica Rift. *Rev. Geophys.*, 27:79-102.

Becker, K., Langseth, M.G., Von Herzen, R.P., and Anderson, R.N., 1983. Deep crustal geothermal measurements, Hole 504B, Costa Rica Rift. *J. Geophys. Res.*, 88:3447-3457.

Becker, K., Morin, R.H., and Davis, E.E., 1994. Permeabilities in the Middle Valley hydrothermal system measured with packer and flowmeter experiments. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F., *Proc. ODP, Sci. Results*, 139: College Station, TX (Ocean Drilling Program), 613-626.

Becker, K., and Von Herzen, R.P., 1983. Heat transfer through the sediments of the Mounds hydrothermal area, Galapagos Spreading Center at 86°W. *J. Geophys. Res.*, 88:995-1008.

Davis, E.E., Becker, K., Pettigrew, T., Carson, B., and MacDonald, R., 1992. CORK: A hydrologic seal and downhole observatory for deep-ocean boreholes. *In* Davis, E.E., Mottl, M.J., Fisher, A.T., et al., *Proc. ODP, Init. Repts.*, 139: College Station, TX (Ocean Drilling Program), 43-53.

Davis, E.E., Chapman, D.S., Forster, C.B., and Villinger, H., 1989. Heat-flow variations correlated with buried basement topography on the Juan de Fuca Ridge flank. *Nature*, 342:533-537.

Davis, E.E., Chapman, D.S., Mottl, M.J., Bentkowski, W.J., Dadey, K., Forster, C., Nagihara, S, Rohr, K., Wheat, G., and Whiticar, M., 1992. FlankFlux: An experiment to study the nature of hydrothermal circulation in young oceanic crust. *Can. J. Earth Sci.*, 29:925-952.

Davis, E.E., Goodfellow, W.D., Bornhold, B.D., Adshead, J., Blaise, B., Villinger, H., and Le Cheminant, G., 1987. Massive sulfides in a sedimented rift valley, northern Juan de Fuca Ridge. *Earth Planet. Sci. Lett.*, 86:49-61.

Davis, E.E., Mottl, M.J., Fisher, A.T., et al., 1992. *Proc. ODP, Init. Repts.*, 139: College Station, TX (Ocean Drilling Program).

Davis, D., Suppe, J., and Dahlen, F.A., 1983. Mechanics of fold-and-thrust belts and accretionary wedges. *J. Geophys. Res.*, 88:1153-1172.

Donnelly, T.W., Thompson, G, and Salisbury, M.H., 1979. The chemistry of altered basalts at Site 417, Deep Sea Drilling Project Leg 51. *Init. Repts., DSDP*, Washington (U.S. Govt. Printing Office), 51-53:1319-1330.

Fisher, A.T., Becker, K., Narasimhan, T.N., Langseth, M.G., and Mottl, M.J., 1990. Passive off-axis convection through the southern flank of the Costa Rica rift. *J. Geophys. Res.*, 95:9343-9370.

Gieskes, J.M., Vrolijk, P., and Blanc, G., 1990. Hydrogeochemistry, ODP Leg 110: An overview. *In* Moore, J.C., Mascale, A., et al., *Proc. ODP, Sci. Results*, 110: College Station, TX (Ocean Drilling Program), 395-408.

Green, K.C., Von Herzen, R.P., and Williams, D.L., 1981. The Galapagos spreading center at 86°W: A detailed geothermal field study. *J. Geophys. Res.*, 86:979-986.

Hekinian, R., Fevrier, M., Bischoff, J.L., Picot, P., and Shanks, W.C., 1980. Sulfide deposits from the East Pacific Rise near 21°N. *Science,* 207:1433-1444.

Hickman, S.H., Langseth, M.G., and Svitek, J.F., 1984. In situ permeability and pore-pressure measurements near the Mid-Atlantic Ridge, Deep Sea Drilling Project Hole 395A. *In* Hyndman, R.D., Salisbury, M.H., et al., *Init. Repts, DSDP,* 78B: Washinton (U.S. Govt. Printing Office), 699-708.

Houtz, R., and Ewing, J.R., 1976. Upper crustal structure as a function of plate age. *J. Geophys. Res.,* 81:2490-2498.

Hyndman, R.D., and Davis, E.E., 1992. A mechanism for the formation of methane hydrate and seafloor bottom-simulating reflectors by vertical fluid expulsion. *J. Geophys. Res.,* 97:7025-7041.

Jacobson, R.S., 1992. Impact of crustal evolution on changes of the seismic properties of the uppermost ocean crust. *Rev. Geophys.,* 30:23-43.

Koski, R.A., Clague, D.A., and Oudin, E., 1984. Mineralogy and chemistry of massive sulfide deposits from the Juan de Fuca Ridge. *Geol. Soc. Am. Bull.,* 95:930-945.

Langseth, M.G., Becker, K., Von Herzen, R.P., and Schultheiss, P., 1993. Heat and fluid flux through sediment on the western flank of the Mid-Atlantic Ridge: A hydrogeological study of North Pond. *Geophys. Res. Lett.,* 19:517-520.

Lister, C.R.B., 1983. On the intermittency and crystallisation mechanisms of sub-seafloor magma chambers *Geophys. J. Roy. Astron. Soc.,* 73:351-366.

Lister, C.R.B., 1990. An explanation for the multivalued heat transport found experimentally for convection in a porous medium. *J. Fluid Mech.,* 214:287-320.

Moore, H.W., Mascale, A., et al., 1988. Tectonics and hydrogeology of the northern Barbados Ridge: results from Ocean Drilling Program Leg 110. *Geol. Soc. Am. Bull.,* 100:1578-1593.

Mottl, M.J., 1989. Hydrothermal convection, reaction, and diffusion in sediments on the Costa Rica Rift flank: Pore-water evidence from ODP Sites 677 and 678. *In* Becker, K., Sakai, H., et al., *Proc. ODP, Sci. Results,* 111: College Station, TX (Ocean Drilling Program), 195-213.

Mottl, M.J., and Wheat, C.G., in press. Hydrothermal circulation through mid-ocean ridge flanks: Heat and magnesium fluxes. *Geochim. Cosmochim. Acta.*

Parsons, B. and Sclater, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. *J. Geophys. Res.,* 82:803-827.

Purdy, G.M., 1987. New observations of the shallow seismic structure of young oceanic crust. *J. Geophys. Res.,* 92:9351-9362.

Rohr, K., Schmidt, U., and Milkereit, B., in press. Multichannel reflection data across the Endeavour segment of the Juan de Fuca Ridge. Geological Survey of Canada Open File.

Rona, P.A., Klinkhammer, G., Nelson, T.A., Trefry, J.H., and Elderfield, H., 1986. Black smokers, massive sulfides and vent biota on the Mid-Atlantic Ridge. *Nature,* 321:33-37.

Sclater, J.G., Jaupart, C., and Galson, D., 1980. The heat flow through oceanic and continental crust and the heat loss of the earth. *Rev. Geophys. and Space Phys.,* 18:269-311.

Wheat, C.G., and Mottl, M.J., in press. Hydrothermal circulation, Juan de Fuca Ridge eastern flank: Factors controlling basement water composition. *J. Geophys. Res.*

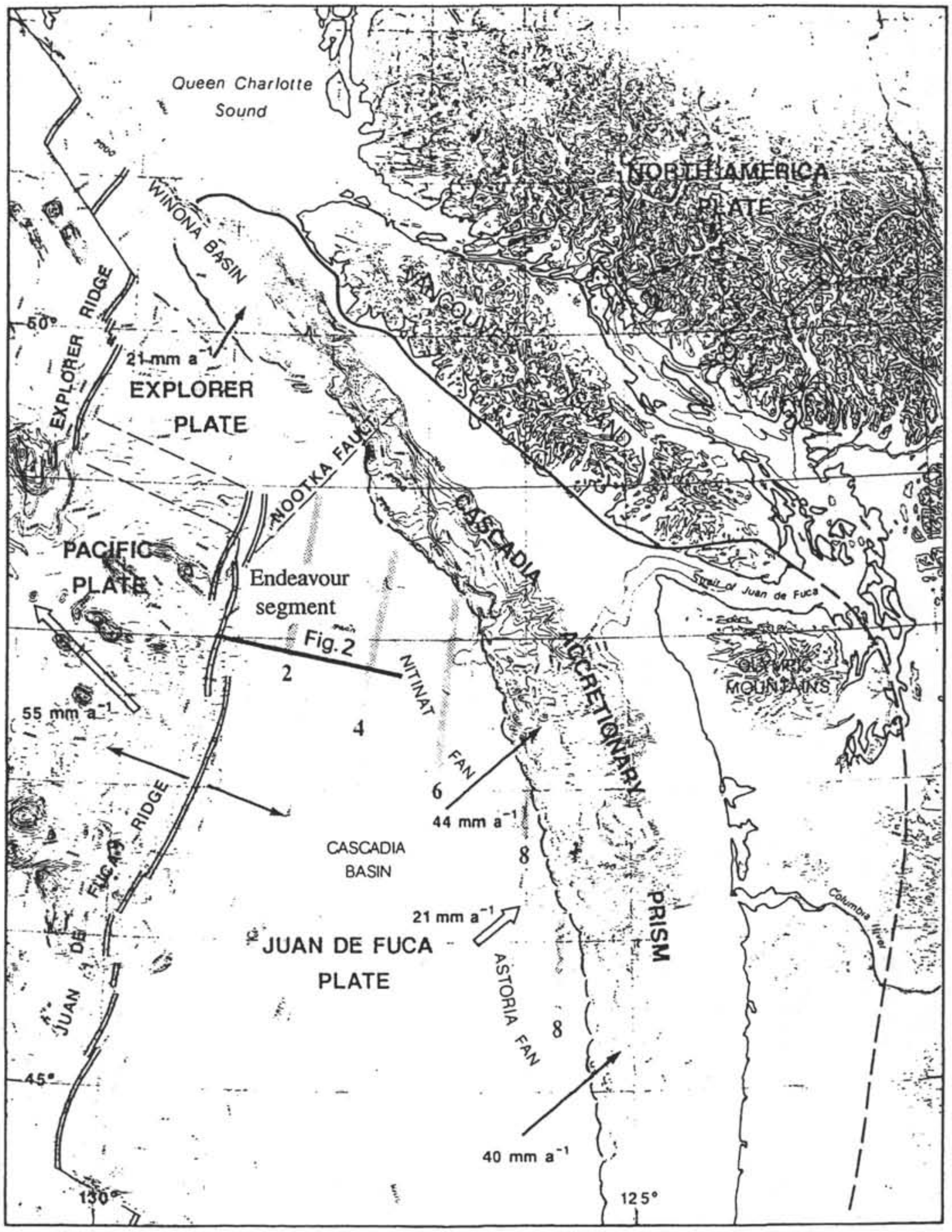


Figure 1. Major elements of the Juan de Fuca Plate system, including relative (solid arrows) and absolute (open arrows) motion vectors, and crustal ages in the vicinity of the eastern Juan de Fuca Ridge flank drilling sites. The location of the transect (Figure 2), along which the drilling sites are situated, is shown by the solid line that extends east from the summit of the Endeavour segment of the Juan de Fuca Ridge.

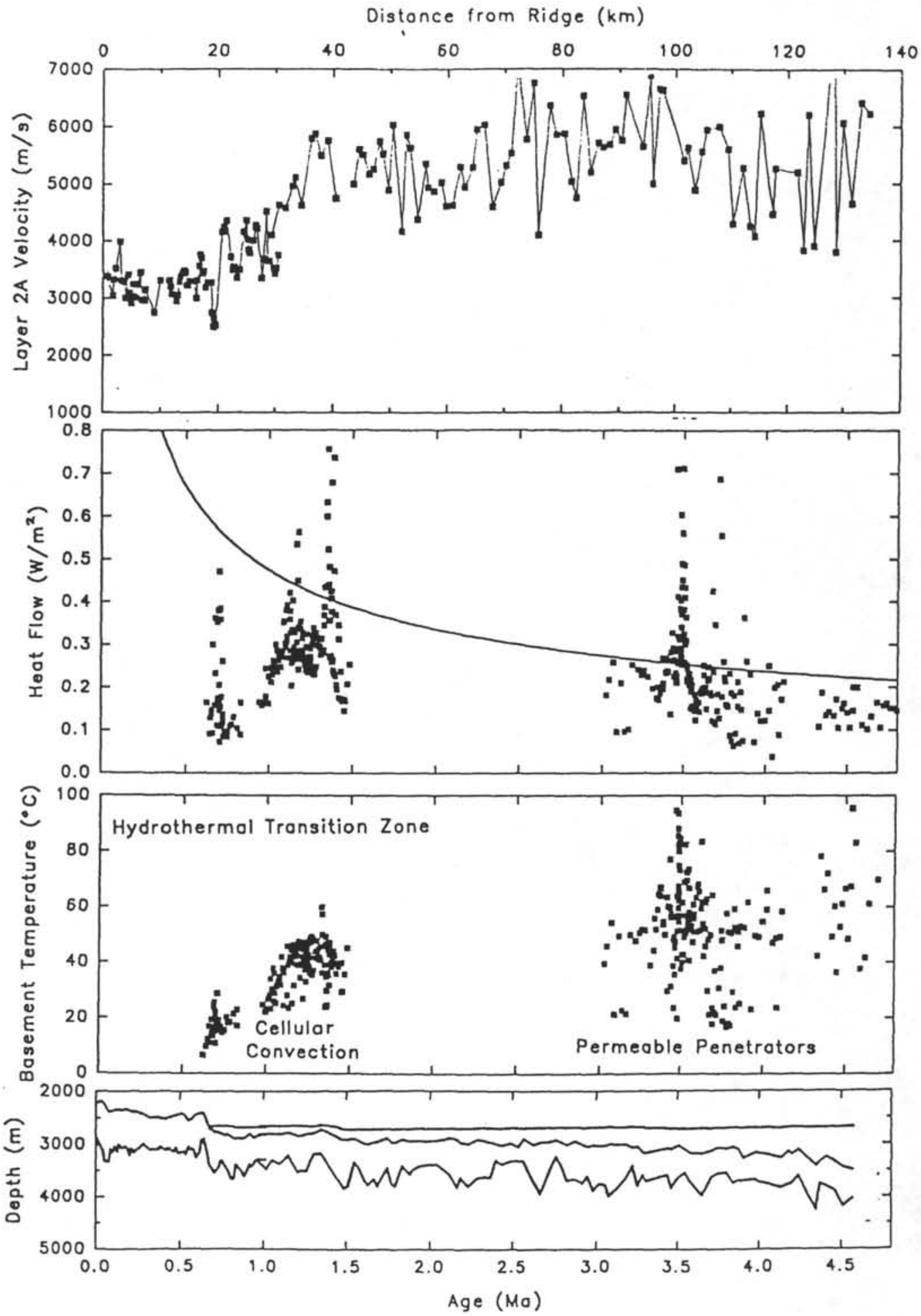


Figure 2. Geophysical transect, including a depth-interpretation of the seismic reflection profile (Rohr and Schmidt, in press; lines are shown for the sediment surface, the top of the igneous crust, and the base of layer 2A); measured (Davis et al., 1992) and predicted heat flow (according to the relationship estimated by Parsons and Sclater, 1977); temperatures estimated at the top of igneous crust from the heat-flow measurements; and interval seismic velocities for seismic layer 2A estimated from wide-angle reflection data with the Dix equation (Rohr and Schmidt, in press).

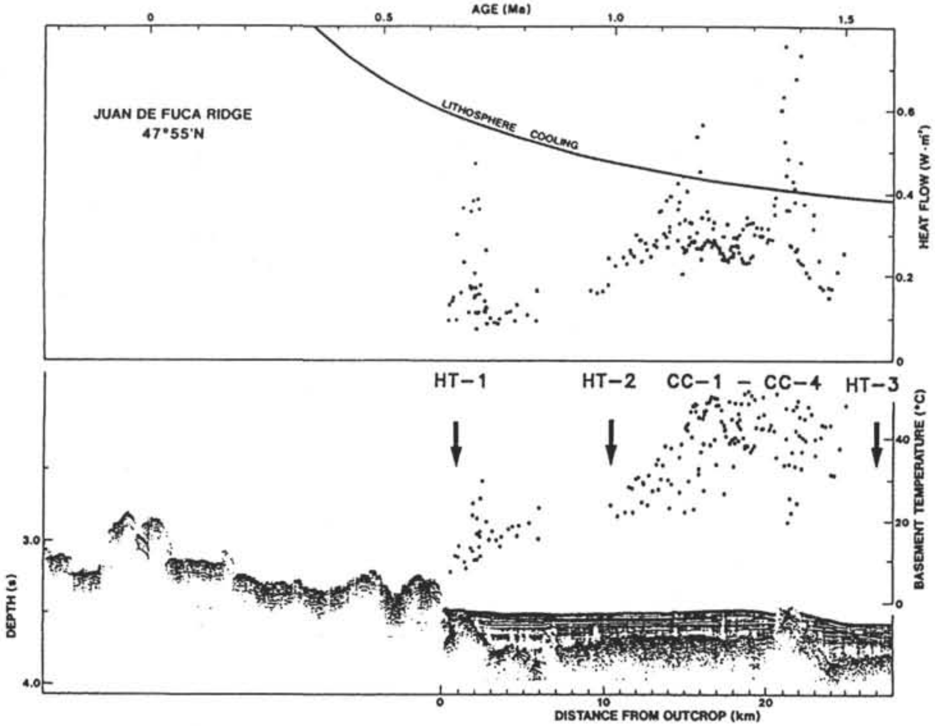


Figure 3a. Single-channel seismic reflection profile crossing the "Hydrothermal Transition Zone", where the "HT" and "CC" sites are located (see text). Estimated basement temperatures, and the projected location of drill sites are indicated. Slow seepage of basement water through the thin sediment covering the buried basement ridge at a distance of 21 km from the outcrop provided the estimates of fluid composition described in the text (Wheat and Mottl, in press).

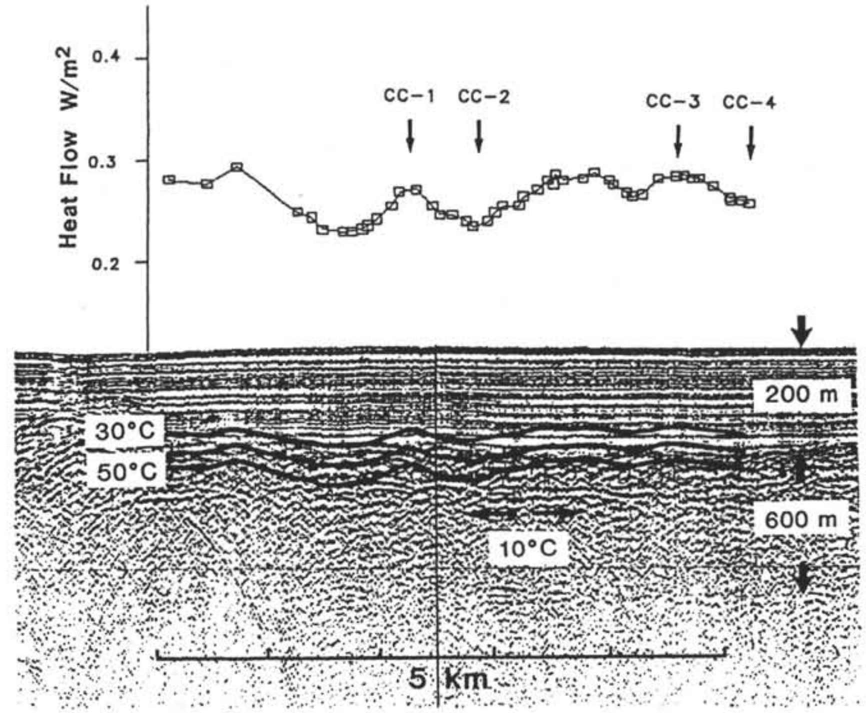


Figure 3b. A 5-km-long segment of a line adjacent to the transect shown in Figure 3a, (extending from about 13 to 18 km from the basement outcrop) where the basement surface is flat and sediment thickness is uniform, and where closely spaced heat-flow measurements reveal a variation that is attributed to cellular convection in the upper igneous crust. Representative locations of proposed holes CC-1 through CC-4 are indicated.

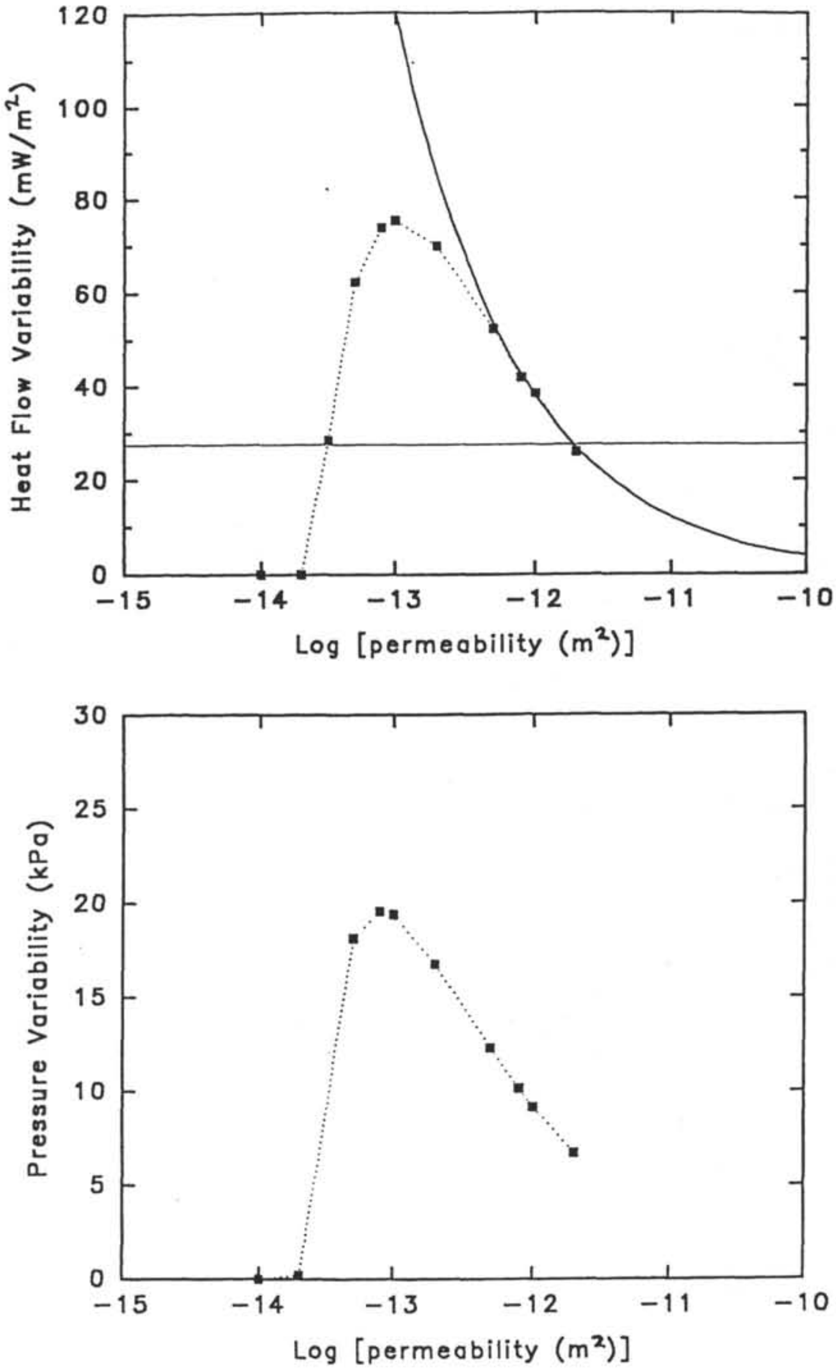


Figure 4. Relationship between the maximum heat flow variability (upper plot) above a 600-m-thick permeable horizon buried by a 200-m-thick impermeable sediment layer and permeability of the convecting horizon, predicted from the results of numerical models (points) and by a simple theoretical upper limit (Davis, Chapman, and Forster, in prep.). The heat flow variability observed in the "Cellular Convection" drilling area is shown by the thin horizontal line. A similar relationship between pressure variability along the sediment/basement interface and permeability is shown in the lower plot. Pressure and temperature at the base of the section will be measured in the "Cellular Convection" drill holes to constrain the vigor of hydrothermal circulation via these relationships.

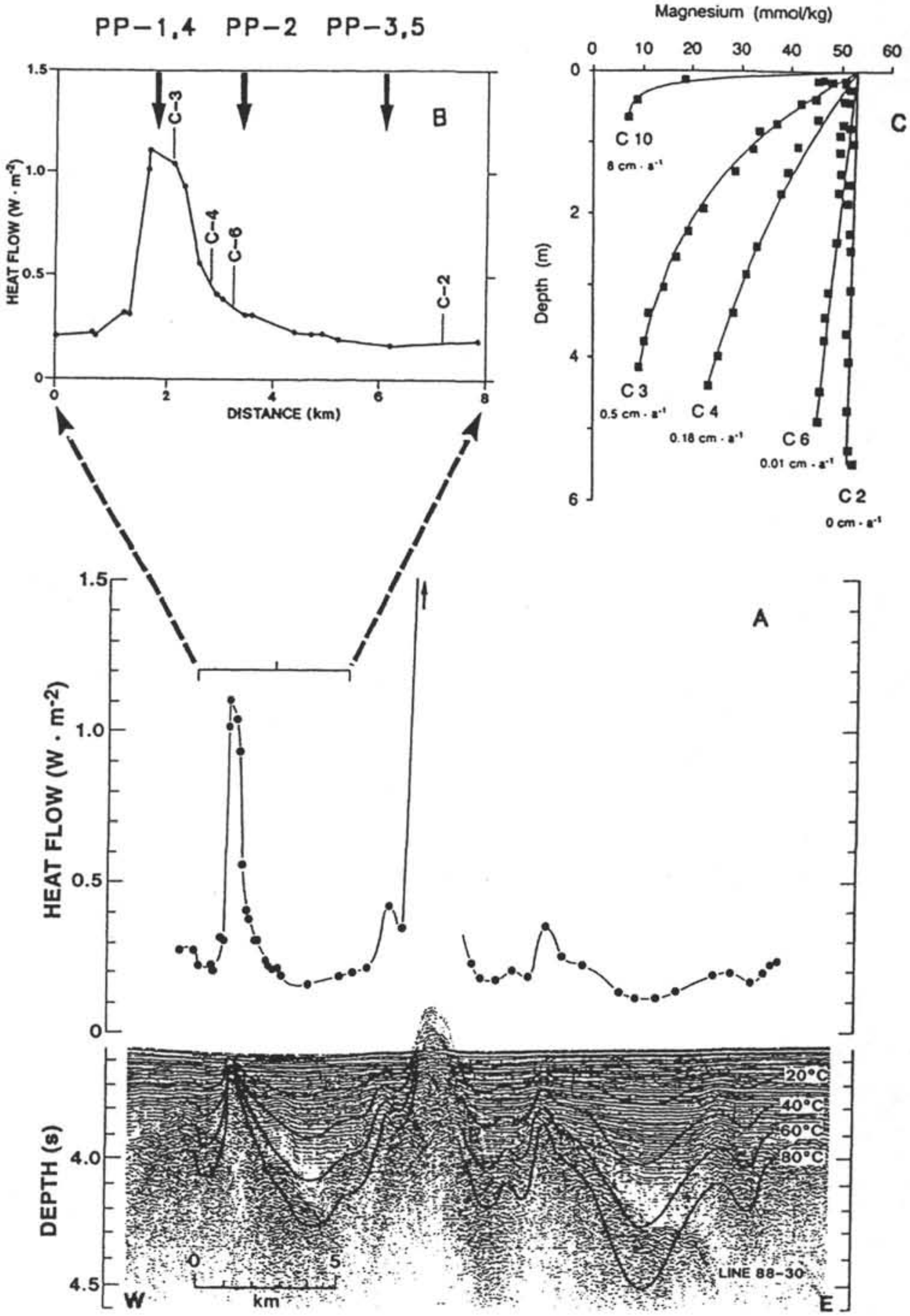


Figure 5. (A) Heat flow, estimated temperature stucture, and proposed drilling holes PP-1 - PP-5 along a single-channel seismic reflection profile. (B) Expanded plot of heat flow along a portion of the profile shown in A, with locations of cores shown in C indicated. (C) Depth-profiles of magnesium concentration in pore fluids extracted from cores (points) shown in B. Calculated profiles (lines) show the effects of vertical seepage of basement fluids at the rates given.

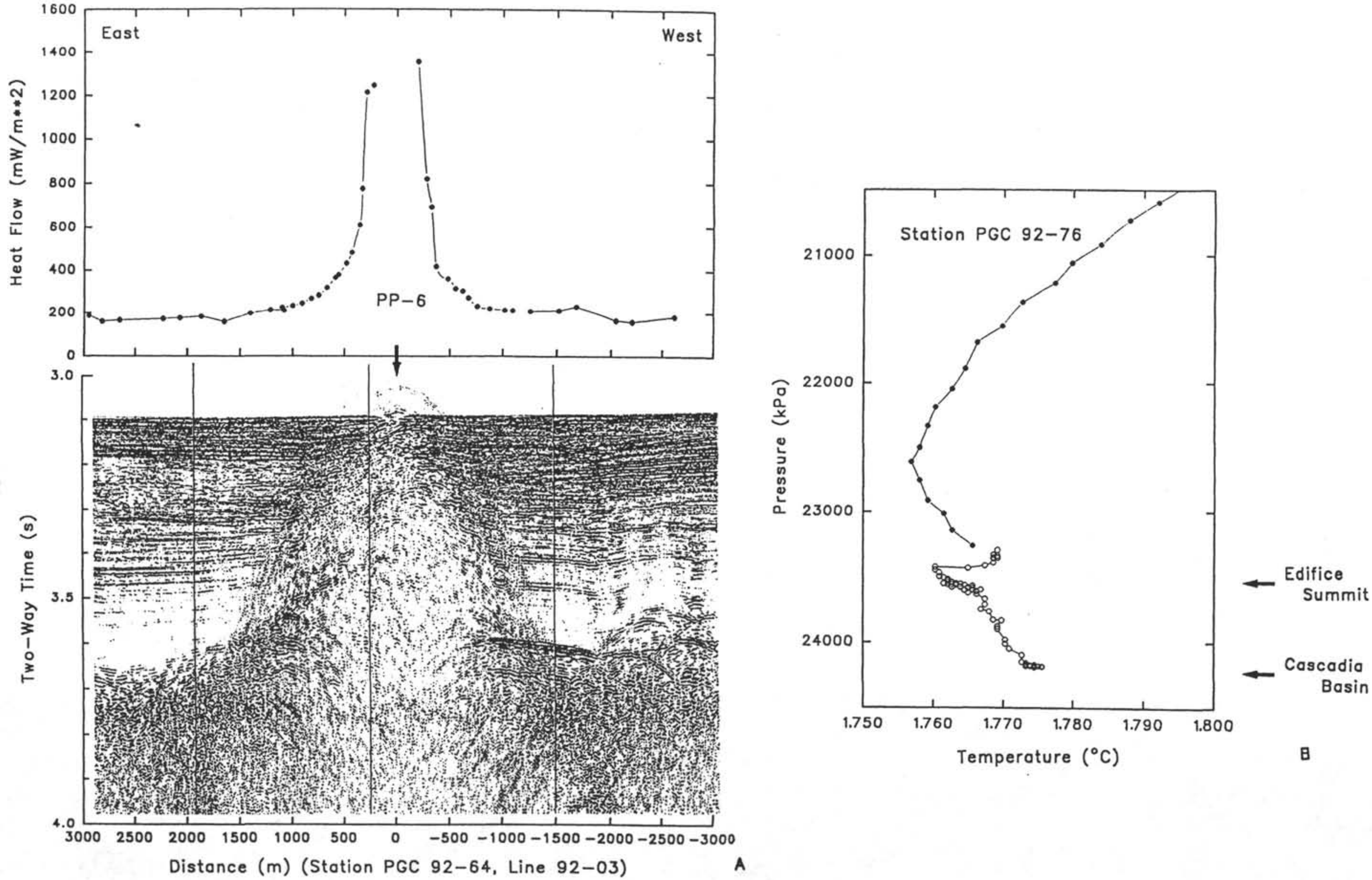


Figure 6. (A) Transect of heat flow across the southernmost "Permeable Penetrator" where proposed hole PP-6 is located. (B) Temperature profile through the water column above the southern penetrator.

TABLE 1

PROPOSED SITE INFORMATION and DRILLING STRATEGY

HOLE: HT-1	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 100 m	**TOTAL PENETRATION**: 150 m
SEISMIC COVERAGE: Line 90-9		

Objectives: To determine the lateral variations in composition and physical properties of upper oceanic crust associated with the transition from an open to a closed hydrothermal regime.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: Quad combo, FMS, and temperature.

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: HT-2	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE: Line 90-9		

Objectives: To determine the lateral variations in composition and physical properties of upper oceanic crust associated with the transition from an open to a closed hydrothermal regime.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: Quad combo, FMS, and temperature.

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: HT-3	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 300 m	**TOTAL PENETRATION**: 350 m
SEISMIC COVERAGE: Line 90-9		

Objectives: To determine the lateral variations in composition and physical properties of upper oceanic crust associated with the transition from an open to a closed hydrothermal regime.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: Quad combo, FMS, and temperature.

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: CC-1	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE:		

Objectives: To examine the nature and consequences of crustal hydrothermal circulation in the absence of basement topography.

Drilling Program: APC and XCB.

Logging and Downhole Operations: -

Nature of Rock Anticipated: Plio-Pleistocene turbidites.

HOLE: CC-2	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE:		

Objectives: To examine the nature and consequences of crustal hydrothermal circulation in the absence of basement topography.

Drilling Program: APC and XCB.

Logging and Downhole Operations: -

Nature of Rock Anticipated: Plio-Pleistocene turbidites.

HOLE: CC-3	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 225 m
SEISMIC COVERAGE:		

Objectives: To examine the nature and consequences of crustal hydrothermal circulation in the absence of basement topography.

Drilling Program: Drill 25 m into basement and CORK.

Logging and Downhole Operations: FMS.

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: CC-4	**PRIORITY**:	**POSITION**: 47°55'N, 128°40'W
WATER DEPTH: 2620 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 225 m
SEISMIC COVERAGE:		

Objectives: To examine the nature and consequences of crustal hydrothermal circulation in the absence of basement topography.

Drilling Program: Drill 25 m into basement and CORK.

Logging and Downhole Operations: FMS.

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: PP-1	**PRIORITY:**	**POSITION**: 47°50'N, 127°40'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: 500 m	**TOTAL PENETRATION**: 500 m
SEISMIC COVERAGE: Line 88-30		

Objectives: To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Drilling Program: APC and XCB.

Logging and Downhole Operations: -

Nature of Rock Anticipated: Plio-Pleistocene turbidites.

HOLE: PP-2	**PRIORITY:**	**POSITION**: 47°50'N, 127°40'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: Line 88-30		

Objectives: To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Drilling Program: APC and XCB.

Logging and Downhole Operations: -

Nature of Rock Anticipated: Plio-Pleistocene turbidites.

HOLE: PP-3	**PRIORITY:**	**POSITION**: 47°50'N, 127°40'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: 50 m	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: Line 88-30		

Objectives: To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Drilling Program: APC and XCB.

Logging and Downhole Operations:-

Nature of Rock Anticipated: Plio-Pleistocene turbidites.

HOLE: PP-4	**PRIORITY:**	**POSITION**: 47°50'N, 127°40'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: 500 m	**TOTAL PENETRATION**: 525 m
SEISMIC COVERAGE: Line 88-30		

Objectives: To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Drilling Program: Drill 25 m into basement and CORK.

Logging and Downhole Operations: -

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: PP-5	**PRIORITY:**	**POSITION**: 47°50'N, 127°40'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: 50 m	**TOTAL PENETRATION**: 75 m
SEISMIC COVERAGE: Line 88-30		

Objectives: To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Drilling Program: Drill 25 m into basement and CORK.

Logging and Downhole Operations: -

Nature of Rock Anticipated: Plio-Pleistocene turbidites and igneous crust.

HOLE: PP-6	**PRIORITY:**	**POSITION**: 47°50'N, 127°40'W
WATER DEPTH: 2650 m	**SEDIMENT THICKNESS**: 0 m	**TOTAL PENETRATION**: 500 m
SEISMIC COVERAGE: Line 92-03		

Objectives: To examine the influence of basement topography and outcrops on hydrothermal flow, and the consequences of long-term upflow through sediment and basement rocks.

Drilling Program: HRGB RCB and CORK.

Logging and Downhole Operations: Quad combo, FMS, and temperature.

Nature of Rock Anticipated: Igneous crust.

LEG 169
Sedimented Ridges II

LEG 169

SEDIMENTED RIDGES II

Modified from Proposal SR-Rev3 & Addendum Submitted by

James M. Franklin and Robert A. Zierenberg & Earl E. Davis, Keir Becker, and Andrew Fisher

To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

Leg 169 constitutes the second in a two-leg program to investigate the large scale hydrogeology of Middle Valley, the formation of massive sulfide deposits, the fine-scale hydrogeology of hydrothermal vent fields, and the formation of oceanic crust under sediment-covered spreading centers. Extensive geological, geophysical, geochemical, and biological mapping, and the presence of instrumented and open, re-enterable drill holes, ensures that these holes will become important natural laboratories for the investigation of ridge crest processes.

At and adjacent to the Bent Hill massive sulfide deposit, Leg 169 will investigate 1) the extent and compositional variation of massive sulfide mineralization, 2) mineralogical and chemical zonation related to late-stage hydrothermal circulation through the massive sulfide, 3) the nature of hydrothermal alteration associated with a high temperature fluid upflow zone, 4) the paleo-hydrographic controls on fluid discharge, and 5) the tectonic and igneous setting of the Bent Hill deposit, in particular the structural controls on location of hydrothermal fluid flow and the relative timing and interaction between fluid flow and faulting. In the area of the Dead Dog vent field, drilling will investigate 1) the small-scale, shallow hydrogeology of the vent field by examining thermal, chemical, and pressure gradients in holes radiating from a mapped and sampled hydrothermal vent, 2) the extent of local-scale hydrothermal recharge and fluid mixing in the shallow subsurface, and 3) the growth mechanism for hydrothermal mounds underlying active vents. Downhole temperature logging and sampling of hydrothermal fluid will be conducted at CORKed Holes 858G and 857D. In the NESCA area of Escanaba Trough, Leg 169 will investigate 1) the formation of a large, hydrothermally active sulfide deposit in an early stage of evolution, 2) the flux of elements from sediment to hydrothermal systems by drilling through a massive sulfide deposit that has a composition dominated by sedimentary input, 3) the nature of altered sediment and basalt underlying a large massive sulfide deposit, (4) the tectonic evolution at on-axis intrusive/extrusive volcanic edifices, and 5) the changing sedimentary source regions and depositional regimes associated with eustatic changes in sea level during the Pleistocene.

INTRODUCTION

Middle Valley and Escanaba Trough are ideal laboratories for systematically establishing the origin of massive sulfide deposits at sedimented ridges. The individual deposits in these two areas are considerably larger than any deposits discovered thus far in volcanic-dominated ridge areas and are large enough to be easily targeted and drilled by *JOIDES Resolution*. Ancient massive sulfide deposits are much larger and are mineralogically and compositionally distinct from the clusters of chimneys typical of bare-rock "black smoker" sites. The size and maturity of the sulfide deposits in Middle Valley and Escanaba Trough make them the best analogs to the economically viable volcanic associated massive sulfide deposits in ancient rock sequences. These ancient deposits are a principal source of the world's zinc, lead, silver, and copper, and are important sources of gold and a number of rare metals.

STUDY AREA

Middle Valley

Middle Valley lies at the northern end of the Juan de Fuca spreading system, forming one leg of a RTT unstable triple junction with the Solvanco Fracture Zone and the Nootka Fault (Figure 1). The tectonic setting of Middle Valley is described by Davis and Villinger (1992). Middle Valley is a medium rate spreading center (58 mm/yr), but the proximity to the cold Explorer Plate results in a reduced magma supply and a slow spreading ridge morphology with a deep and wide axial trough (Figure 1). A ridge jump is in progress and current magmatic activity is shifting to the West Valley spreading center. Proximity of the Middle Valley spreading center to an abundant supply of terrigenous sediment during the Pleistocene low stand of sea level has resulted in burial of the spreading center by 200 to >1000 m of turbiditic and hemipelagic sediment with sediment thickness increasing towards the north. In the area of the Leg 169 drilling targets, the sediment fill results in a flat bathymetry broken by ridge parallel normal faults that define the rift. Two main areas are targeted for drilling (Figure 1), the Dead Dog vent field in the Area of Active Venting (Site 858) and the Bent Hill area (Site 856).

Dead Dog Vent Field

The principle center of hydrothermal activity in Middle Valley is the Dead Dog vent field (Figure 2). Contoured heat flow values show a concentric high which is coincident with a side scan acoustic anomaly that outlines the vent field. The vent field contains at least 20 active vents with temperatures ranging up to 276°C (Ames et al., 1993). Active vents occur predominantly on top of 5-15 m high sediment covered mounds a few tens of meters in diameter. The vent fluid composition indicates significant interaction of hydrothermal fluid with sediment and the resultant chimneys are predominantly composed of anhydrite with only minor Mg-rich phyllosilicates and sulfide minerals. Seismic profiles across the vent field show it is located about 2 km east of prominent basement fault (Figure 2; Site 858 fault of Rohr and Schmidt, 1994). Sediment cover of the fault block in the area surrounding the vent field is approximately 450 m and overlies a sill-sediment complex that forms the transition to oceanic crust (Davis et al., 1992). However, hard acoustic reflectors that occur only immediately beneath the vent field were confirmed by drilling to be the top of a volcanic edifice at only 250 m depth. The presence of more permeable volcanic basement penetrating up in to the sediment cover acts as a chimney to focus the flow of hydrothermal fluid to the sea floor (Davis and Fisher, in press).

Bent Hill

Bent Hill (BH) is one of a string of small topographic highs that run parallel to the eastern rift bounding normal fault scarp (Figure 1). These bathymetric highs include volcanic cones to the south, where sediment cover thins, and uplifted sediment hills to the north. These features lie close to a normal fault that offsets basement reflectors (herein referred to as the Site 856 fault), but near surface sediment layering appears to be continuous across this fault. The transition from essentially nonmagnetic oceanic crust that typifies the center of Middle Valley to crust with normal levels of magnetization passes through this area and probably marks the boundary between normal extrusive basalt and the sill-sediment complex that forms the upper oceanic crust in center of Middle Valley (Currie and Davis, in press). Bent Hill, a roughly circular feature 400 m in diameter, has been recently uplifted approximately 50 m (Figure 3). It is bounded on the west by a steep scarp that parallels the rift bounding faults and exposes semiconsolidated turbiditic sediment. A very primitive olivine-rich sill, which is petrogenetically distinct from the diabases and basalts recovered by drilling elsewhere in Middle Valley, was recovered at the base of the two drill holes that penetrate Bent Hill (Figure 3). Bright, reverse polarity seismic reflections that are limited in extent to the area under Bent Hill are interpreted to be generated at the interface between the base of these sills and the underlying sediments (Rohr and Schmidt, 1994).

A ridge of massive sulfide that rises 35 m above the surrounding turbidite fill of the valley is located approximate 100 m south of the southern edge of Bent Hill and is referred to in this prospectus as the Bent Hill deposit (Figure 3). The massive sulfide mound is highly weathered to iron oxyhydroxides and partially sediment buried. Massive sulfide extends a minimum distance of 60 m north-south and 90 m east-west. Hole 856H penetrated 94 m of massive sulfide (Figure 3) before the hole had to be abandoned due to inflow of heavy sulfide sand from the upper weathered section of the hole. A strong near bottom magnetic anomaly over this mound is related to late stage hydrothermal alteration of pyrrhotite to pyrite plus magnetite and has been modeled to suggest that mineralization continues at least another 30 m below the level drilled and possibly much deeper (Tivey, in press).

A second mound of massive sulfide occurs approximately 300 m further south, referred to in this prospectus as the Sunnyside Up deposit. The morphology, degree of oxidation and sediment cover indicate that this deposit is younger than the Bent Hill deposit. A single 264°C hydrothermal vent is present on the north flank of this deposit. Contoured heat flow values for the Bent Hill area show high values center around this active vent (Figure 2). The composition of the vent fluids is similar to those from the Dead Dog vent field, but this vent has only half as much dissolved Ca.

Escanaba Trough

The Gorda Ridge spreading center is located offshore of Oregon and Northern California and is bounded by the Mendocino Fracture Zone on the south and the Blanco Fracture Zone on the north (Figure 1). A small offset in the spreading axis at 41°40'N latitude marks the northern boundary of Escanaba Trough, which forms the southernmost part of Gorda Ridge. Escanaba Trough is opening at a total rate of approximately 24 mm/yr and has a morphology consistent with the slow spreading rate. The axial valley, which is at a depth of 3,300 m, increases in width from about 5 km at the north end to more than 15 km near the intersection with the Mendocino Fracture Zone.

South of 41°17'N latitude, the axial valley of Escanaba Trough is filled with several hundred meters of turbiditic sediment. The sedimentary cover thickens southward and is a kilometer or more in thickness near the Mendocino Fracture Zone. Turbiditic sediment enters the trough at the southern end and is channeled northward by the axial valley walls (Vallier et al., 1973; Normark et al., 1994). Sedimentation was relatively rapid (up to 25 mm yr^{-1}) during low stands of sea level in the Pleistocene, and the entire sediment fill of the trough probably was deposited within the last 100,000 years (Normark et al., 1994; Davis and Becker, 1994).

Seismic reflection surveys show that the floor of Escanaba Trough is generally a smooth, flat plain underlain by continuous and relatively undisturbed turbidites (Davis and Becker, 1994; Morton and Fox, 1994). However, local areas along the axis of spreading have irregular seafloor topography characterized by circular hills 0.5 to 1.2 km in diameter that are uplifted 50 to 120 m above the surrounding seafloor. The sediment cover in these areas is described as moderately to highly disturbed based on the discontinuity or absence of seismic reflectors (Morton and Fox, 1994). Morton et al. (1994) mapped the distribution of the topographically rough, seismically disturbed zones (Figure 4), which typically are 3 to 6 km wide, oval-shaped areas aligned along the spreading axis. The strongly disturbed zones are also areas of high heat flow (Figure 4; Davis and Becker, 1994).

The areas of sediment disruption are sites of recent axial rift igneous activity. The geologic and geophysical evidence suggests that axial rift igneous activity at these sites is manifested by intrusion of dikes, sills, and laccoliths into the sediment with less abundant volcanic flows (Morton and Fox, 1994; Zierenberg et al., 1994). Sulfide mineralization has been sampled by dredging, sediment coring, or submersible at four igneous centers within the sediment-covered part of Escanaba Trough. The NESCA area (Figure 5) contains several large massive sulfide deposits including an area of active hydrothermal venting. The dominant morphologic features in the NESCA area are the SW Hill and the Central Hill (Figure 5). The SW Hill is an elongated sediment hill that has been uplifted by 120 m above the surrounding turbidite plain. The steep sides of the hill expose semiconsolidated turbiditic sediment. Massive sulfide deposits occur at the base of the scarp that bounds the uplifted sediment hill. SW Hill is interpreted to have formed by uplift of sediment over a laccolithic sill; high permeability fault zones that accommodated the uplift provided pathways for flow of hydrothermal flow to the seafloor (Figure 6; Denlinger and Holmes, 1994).

A large exposure of volcanic rock occurs east of the crest of the Central Hill (Figure 5). The elevated area east of the Central Hill is covered by glassy basalt pillows 1 to 2 m in diameter. Lava tubes drape the north flank of the hill, indicating flow to the north, toward sheet-flow basalt ponded within the central depression of the spreading center. The area of Central Hill west of the outcropping pillow basalt is interpreted to have been uplifted by intrusion of basalt into the sediment. The central peak of the sediment hill is surrounded by steep sediment-covered scarps, and the north slope of the hill is a series of normal faults down-dropped to the north. The western, sediment-covered part of the Central Hill is the area of the most extensive sulfide deposit observed in Escanaba Trough. The massive sulfide deposits on the west and southeast flanks of the Central Hill are actively venting hydrothermal fluid, and the area on the northern flank shows indications of very recent hydrothermal activity, suggesting that these deposits are all part of the same hydrothermal system. An extensive area of massive sulfide is exposed on the north slope of the Central Hill. Massive sulfide extends more than 270 m from north to south and more than 100 m from east to west, but the western edge has not been determined. Within this area there is nearly continuous outcrop of massive sulfide with few sediment-covered areas. The best explored and most hydrothermally active area of sulfide mineralization on the Central Hill extends west from the northern end of the sediment-covered hill top. This is not an area of continuous sulfide outcrop, but rather a region of abundant, closely spaced sulfide mounds. The mounds are typically 20 to 60 m in diameter and 5 to 10 m high. Two mounds were observed to actively discharge high-temperature hydrothermal fluid; one near the eastern margin of the sulfide area was venting 217°C fluid, and one on the western edge of the explored area was venting 108°C fluid. Even though these mounds are 275 m apart, the major-element composition of the end-member fluid at each vent is identical (Campbell and others, 1994), a result that is consistent with the hypothesis that this large mineralized area is a single hydrothermal system hydrologically interconnected at depth.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

1) To investigate the large-scale hydrogeology of Middle Valley and Escanaba Trough by sampling borehole fluids at previously CORKed sites, examining the relationship of active fluid flow to alteration of the southern sulfide mound and the controls on fluid flow under the Bent

Hill massive sulfide deposit, by conducting a detailed packer experiment, and retrieving detailed temperature records.

2) To investigate the small-scale hydrogeology of Middle Valley by establishing the extent and composition of the caprock and the relationship of lateral flow to active vents.

3) To examine sulfide genesis at Bent Hill and the Escanaba Trough, in particular its structural controls, limits of mineralization and alteration, depositional history, and the extent and geometry of mineral zoning, in addition to determining the geochemical relationship between these deposits and actively venting massive sulfides, mapping the extent and nature of these high-temperature sulfide-depositing hydrothermal system, and contrasting the Bent Hill system with the Escanaba Trough which has a dominantly sedimentary metal source.

4) To investigate the tectonic and structural history of the area, in particular the mechanism of basement sill emplacement and sediment deformation and the relative timing of fault movement and fluid flow.

5) To establish a normal sedimentary and physical properties reference section beyond the thermal effects of the hydrothermal upflow zone.

6) To establish pore water, organic geochemistry, and sulfur isotope profiles, and the geothermal gradient for the region.

Specific Objectives and Methodology

Genesis and Evolution of Massive Sulfide Deposits

Localization of the Deposits

Leg 139 determined that the Dead Dog vent field is located above a buried volcanic edifice that acts a "choked-chimney" that effectively focuses fluids from the relatively more permeable basement through the overlying sediment (Davis and Fisher, in press). Geologic relationships in Escanaba

Trough suggest the sulfide deposits there are localized by large laccolithic intrusions near the base of the sedimentary sequence (Denlinger and Holmes, 1994). A similar relationship was suggested for the sulfide deposit south of Bent Hill, but drilling on Leg 139 established that the uplift of the hill by sill emplacement postdated the formation of the sulfide deposit (Mottl et al., in press). We suspect that the location of both the Bent Hill intrusions and the two sulfide deposit are associated with ridge-parallel faulting; the Leg 169 transect of sites will test this hypotheses.

Size and Geometry of Deposits

Our knowledge of the extent of the sulfide deposits was limited to areas of surface outcrops until the Bent Hill deposit was drilled on Leg 139. Drilling established a minimum north-south extent of 60 m and a minimum thickness of 95 m. Massive sulfide deposits on land range form mound-like bodies to tabular sheets with typical width to thickness aspect ratios of 4:1 to >100:1. The vertical extent of the Bent Hill deposit was a major discovery. We need to determine the extent and geometry of this deposit for comparison to on-land analogs. The surface extent of massive sulfide at Escanaba Trough is much larger than at Middle Valley. Is this an indication that the deposits are much larger, or are they of similar size, but thinner, with an aspect ratio more typical of on-land deposits?

Timing of Mineralization

We wish to understand when hydrothermal activity started at each site and how long hydrothermal discharge was active. The length of time required to form an ore deposit is an important problem that is beyond the resolution of available dating techniques in ancient deposits. Was fluid flow continuous or episodic? The sediments cored on the south flank of Bent Hill contain clastic sulfide that show that the massive sulfide deposit formed prior to the uplift of the sediment hill, but the precise timing is uncertain due to sediment slumping at that site. The Sunnyside Up deposit is morphologically younger than the Bent Hill deposit and is still venting hydrothermal fluid, but the timing of onset of hydrothermal activity is uncertain. The Central Hill deposit at the NESCA site in Escanaba Trough appears younger still, even though it appears to be larger. How long does it take to form a large ore deposit?

Metal Zoning

What is the distribution of metals throughout the deposits and how was this established? On-land massive sulfide deposits do not have a homogeneous distribution of metals. Deposits are typically zoned with copper-rich bases and zinc-rich tops. Precious metals tend to be enriched on the peripheries of the deposits. Several mechanisms have been proposed to account for the distribution of metals in these deposits, but much evidence supports remobilization of metals in a zone refining process. Drill core from the mature Bent Hill deposit shows extensive recrystallization of sulfide minerals and mobilization of base metals, causing an increase in Cu/Zn ratios downhole. The extent and geometry of this zoning remain unknown. The Sunnyside Up deposit may be actively undergoing metal redistribution in response to flow of lower temperature hydrothermal fluids through the deposit. The morphologically younger Central Hill deposit at Escanaba Trough may still retain its original metal distribution and therefore may provide evidence for the primary deposition of metals.

Fluid Composition

What constraints do the hydrothermal precipitates and alteration minerals place on the temperature and composition of the hydrothermal fluids? Study of fluid inclusions, mineral assemblages, and mineral compositions from the Bent Hill deposit show that it formed from hydrothermal fluids with a higher temperature, lower sulfur fugacity, and less sediment input than fluids presently venting at the Dead Dog vent site (Peter et al., in press). Hydrothermal fluids venting from the massive sulfide deposits at Sunnyside Up and Central Hill have been sampled, but these fluids are not presently depositing massive sulfide at the seafloor. What is the relationship of these fluids to the sulfide deposits through which they vent? Are they depositing massive sulfide in the subsurface? Are they altering the mineralogy of the deposits through recrystallization and remobilization of metals?

Hydrothermal Alteration

An alteration zone underlying an active seafloor massive sulfide deposit has never been sampled by drilling and is one of the highest priority goals of Leg 169 as a means to increase our understanding of the mechanisms of alteration and to allow comparison to on-land ore deposits. Because hydrothermal alteration extends to a larger area than economic mineralization, mapping alteration is a prime tool in exploration for massive sulfide deposits. However, tectonic deformation, metamorphism, and late stage hydrothermal overprinting make interpretation of the alteration observed below on-land massive sulfide deposits difficult.

Source of Metals

The composition of massive sulfide deposits is a first-order control on the economic value of the deposits. It is also a complex indicator of hydrothermal processes occurring in the subsurface. How does the composition of the underlying rock influence the composition of the deposits? Pyrrhotite-rich massive sulfide from the Bent Hill deposit contains zones rich in Cu and Zn, but has very low values of Ag, Au, and trace metals derived from sedimentary source rocks. Lead and strontium isotopes indicate that the Bent Hill deposit had a predominantly basaltic source. In contrast, pyrrhotite-rich massive sulfide samples from Escanaba Trough are highly enriched in Au (to 10.1 g/t), Ag (to 681 g/t), Cu (to 20.6%), Zn (to 42.6%), Pb (to 13.7%), As (to 2.75%), and Sn (to 1400 ppm) (Koski et al., 1994). The trace element content and Pb isotope ratios require a major contribution of metals from sedimentary source rocks. Is this difference an indication that there is an, as-yet undiscovered, volcanic plug directly underlying the Bent Hill deposits or is it related to a substantially different hydrologic regime in the high-temperature reaction zone and upflow zone? Drilling through and beneath the massive sulfide deposits at both sites is required to understand the factors that control the compositional variations in massive sulfide deposits.

Tectonics of Sedimented Rifts and Structural Controls of Fluid Flow

Spreading Mechanisms in Sedimented Rifts

Neither Middle Valley nor Escanaba Trough formed as simple mid-ocean rifts that were later buried by sediment. Both systems were actively extending during periods of rapid sedimentation. As such, these systems provide an important analog to processes occurring during the opening of ocean basins. How does the structure of the upper oceanic crust formed under conditions of high sedimentation differ from normal oceanic crust? Drilling at Site 857 in Middle Valley showed the uppermost oceanic crust is a transitional zone of interbedded sills and sediment. The upper 450 m of this sill complex consists of approximately 30% basaltic sills ranging in thickness from 1 to 25 m. The prevalence of deformational structures in sediments, some of which is presumably related to sill emplacement, was not anticipated prior to drilling. Seismic evidence (Rohr and Schmidt, 1994) suggests that packages of sills are emplaced parallel to the ridge strike, consistent with control by ridge-parallel faulting. Orientation of core, either magnetically or through use of the Hard Rock Orientation Tool, could be combined with the geometry of deformation fabrics and the anisotropy of magnetization to determine the direction of emplacement stresses and igneous flow directions, respectively. Other aspects of sill emplacement remain unknown, such as the controls on the level of neutral buoyancy, the timing of sill emplacement, and the physical properties of the sediment during emplacement.

Timing and Feedback of Faulting and Fluid Flow

Fluid flow and deformation in the upper oceanic crust are inextricably linked. For example, changes in effective stress induced by pore-fluid pressure variations will modify the role of different failure mechanisms (e.g., pressure solution, cataclasis, independent particulate flow, hydrolytic weakening, subcritical fracturing (Etheridge et al., 1983)). The microstructures that accommodate the different failure mechanisms in conjunction with the alteration history will vary the distribution and character of the porosity and permeability. During Leg 169, we will emphasize the integration of structural observations of core, logging, and physical property data as an essential complement to studies of water-rock interaction and the generation of massive sulfide deposits.

What was the fracture density and evolution, as constrained by cross-cutting relations, among open and sealed fractures in the core? How are the paleo-fracture-related porosity variations distributed relative to the hydrothermal upflow zones that formed the sulfide deposits? Can the fracture sequence be tied to the alteration history and related to different phases of fluid flow? Modeling of the upflow zone at Site 858 based on the CORK records indicate that fluid pore pressure can exceed hydrostatic overburden at relatively shallow depths in the sediment (Davis and Becker, in press). Is there evidence for hydrofracturing in cores from either the active or paleodischarge zones? What is the timing and relationship between faulting and sulfide deposition? Sedimentary layering in areas adjacent to the inactive Bent Hill deposit appear to be continuous in the shallow subsurface, but offset in apparent basement reflectors indicate previous fault movement to the west of the Bent Hill deposit. Can the stratigraphic record of the footwall and hanging wall blocks, including the distribution of plume fall out and transported sulfide, be used to correlate fault movement and hydrothermal fluid discharge? If hydrothermal fluids are channeled by active faulting, do these fluids affect the kinematics of fault displacement?

Hydrogeology

The large-scale controls on fluid circulation at Middle Valley was the primary focus of Leg 139. Leg 169 drilling will add to the knowledge gained by increasing the data base on the physical properties and temperature structure in the proposed holes. The primary objectives involve study of the local controls on fluid circulation at the scale of individual hydrothermal vents.

Direct Sampling of Vent Fluid Below the Seafloor

The difficulty in drilling a "producing" well at the seafloor has resulted in most borehole fluid samples being little more than surface seawater. CORKed Hole 858G is now a producing hole as evidenced by *Alvin* observations of shimmering water issuing from the reentry cone and deposition of hydrothermal precipitates on the data logger. Unfortunately, the borehole seal and some electronic connections have failed, which precludes using this instrumented hole in any hydrologic experiments to be conducted during Leg 169 drilling. However, for the first time we are presented with the opportunity to sample hydrothermal vent fluids in the subsurface below the zone where mixing with entrained seawater can contaminate the samples and before changes related to adiabatic cooling along the upflow path. This unique opportunity will also allow a detailed temperature log of the hole. We propose leaving this hole unCORKed as a future resource for vent sampling to allow comparison of fluids delivered from the volcanic basement through the casing string to the seafloor with the composition of adjacent natural vents that include a flow path through the sediments.

Permeability Distribution in the Sill-Sediment Complex

The data logger for Hole 857D was damaged on Leg 146 during an unsuccessful attempt to replace the thermistor string. We therefore do not know if this hole has thermally recovered from drilling. Although damaged, the data logger may still have a record of the recovery of the hole stored in memory. The need to replace the thermistor sting and data logger presents an opportunity to obtain temperature logs and borehole fluid samples from the high temperature reaction zone. Flowmeter measurements in this hole on Leg 139 prior to CORKing the hole showed one zone of extreme hydraulic conductivity (>10,000 l/min). We will check to see if the formation is still capable of accepting this large volume of cold seawater. We also wish to measure the permeability structure of sill-sediment complex that constitutes the upper portion of the hydrothermal reaction zone in more detail by conducting a detailed packer/flowmeter experiment in this hole. Circulation of surface seawater while drilling to bit destruction (approx. 200 m) will cool the hole sufficiently for the packer experiment, while providing new data on the structure, stratigraphy, and rock alteration in the hydrothermal reaction zone. The bottom of the hole will be logged and a new thermistor string and CORK installed after the hole is deepened.

Vent Scale Hydrology

Hydrothermal venting occurs at discreet sites in the Dead Dog vent field; diffuse low temperature venting is only rarely observed. Furthermore, large anomalies in pore-fluid composition in the shallow portion of the vent field are an indication of lateral advection of hydrothermal fluid in the shallow subsurface. A model consistent with these observations is that the vent field is capped by a hydrologic seal of altered and cemented sediment. Drilling records show a hard layer was encountered, but not recovered, at approximately 30 m depth in the vent field. This caprock could control lateral flow of hydrothermal fluids and localize vents to area where the seal is either absent or fractured. We wish to test this model by drilling a transect of shallow holes across an actively venting hydrothermal mound and determine the nature of the shallow hard layer interpreted to be a hydrologic seal. Detailed temperature (APC temperature tool and rebuilt WSTP), pressure (rebuilt WSTP), and fluid (rebuilt WSTP and squeezing) gradients will be used to determine the direction and magnitude of fluid advection near the hydrothermal mounds.

Formation of Hydrothermal Mounds

The mechanism that forms the 5-15-m high mounds on which the active vents sit is unknown. The sides of the mounds are covered by semi-indurated hemipelagic sediment, and talus aprons of this sediment surround the large mounds, indicating that the mounds are not formed solely by the build up of collapsed chimney debris. The abundance of anhydrite and Mg-rich smectite in core from Hole 858B, drilled on the side of a mound, is consistent with a model of inflationary mound growth by subsurface precipitation of minerals in the mixing zone between venting hydrothermal fluid and entrained seawater. Entrainment of seawater in secondary hydrothermal convection cells has been interpreted to be an important process in the metasomatic alteration that underlies many on-land massive sulfide deposits. This model can be tested using core material from the same drill transect across a hydrothermal mound that will be used to investigate the near-surface advection of vent fluids.

Sedimentation and Diagenesis

Reference Sediment Section

In order to fully quantify the changes in physical properties associated with high heat flow and hydrothermal circulation, we need good reference holes drilled outside of the thermal anomalies of the hydrothermal upflow zones. The only holes drilled in a low heat-flow environment on Leg 139 were at the "recharge" site, Site 855. These cores were rotary drilled and only recovered a short section of highly disturbed sediment. We also hope to establish the stratigraphy of the sediment fill at both Middle Valley and Escanaba Trough in more detail. A distinctive, acoustically-transparent, seismic horizon has been mapped though out Escanaba Trough. This event has been speculatively tied to the Bretz floods (Davis and Becker, 1994), but the timing and composition of this interval need to be confirmed by drilling.

Diagenetic Reactions

Leg 139 established pore water, organic geochemical and sulfur isotopic gradients downcore that could be correlated with either present or paleoheat flow gradients. A reference section is needed outside the thermally anomalous upflow zones to quantify the hydrothermally induced changes.

DRILLING PLAN/STRATEGY AND PROPOSED SITES

Bent Hill Area

Our highest priority for drilling at the Bent Hill is to complete an east-west drilling transect across the Bent Hill massive sulfide deposit and the rift-parallel normal fault that off sets basement west of the deposit. The transect will be anchored by a hole (BH-1) that penetrates through the core of the sulfide deposit with succeeding holes (BH-2 through BH-6) at nominal spacing intervals of 50, 100, 200, 400, and 650 m to the west (Figure 3). Results of drilling during the transect may be used to refine the spacing of the holes. The westernmost end of the transect (proposed site BH-6) is approximately midway between Sites 856 and 857, and is placed so as to penetrate the Site 856 fault at the approximate depth of the local acoustic basement reflectors.

Proposed site BH-1 through the core of the deposit will for the first time establish the thickness of a seafloor massive sulfide deposit. We will be able to determine the nature of the high temperature alteration underlying the massive sulfide and compare it to the alteration underlying the lower temperature Dead Dog vent field. We will also determine if there is a narrow volcanic high underlying the deposit (similar to the Dead Dog vent field), if there is a sill-sediment complex (similar to Site 857 and areas to the west), or if it is underlain by sediment-covered, normal extrusive basaltic oceanic crust (similar to Site 855 and areas to the east). Continuing the transect to the west will constrain the size and the geometry of the deposit, the compositional zoning of both mineralization and alteration, the timing of mineralization, and the controls on the location of this paleo-fluid upflow zone, including the role of near-surface faulting. The temperature of mineralization and alteration will be constrained by analysis of fluid inclusions (Peter et al., in press) and oxygen isotope geothermometry on alteration minerals, including carbonate nodules and cements, which Leg 139 drilling showed preserved the paleothermal gradient on the fringes of hydrothermal upflow zones (Baker et al., in press). Timing of hydrothermal activity will be constrained by the sedimentary record of hydrothermal plume fall out and distribution of redeposited sulfide from the high standing sulfide mound (as observed at Hole 856B). Stratigraphic variations and microstructural studies will provide evidence for the extent and nature of shallow normal faulting near the deposit. This transect should also help to constrain the paleohydrologic controls on the upflow zone by allowing us to map the distribution of alteration, cementation, fracturing, and vein filling. The relationship of fault movement and fluid flow will be investigated by the methods described below and may provide an important contrast to the deeper faulting to be investigated at proposed site BH-6. The westernmost hole will be drill through a thick section of sediment in the hanging wall of a normal fault and will provide a reference section of sediment away from the thermal effects of either the paleo or active upflow zone to calibrate the changes in physical properties with temperature and depth that were established on Leg 139.

Based on the results from Leg 139, we anticipate the recovery of core containing polyphase fracture arrays, various sediment microfabrics, and variably altered igneous and sedimentary units with complex cementation histories. The core will provide the basis for a detailed investigation of the timing of fluid flow relative to deformation and magmatism. Fluid flow and deformation are inextricably linked. For example, changes in effective stress induced by pore-fluid pressure variations will modify the role of different failure mechanisms (e.g., pressure solution, cataclasis, independent particulate flow, hydrolytic weakening, subcritical fracturing (Etheridge et al., 1983)). The microstructures that accommodate the different failure mechanisms, in conjunction with the alteration history, will vary the distribution and character of the porosity and permeability. The integration of structural observations of core, logging, and physical property data will compliment studies of water-rock interaction and the generation of massive sulfide deposits. Integrated microfabric and physical property investigations will provide valuable constraints for modeling acoustic signatures of the upper oceanic crust and assessing the role of deformation and cementation histories on seismic velocities.

The fracture evolution will be constrained by the orientations and crosscutting relations among open and sealed fractures in the core, together with their fracture-fill phases and textural relations. These will be integrated with the interpretation of the alteration history so that the fracture evolution can be related to different stages of fluid flow. The fracture data will also provide some constraints on local paleo-fracture porosity variations for comparisons with logging data. Fracture-fill fabrics (e.g., curved fibers, crack-seal histories) will be used to interpret the opening modes of fractures, local incremental strain paths, and spatial and temporal variations in local paleostress fields. Even where an azimuthal direction can not be established, the kinematic indicators from the core are still useful in terms of the relative changes in strain paths they record. We may be able to constrain semi-quantitative estimates of strain variations with depth if the Site 856 fault zone continues to shallow depths.

In addition to discrete fracture arrays, investigations of the cementation histories of sediments and the textural relations between cement phases, dissolution cavities, and microstructures will provide constraints on the relative timing of intergranular fluid flow and deformation in sediments for comparison with fracture evolution both in sedimentary and igneous units. One aspect of these studies will be to document the evidence for the generation of fluid-flow paths by transient dilation events that accompany deformation in unconsolidated or lithified sediments. We will also investigate the impact of flow units and sill intrusion on the distribution of sediment-compaction fabrics that may restrict fluid flow, both at this site and while deepening Hole 857D.

Drilling will provide an opportunity to contrast the mechanical response of different lithologies in the uppermost oceanic crust and investigate the role of different failure mechanisms, such as independent particulate flow, cataclasis, distributed cracking, discrete localized fractures or penetrative foliations that may be associated with frictional sliding. The core data will enable a correlation of microstructures with primary textural characteristics of lithologies, where preserved, and different generations of hydrothermal alteration phases. It will also be possible to evaluate the impact of different lithologies and structures on the porosity of the uppermost oceanic crust. Determination of the pre-, syn-, and post-kinematic hydrothermal phases will also help to constrain the conditions of deformation. Textural characteristics in hydrothermally altered zones will provide clues to qualitative variations in paleo-flow rates and paleo-pore-fluid pressure conditions. For example, evidence for pressure solution in sediments would also indicate low effective stresses and relatively low strain rates (Rutter, 1976) Jigsaw puzzle textures in breccias sealed by hydrothermal phases indicate high strain rates during failure and possible hydrofracturing, as predicted for the hydrothermal upflow zone underlying the Dead Dog vent field (Davis and Becker, in press).

Proposed site BH-6 provides an opportunity to obtain a detailed record through a fault zone in the uppermost oceanic basement. Combined FMS and core data will provide detailed complementary data to compare the structures within the hanging wall, footwall, and fault zone. Suggestions that the fault zones form major fluid-flow conduits can be tested by examining the textural evolution of the fault rock (gouge, breccia, etc.) and determination of at least qualitative estimates of water-rock ratios based on alteration mineralogy and stable isotope shifts. Some fault gouges may act as impermeable horizons. By assessing the textural evidence for pre-, syn-, and post-fault-slip fluid flow it will be possible to relate the timing of fault slip to different stages and conditions of fluid flow represented by different hydrothermal assemblages.

The second priority for drilling in the Bent Hill area is to extend the north-south transect begun on Leg 139 to the actively venting Sunnyside Up sulfide deposit (Figure 3). Proposed hole BH-7 will provide further constraints on the extent, geometry, and timing of sulfide mineralization and alteration. It will also provide a less disturbed section through the sediment column overlying the footwall block of the Site 856 fault for comparison to the hanging wall section to be drilled at proposed site BH-6. The final hole in the transect (proposed site BH-8) would investigate the Sunnyside Up deposit to determine the composition, relative age, and relationship to the Bent Hill massive sulfide, as well as the relationship to the active hydrothermal vent that is located on the north fringe of the deposit.

The two sulfide deposits in Middle Valley and one deposit in Escanaba Trough-that we propose to drill are in different stages of an evolutionary sequence allowing investigation of temporal changes that ultimately lead to the formation of massive sulfide deposits; processes that are difficult to study in ancient ore deposits. The Bent Hill deposit is a mature deposit that has been highly modified by post depositional recrystallization. Deeper portions of the deposit have increased copper content and preserve a primary high-temperature sulfide assemblage dominated by pyrrhotite. However, upper parts of the deposit have been extensively modified by recrystallization to pyrite and magnetite. Petrographic data indicate that magnetite formed during high-temperature (200-300°C) recrystallization of pyrrhotite to pyrite plus magnetite. This alteration occurred due to the passage of hydrothermal fluid through previously deposited pyrrhotite-rich sulfide. Base-metal sulfide minerals have been remobilized in a zone-refining process that has formed a vertical metal zonation in the deposit, with Zn/Cu ratios increasing upwards.

The Sunnyside Up deposit is known from its surface morphology, degree of weathering, and extent of sediment cover to be younger than Bent Hill, but the timing of deposit formation needs to be constrained by examining the sedimentary record of hydrothermal activity. The single 264°C hydrothermal vent that is active at the north end of this deposit is not presently depositing any sulfide. The chemical composition of fluid venting from the southern sulfide body is similar to the fluids that are venting at the Dead Dog vent field, but is very different from the higher temperature (ca. 350-400°C), low pH, metal-transporting fluid that formed the massive sulfide deposits (Peter et al., in press). The Sunnyside Up deposit does not appear to contain a large amount of magnetite (Tivey, 1992), and thus may be a more "pristine" deposit than Bent Hill. This deposit appears to represent an important intermediate evolutionary stage between high-temperature primary sulfide deposition (Escanaba Trough) and highly recrystallized massive sulfide (Bent Hill deposit). This sulfide body may be undergoing the type of recrystallization and alteration that has extensively modified the Bent Hill deposit in response to flow of lower temperature (264°C) fluid through the deposit. A hole through the Sunnyside Up sulfide body may provide the opportunity to examine active recrystallization and zone-refining processes in this mature, but still active, deposit.

Escanaba Trough

The morphology of massive sulfide deposits at the NESCA site in Escanaba Trough (Figures 4 and 5) indicate that these large sulfide deposits are younger than the deposits at Middle Valley, and therefore may contain a more complete record of the earliest stage massive sulfide formation. Sediment cover and seafloor oxidation is virtually absent from the Central Hill sulfide deposit at the NESCA site in Escanaba Trough. Seafloor samples from the Escanaba Trough deposits indicate that they are somewhat similar to the least recrystallized portions of the Middle Valley deposits, with pyrrhotite as the dominant sulfide mineral. The contents of base metals (including Pb), Au, and Sn in the Escanaba deposits are much higher than those from Middle Valley, due primarily to increased contribution from the sediment, but perhaps in part because these deposits are as yet unaffected by remobilization and recrystallization. Carbon and helium isotopic data from the actively venting fluids associated with these deposits indicate a major component of magmatically-derived gases, in distinct contrast to the fluids at Middle Valley, whose CO_2 is derived from organic matter (B. Taylor, pers. comm.). The tectonic and depositional settings of the deposits in the Escanaba Trough and Middle Valley areas are similar, but the chemical compositions of the two deposits are quite different. These two areas thus provide a common geological framework within which to study the processes of hydrothermal interaction of basalt and sediment with hydrothermal fluids, and the deposition and recrystallization of massive sulfides.

The drilling strategy for Central Hill deposit is similar to that proposed for the Bent Hill deposit. We will drill an east-west transect of holes (proposed sites ET-1 through ET-6) across the deposit with our highest priority goal being to penetrate through the core of the massive sulfide and examine the underlying high-temperature alteration zone. The questions to be addressed regarding massive sulfide genesis and fluid flow and the approaches we will use are the same as outlined above for drilling in the area of the Bent Hill deposit. The drilling strategy at Escanaba Trough was also designed to address additional questions as outlined below.

Isolated volcanic centers pierce the sedimentary cover of the trough at approximately 15 km intervals along the spreading axis (Figure 4; Morton et al., 1994). Hydrothermal deposits are spatially associated with these volcanic centers. Is the formation of oceanic crust at slow-spreading sediment-covered ridges fundamentally different than what we observed in Middle Valley, or do these large volcanic edifices, that locally built to the seafloor in Escanaba Trough, simply represent a different stage of development of the spreading center than presently observed in Middle Valley? The transect of drill holes at Escanaba Trough crosses from the intrusion-related SW Hill to the margin of the pillow dome east of Central Hill and should provide important information on the interrelationship of igneous activity and tectonics in the shallow parts of sediment-covered spreading centers.

Central Hill is a sediment hill located on the flank of a pillow dome that is astride the spreading axis (Figure 5). Sheet flows extend north and south from the pillow dome, and at least those to the north overlie the sedimentary fill of the rift (Zierenberg et al., 1993). No volcanic rocks are exposed on Central Hill west of the contact with the pillow dome. Geologic observations indicate that the pillow lavas have ponded against a preexisting sediment hill. The north flank of the hill is a series of stepped normal faults, indicating relatively recent uplift of the hill. Massive sulfide is exposed from the base of the hill to near the top. Proposed site ET-1 is the easternmost hole of the transect and will be drilled on the top of the sediment-covered Central Hill between the two areas of active hydrothermal venting (Figure 5). This location is in the footwall block of the normal fault that forms the scarp bounding the west side of Central Hill. This fault projects through the vent field, but does not show a topographic expression in the area of mineralization and is not observed on seismic line 2, located several hundred meters to the north (Figure 5). This fault probably terminates at the east-west faults that bound the north slope of Central Hill and is likely related to uplift of the hill above an intrusive complex. This hole will establish the thermal structure and pore- fluid composition of the sediments within the area of the vent field. This hole should also provide information on the nature of basaltic basement, including the composition and extent of the adjacent pillow volcano or associated sills in the subsurface, the timing and mechanism of formation of the sediment hill, and the extent and composition of both sediment and igneous alteration in the shallow part of the hydrothermal field. The proximity of the outcropping volcanic rocks makes estimation of the depth to basement uncertain from the available seismic profiles. Sediment fill in the NESCA area is typically about 600 m thick, but the proximity of this hole to an on-axis volcanic center suggest that the total depth is likely to be less than 250 mbsf. If this hole intersects significant high- temperature hydrothermal alteration, it could be outfitted with a free-fall funnel for deepening into the high-temperature reaction zone.

The second hole in the transect (proposed site ET-2) will be sited near a 220° hydrothermal vent and will drill through massive sulfide and into the underlying alteration zone to determine the extent, composition, and structural setting of the sulfide deposits. It is part of a three-hole, east-west transect of shallow holes through the sulfide deposit. If the fault bounding the west side of Central Hill continues under the vent field, these holes will penetrate the hanging wall and intersect the fault at increasing depth, assuming the fault dips to the west. The results of the drilling transect will be used to site a reentry hole (proposed site ET-5) that will be drilled into the core of the hydrothermal upflow zone to provide samples of hydrothermally-altered sediment and basalt from deeper in the system. This hole will be extensively logged and will be available for further reentry and deepening, or for post-drilling hydrothermal and downhole experiments. The westernmost hole in the transect (proposed site ET-6) is a second-priority hole drilled to investigate the igneous and hydrothermal processes related to the emplacement of large laccolithic sills near the spreading axis. This hole will be located on the flat top of the large, recently uplifted SW Hill. This hill is similar to Bent Hill in Middle Valley, but is larger and rises 120 m above the surrounding turbidite plain (Figure 5). The steep sides expose only interbedded turbiditic and hemipelagic sediment, except near the base of the southern end of the hill, where an upfaulted remnant of massive sulfide is exposed. Massive sulfide was also observed on each camera or submersible track that crossed the basal scarp that defines the hill, and massive sulfide may discontinuously ring this structure. This site is an excellent area to test the hypothesis that large "punched laccolith" intrusions (Figure 6) are responsible for the uplift of these hills, which are a common tectonic feature in Escanaba Trough (Denlinger and Holmes, 1994; Zierenberg et al., 1994).

A reference hole is needed to provide the necessary background information to evaluate the sedimentary and thermal history in an area away from a hydrothermal upflow zone. Determination of the nature of the igneous basement at a site away from the large intrusions is important to our understanding of the larger scale thermal and hydrologic structure of sediment-covered spreading centers. For example, are the sheeted sills drilled at Site 857 truly representative of the structure of the uppermost oceanic crust formed at a sediment-covered slow-spreading center? What is the nature of hydrothermal alteration/metamorphism away from hydrothermal upflow zones? Is there a reservoir of high-temperature hydrothermal fluid in the sandy turbidites, the igneous basement, or both? Do the pore fluids near the basement approach the composition of nearby hydrothermal vents, as observed in Middle Valley? The reference hole will be sited along seismic line 89-05, which shows relatively little disturbance of the sediment and along which a heat-flow profile was collected.

Other important questions regarding the sedimentary history of Escanaba Trough will also be addressed at this site. The only previous drilling in Escanaba Trough was DSDP Site 35, approximately 35 km south of the NESCA area, but this site was located east of the spreading axis. This hole was drilled to 390 mbsf without reaching basement, but was spot-cored with only 95 m of the interval cored. Many of these cores were never opened and described by the shipboard scientists. Theses cores have been re-examined and are described by Normark et al. (1994). The turbidite sequence records the sedimentary record of glacial activity and sea-level variations during the Pleistocene. A major change in provenance from the Columbia River drainage in the upper part of the hole to the Klamath Mountains at the base of the hole was recognized by the Leg 5 scientists (Vallier et al., 1973). Petrographic evidence from previously unsampled core shows that the change in source area occurred much later than previously recognized (Zuffa et al., in prep), but the discontinuous nature of the coring prohibits detailed reconstruction of the sedimentary history.

A second area of investigation into the sedimentary history of Escanaba Trough involves the controversial "transparent" layer present in all seismic profiles across the Trough (Morton and Fox, 1994; Davis and Becker, 1994). This layer occurs at approximately 100 ms depth and is about 50 ms thick. Davis and Becker (1994) have interpreted this zone as a homogeneous sandy layer related to the Bretz floods caused by the catastrophic draining of ice-dammed Lake Missoula at approximately 13,000 ka. Normark et al. (1994), however, interpret this zone as a muddy interval formed during an interglacial high-stand of sea level. Either interpretation has testable ramifications for the large-scale hydrology of the Escanaba Trough. The former scenario would imply that this unit could be an aquifer for transport of hydrothermal fluid to sites of cross-stratal permeability, such as faults or volcanic highs. The second scenario would suggest that this unit may be an aquiclude that seals the hydrothermal system.

Dead Dog Vent Field

The three main objectives for the area around the Dead Dog vent field are to deepen and reCORK Hole 857D, unCORK and sample Hole 858G, and complete a piston coring transect across an active hydrothermal mound.

The original thermistor string in Hole 857D did not reach below the cased section of the hole. A proposal by Becker and Davis to replace the thermistor string in Hole 857D with a longer string was approved and scheduled for Leg 146. Difficult weather conditions prevented completion of this operation and resulted in damage to the instrument package. Hole 857D was drilled into the sill-sediment complex that represents the reaction zone for the fluids venting at the Dead Dog vent field (Davis et al., 1992). We consider replacement of the thermistor string and data logger to be a high-priority objective. Our strategy will be to remove the damaged data logger and obtain a temperature log and borehole fluid samples. We then propose to deepen the hole by drilling approximately 200 m until bit destruction. Besides providing important samples of basalt and sediment from deeper within the reaction zone, circulation while drilling will provide the necessary cooling for logging the newly drilled section of the hole and performing a detailed packer/flow-meter experiment to determine the permeability distribution of the sill-sediment complex. The hole will be left with a new thermistor string extending to the bottom of the hole and reCORKed so that the return of the hole to thermal equilibrium can be monitored for comparison to the data obtained from Hole 858G in the Dead Dog vent field.

The thermal recovery of Hole 858G provides a truly unique opportunity to sample hydrothermal fluid beneath the seafloor. High temperature in the hole has resulted in the failure of both the data logger and the borehole seal and the hole is now producing hydrothermal fluid. For the first time we will be able to collect a borehole fluid sample that represents formation fluid rather than surface seawater. Our plan is to immediately log the temperature and sample fluids in the hole after the CORK is removed. We propose to leave the hole open for future sampling of hydrothermal fluid. The ability to sample fluids at the seafloor that have a direct path through a cased hole from the igneous basement and compare these with vent fluids from the same area that have a flow path through sediments is an exciting experiment. Furthermore, because there are no vents in the immediate vicinity of Hole 858G, we will have created a true point-source vent that can be used in experiments on plume dynamics and mass and heat flux.

Our final objective for the Dead Dog vent field is to drill a series of systematically navigated APC/XCB holes (proposed sites DD-1 through DD-3) across an active hydrothermal mound. Particular emphasis will be given to establishing the lateral continuity of the postulated caprock and to recovering samples from this critical zone. Detailed temperature, pore-fluid, and pore-pressure profiles across this zone will help to establish the hydrological control of this unit on formation of the vent field, including the ponding and lateral migration of vent fluids and extent and location of mixing zones between seawater and hydrothermal fluid.

The Dead Dog Mound vent site (Figure 2) is ideal for this study in that it has not been locally disturbed by earlier drilling. The mound is 10 m high and about 35 m in diameter, and is the westernmost mound in the southern part of the vent field. It is midway between holes 858C and 858G, therefore the drilling can be tied in to the results from Leg 139. The Dead Dog Mound vent appears to be the most vigorous vent in the vent field (Franklin and Embley, 1992), and it now has the largest chimney structure (9 m in height) of all vent sites at Middle Valley. Drilling through the mound will establish whether the hard layer, interpreted as a hydrothermal barrier, exists directly below the actively venting mounds. This site will also test the hypothesis that mounds build above the level of the ambient seafloor primarily by subsurface deposition of Mg-rich smectite, anhydrite, and pyrite in the zone of mixing of hydrothermal fluids with colder seawater. Previous evidence supporting this hypothesis includes the Mg-smectite- and anhydrite-rich sediment cored in Hole 858B, and detailed *Alvin*-deployed heat-flow measurements indicating lower heat flow on the flanks of the mound than in areas more distal to the vents, suggesting inflow of cold seawater on the flanks of the mounds. Inflow of cold seawater would also explain the paucity of vent- specific fauna on the flanks of the mounds. Vent fauna tend to be concentrated either near the active vents or peripheral to the mounds.

At least two more shallow holes will be drill at approximately 20 and 50 m from the center of the mound to provide a transect of the temperature, pore fluid, and pore pressure away from an active vent to test the continuity of the proposed hydrothermal caprock and to examine lateral fluid flow and shallow fluid mixing with seawater. We plan to supplement data from the APC temperature shoe and squeezed pore fluids with in situ measurements and samples collected with the redesigned WSTP tool.

Alternate Program of CORK Deployment

A workshop entitled Sedimented Covered Ocean Ridges Experiments (SCORE) was held recently to determine and prioritize pre- and post-drilling observations and experiments that would maximize the scientific return from oceanic drilling on sedimented ridges. One of the conclusions of the meeting was that the pair of reentry holes, Holes 857D and 858 G, could be taken advantage of by attempting a hole-to-hole hydrologic communication experiment. The experiment requires deployment of new CORKs in the two holes.

Summary of Holes 857D and 858G

Each hole penetrated through the turbidite sediment section that buries permeable basement rocks in the Middle Valley rift. Hole 857D was drilled into what is believed to be the "reservoir" from which fluids that flow through the seafloor at Site 858 are tapped. The Dead Dog vent field (Site 858) formed where the sediment cover is locally attenuated above a buried basement edifice. CORKs were installed in each of these reentry holes, and these first attempts to seal holes and to determine in-situ hydrothermal conditions were very successful. In summary:

1) The feasibility of long-term seafloor hydrologic monitoring was demonstrated.

2) Hole 857D penetrated several highly permeable zones; results of a packer/flowmeter experiment showed that one of these accepted over 10,000 l/min of water from the hole. The pressure driving the flow originated from the high density of the seawater circulated in the hole relative to that of the high-temperature formation fluid. At the time the CORK was initially sealed in, this pressure was determined to be over 1 MPa in amplitude. The natural formation pressure was estimated to be close to hydrostatic (as defined by the local formation geotherm).

3) The pressure record in Hole 858G also began with a large perturbation associated with the circulation of cold seawater during drilling and logging operations. Correction for this effect showed that the natural state of the formation beneath this vent field is highly super-hydrostatic, possibly as high as 450 to 500 kPa, high enough to promote hydrofracturing and brecciation in the upper part of the sediment section.

4) Attenuation and phase delay of the seafloor tidal loading function by the formation in both holes provided constraints on the mechanical and hydrologic properties of the sediment section.

5) Several temperature and pressure transient "events" were recorded in Hole 858G. The events were correlated with changes in tidal signal attenuation. Their cause was undetermined; possibilities include slumping in a nearby open exploratory hole, and changes in the hydrology at depth due to tectonically- or hydraulically-induced fracturing.

Along with the successes, the experiment had some shortcomings. In addition to carrying out the hole-to-hole communication experiment, we hope to reach several objectives with the re-fitted CORKs that could not be reached with the first deployments. Partially or unrealized objectives are as follows:

1) While even subtle changes in temperature associated with tidally-induced flow could be resolved, the absolute formation temperature could not. Accurate determinations of the temperature structure at both sites are extremely important for understanding the Middle Valley hydrothermal system.

2) Only the first three weeks of data have been recovered from the Hole 857D CORK due to technical problems. If no O-ring seals have been damaged, data which should be still resident in memory can be recovered once the logger is returned. This will allow us to check our inferences about the natural formation pressure made on the basis of the data from the initial, short recording period.

3) The cable installed in the nearly 1-km-deep Hole 857D extends to only 300 mbsf, well above the suspected depth of the transition from a conductive to convective thermal regime. During Leg 169, a cable will be installed that will allow us to examine this transition, and to determine the temperature structure and possible temporal variability in the permeable part of the section.

4) Despite the successful completion of reentry Hole 858G and installation of the CORK in this hostile environment, long-term observations were compromised by the hydraulic "short- circuit" caused by the exploratory Hole 858F. An attempt will be made to backfill the full volume of the troublesome exploratory hole so that accurate determinations of formation temperatures and pressures in Hole 858G can be made.

5) The CORK seal in Hole 858G began to leak 17 months after installation. An attempt must be made to re-grout the casing prior to re-fitting a new CORK in the hole.

"Active" Pressure-Pulse Experiments

The real objective of retrofitting new CORKs in holes 857D and 858G is to perform two "active" experiments. It is known that the local effect of circulating cold water in Hole 857D was great; pressures in the hole relative to the formation of over 1 MPa were created. We propose that this pressure anomaly be recreated after recovery of the Hole 857D CORK and data logger, and used as follows.

A 1-MPa fluid overpressure is significant with respect to the effective stress in this rift valley environment. Assuming that the basemen- normal faults are in a state of stress near failure, then a large induced pore-fluid pressure anomaly could stimulate microseismicity. This presents a fascinating opportunity to investigate the geometry and mechanism of faulting in this hydrothermally-active rift. The experiment will require deployment of an ocean-bottom seismometer array, prior to drilling, to assess the level of natural microseismicity, and during and after drilling, to examine the effects of the borehole fluid-pressure pulse. The pulse will have a sudden onset, and will last for several days, over the full period of hole deepening, logging, and packer testing before the new CORK is installed. In addition to seismic monitoring, formation pressure would be monitored in the refurbished Hole 858G during the "pulse test", and in both Holes 857D and 858G after the "pulse test", so that pressure changes associated with seismic events could be detected.

The second "active" experiment to be carried out is a two-hole hydrologic communication test. In this experiment, effects of the pressure pulse generated during the time that cold water is allowed to flow down Hole 857D will be monitored in the refurbished and re-CORKed Hole 858G. The speed with which the pulse will diffuse through the capped, permeable basement formation will depend primarily on the permeability (hydraulic transmissivity) of basement. The amplitude of the response will constrain the storage capacity.

REFERENCES

Ames, D.E., Franklin, J.M., and Hannington, M.D., 1993. Mineralogy and geochemistry of active and inactive chimneys and massive sulfide, Middle Valley, Northern Juan de Fuca Ridge: An evolving hydrothermal system. *Can. Mineral.*, 31:997-1024.

Baker, P.A., Cross, S.L., and Burns, S.J., in press. Geochemistry of carbonate nodules and cements and implications for hydrothermal circulation, Middle Valley, Juan de Fuca Ridge. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Campbell, A.C., German, C.R., Palmer, M.R., Gamo, T., and Edmond, J.M., 1994. Chemistry of hydrothermal fluids from the Escanaba Trough, Gorda Ridge. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:201-221.

Currie, R.G., and Davis, E.E., in press. Low crustal magnetization of the Middle Valley sedimented rift inferred from sea surface magnetic anomalies. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Davis, E.E., and Becker, K., 1994. Thermal and tectonic structure of the Escanaba Trough: New heat-flow measurements and seismic-reflection profiles. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:45-64.

Davis, E.E., and Becker, K., in press. Formation temperatures and pressures in a sedimented rift hydrothermal system: Ten months of CORK observations, Holes 857D and 858G, ODP Leg 139. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Davis, E.E., and Fisher, A.T., in press. On the nature and consequences of hydrothermal circulation in the Middle Valley sedimented rift: Inferences from geophysical observations. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Davis, E.E., Mottl, M.J., Fisher, A.T., et al., 1992. *Proc. ODP, Init. Repts.,* 139: College Station, TX (Ocean Drilling Program).

Davis, E.E., and Villinger, H., 1992. Tectonic and thermal structure of the Middle Valley sedimented rift, Northern Juan de Fuca Ridge. *In* Davis, E.E., Mottl, M J., Fisher, A.T., et al., *Proc. ODP, Init. Repts.,* 139: College Station, TX (Ocean Drilling Program), 9-41.

Denlinger, R.P., and Holmes, M.L., 1994. A thermal and mechanical model for sediment hills and associated sulfide deposits along the Escanaba Trough. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:65-75.

Etheridge, M., Wall, V.J., Vernon, R.H., 1983. The role of the fluid phase during regional metamorphism and deformation. *J. Metamorph. Geol.*, 1:205-226.

Franklin, J., and Embley, B., 1992. The HYSUB 5000 - a remotely operated vehicle for ocean research. *Ridge Events*, 3 (2):10-11.

Koski, R.A., Benninger, L.M., Zierenberg, R A., and Jonasson, I.R., 1994. Composition and growth history of hydrothermal deposits in Escanaba Trough, southern Gorda Ridge. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:293-324.

Morton, J.L., and Fox, C.G., 1994. Structural setting and interaction of volcanism and sedimentation at Escanaba Trough: Geophysical results. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:21-43.

Morton, J.L., Zierenberg, R.A., and Reiss, C.A., 1994. Geologic, Hydrothermal, and Biologic Studies at Escanaba Trough: An Introduction. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:1-18.

Mottl, M., Wheat, C.G., and Boulegue, J., in press. Timing of ore deposition and sill intrusion at Site 856: Evidence from stratigraphy, alteration, and sediment pore water compositions. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program.

Normark, W.R., Gutmacher, C.E., Zierenberg, R.A., Wong, F.L., and Rosenbauer, R.J., 1994. Sediment fill of Escanaba Trough. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:91-130.

Peter, J., Leybourne, M., and Goodfellow, W.D., in press. Fluid inclusion petrography and microthermometry of the Middle Valley hydrothermal system, northern Juan de Fuca Ridge. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Rohr, K.M.M., and Schmidt, U., in press. Seismic structure of Middle Valley near Sites 855-858, Juan de Fuca Ridge. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Rutter, E.H., 1976. The kinetics of rock deformation by pressure solution. *Philos. Trans. R. Soc. London (A)*, 283:203-219.

Tivey, M.A., 1992. Leg 139 drilling tests magnetic models. *JOI/USSAC Newsletter*, 5 (2):8-12.

Tivey, M.A., in press. High-resolution magnetic surveys over the Middle Valley mounds, northern Juan de Fuca Ridge. *In* Mottl, M.J., Davis, E.E., Fisher, A.T., and Slack, J.F. (eds) *Proc. ODP, Sci. Results, 139*: College Station, TX (Ocean Drilling Program).

Vallier, T.L., Harold, P.J., and Girdley, W.A., 1973. Provenances and dispersal patterns of turbidite sand in Escanaba Trough, northeastern Pacific Ocean. *Mar. Geol.*,15:67-87.

Zierenberg, R.A., Koski, R.A., Morton, J.L., Bouse, R.M., Shanks, W.C., III, 1993. Genesis of massive sulfide deposits on a sediment-covered spreading center, Escanaba Trough, 41°N, Gorda Ridge. *Econ. Geol.*, 88:2069-2098.

Zierenberg, R.A., Morton, J.L., Koski, R.A., and Ross, S.L., 1994. Geologic setting of massive sulfide mineralization in the Escanaba Trough. *In* Morton, J.L., Zierenberg, R.A., and Reiss, C.A. (eds.) *Geologic, hydrothermal, and biologic studies at Escanaba Trough, Gorda Ridge, offshore Northern California.* U.S. Geol. Surv. Bull., 2022:171-197.

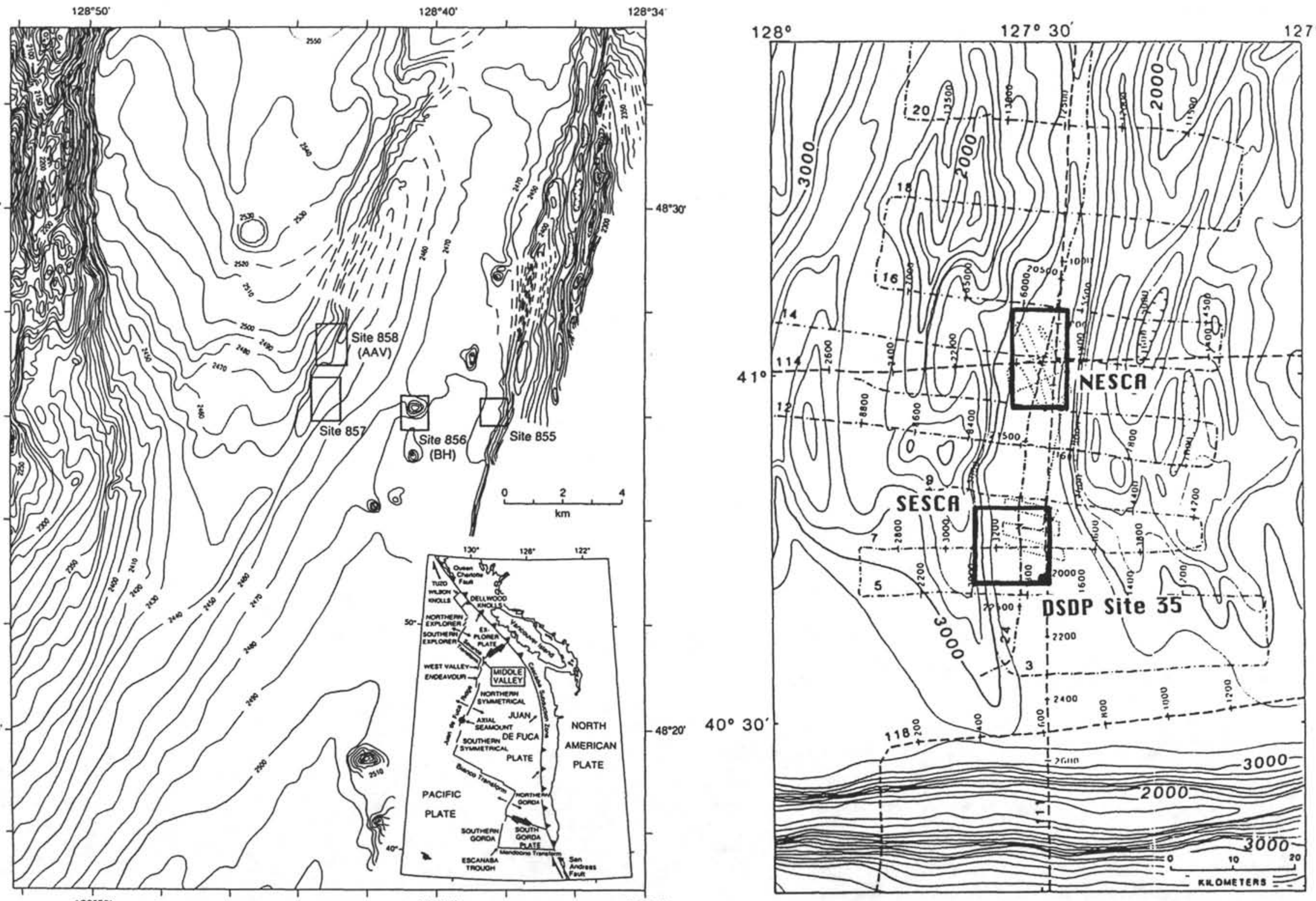
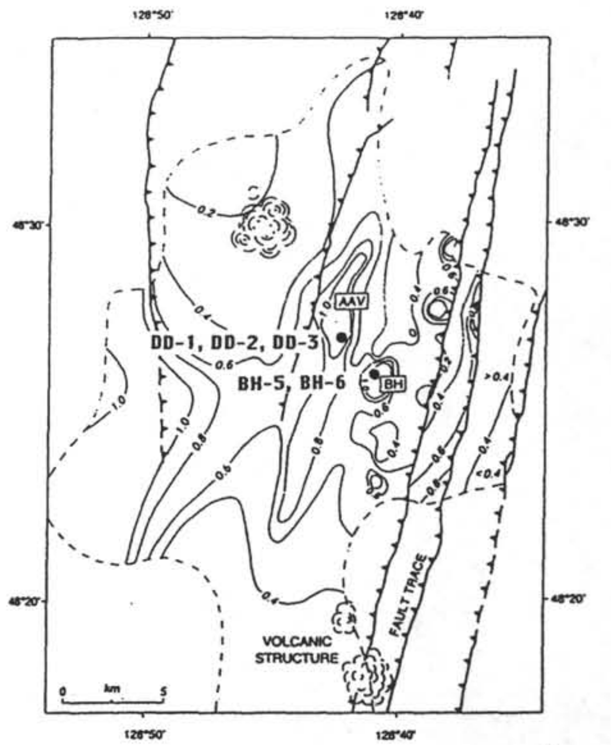
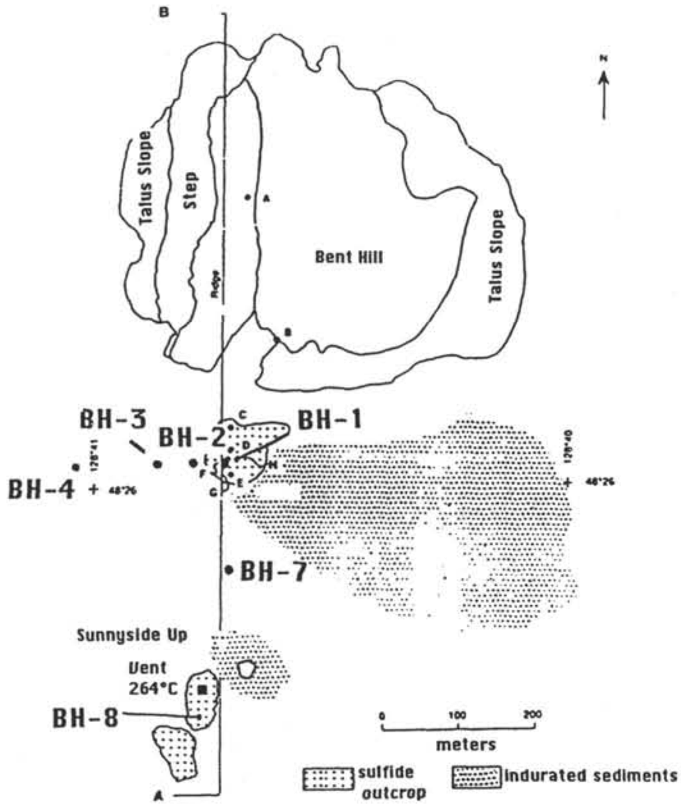


Figure 1. Location map showing the tectonic setting of the sediment-covered spreading centers at Middle Valley and Escanaba Trough on the Juan de Fuca-Gorda spreading system. Areas of proposed drilling are the Dead Dog vent field (Site 858) in the Area of Active Venting (AAV), Bent Hill (BH), and the NESCA area in the Escanaba Trough.

Figure 2. Map of the Middle Valley showing contoured heat flow values centered around the Dead Dog vent field in the Area of Active Venting (AAV) and around the active vent south of Bent Hill (BH). Surface trace of scarps of rift-parallel normal faults is shown by hatchured lines. Proposed sites DD-1 through DD-3, BH-5, and BH-6 are shown.





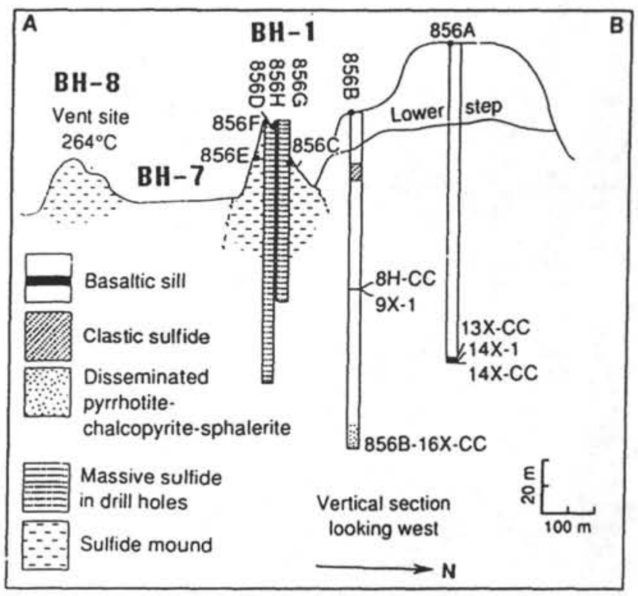


Figure 3. Left: Map of Site 856 area showing the location of Bent Hill and the two sulfide mounds to the south. A ridge-parallel normal fault (not shown) bounds the west side of the sulfide deposits, Bent Hill, and similar uplifted sediment hill that occur south of the map area. Proposed sites BH-1 through BH-4, BH-7, BH-8 are shown. Right: North-south cross section (5 x vertical exaggeration) of Site 856 area showing the extent of penetration of the massive sulfide deposit south of Bent Hill and the location of basaltic sills beneath Bent Hill.

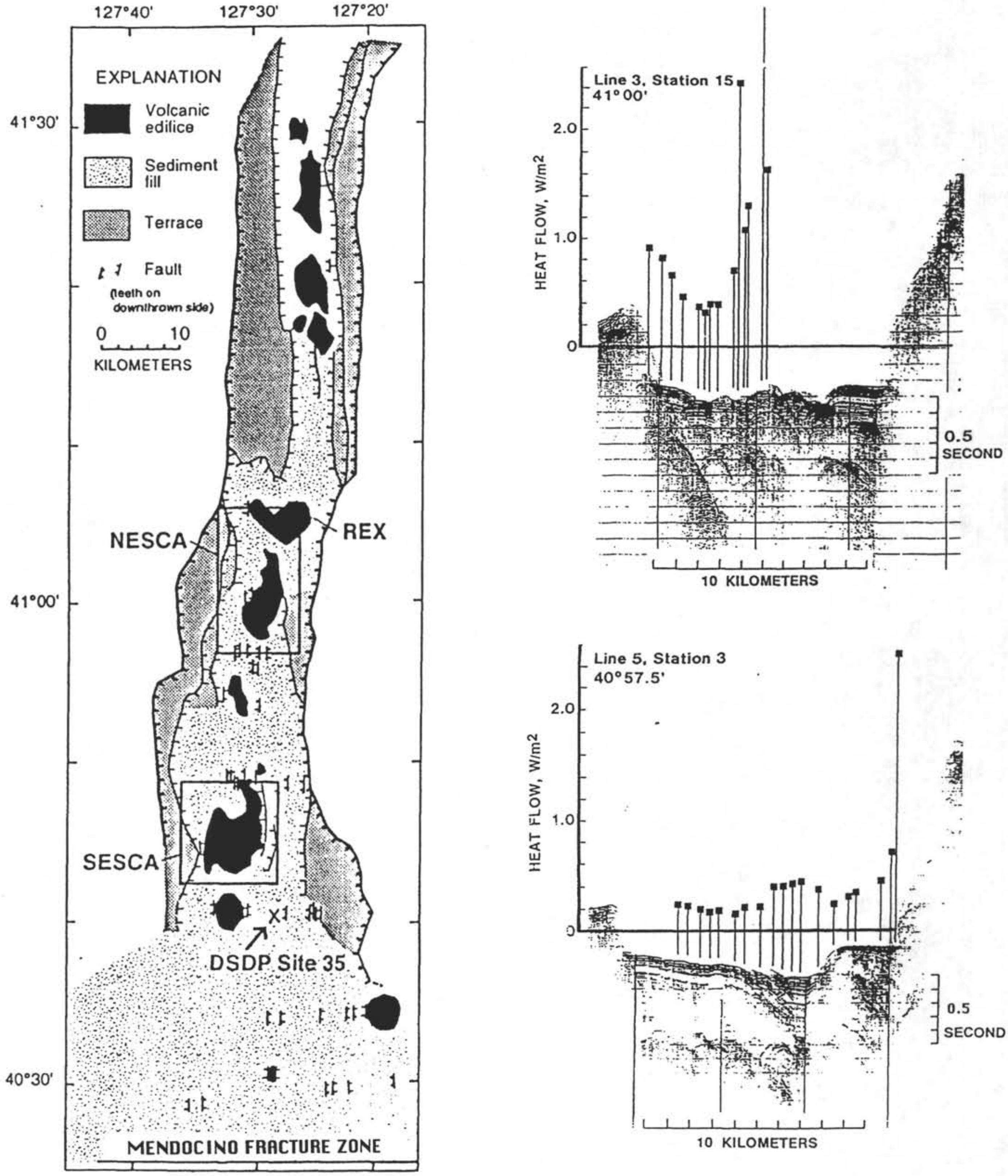


Figure 4. Map of the southern portion of the Gorda Ridge spreading center, showing the sediment-filled portion of Escanaba Trough and the volcanic centers that rise through and locally pierce the sediment cover. Heat-flow profile along seismic line 3 (proposed sites ET-1 through ET-5) and line 5 (proposed site ET-7).

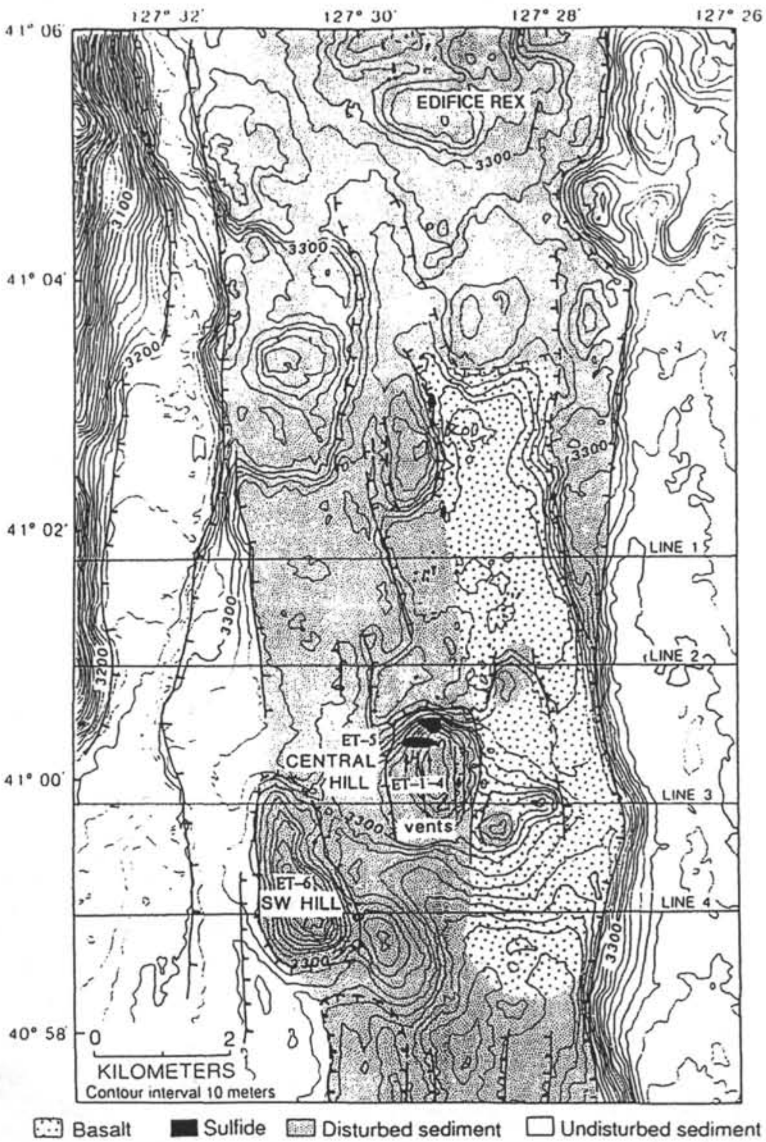


Figure 5a. Map of the NESCA area of Escanaba Trough, showing the location of the SW Hill, Central Hill, on-axis volcanic rocks, sulfide deposits (black), and active vent sites. Location of proposed sites ET-1 through ET-6 are shown. The location of the faults is constrained by the seismic profiles and camera and submersible mapping of scarps.

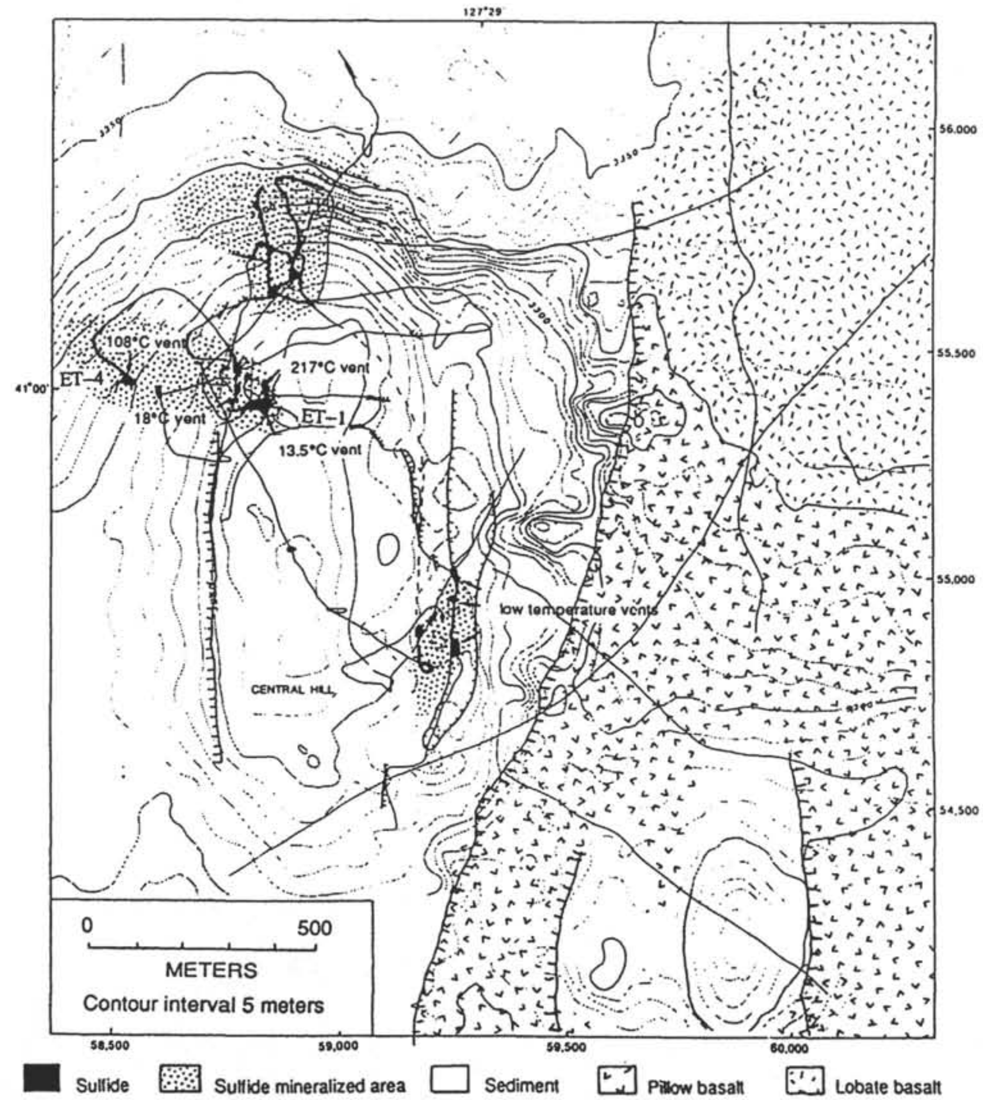


Figure 5b. Map of the Central Hill area of the NESCA site, Escanaba Trough, showing proposed transect ET-1 through ET-4 across the hydrothermally active massive sulfide deposit. Location of active vents, fault scarps, and exposed volcanic rock are based on camera tow and submersible tracks, shown as thin lines. Proposed site ET-5 will be a reentry hole located within the ET-1 through ET-5 transect.

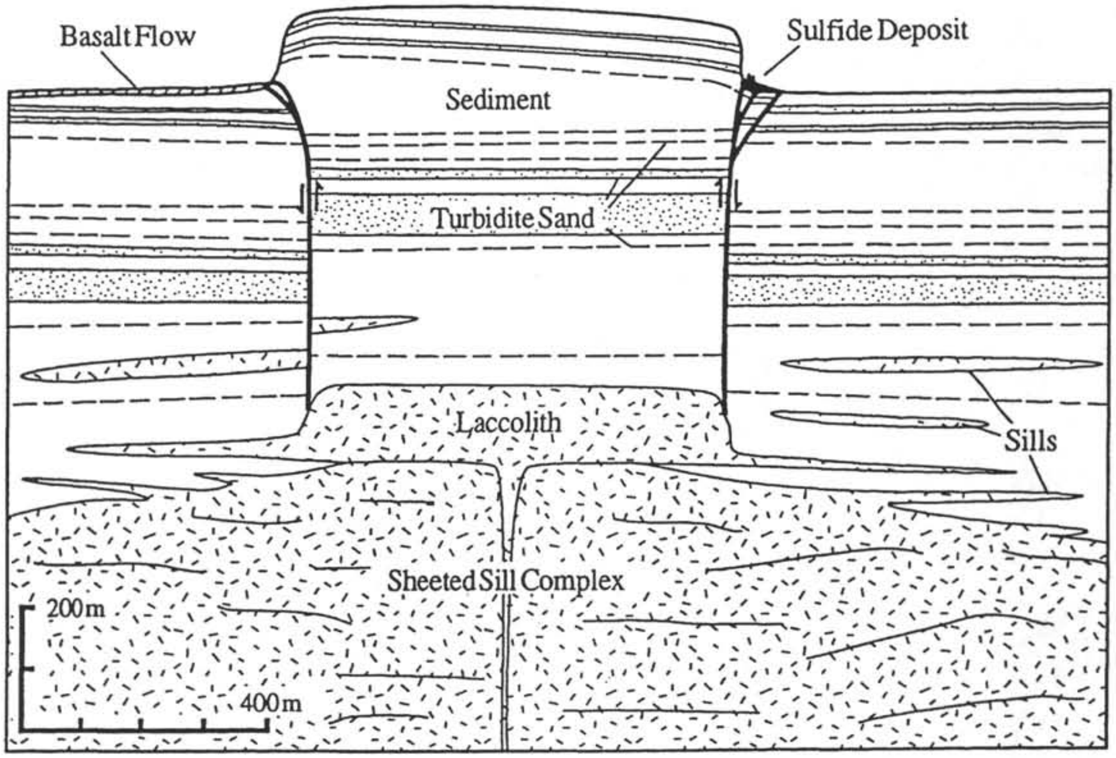


Figure 6. Schematic diagram showing the relationship of uplifted hills to large basaltic intrusions. The faults that accommodate uplift of the sediment hills (e.g., SW Hill) provide high permeability pathways for hydrothermal fluids forming massive sulfide deposits that are observed to occur around the base of most of the sediment hills.

TABLE 1

PROPOSED SITE INFORMATION and DRILLING STRATEGY

SITE: 857 Hole D	**PRIORITY**: 1	**POSITION**: 48°26.5'N, 128°42.65'W
WATER DEPTH: 2420 m	**SEDIMENT THICKNESS**: 470 m	**TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: ODP Leg 139 survey data		

Objectives: Remove CORK, measure temperature, sample borehole fluids, and drill to bit destruction while cooling hole. Conduct packer and flow meter experiments and replace thermistor string ad CORK. Investigate mechanism of sill emplacement and sediment deformation.

Drilling Program: RCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: 200 m of interlayered diabase sills and metasediments.

SITE: 858 Hole G	**PRIORITY**: 1	**POSITION**: 48°27.36'N, 128°42.531'W
WATER DEPTH: 2415 m	**SEDIMENT THICKNESS**: 250 m	**TOTAL PENETRATION**: -
SEISMIC COVERAGE: ODP Leg 139 survey data		

Objectives: Remove CORK, measure temperature, and sample borehole fluids.

Drilling Program: -

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: -

SITE: DD-1	**PRIORITY**: 2	**POSITION**: 48°27.35'N, 128°42.6'W
WATER DEPTH: 2410 m	**SEDIMENT THICKNESS**: 250 m	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: ODP Leg 139 survey data		

Objectives: To determine the structure, composition, and physical properties of the hydrothermal mound. To determine the temperature, structure, pore pressure, and pore fluid composition in the hydrothermal upflow zone.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, HEL and third party tools.

Nature of Rock Anticipated: Hydrothermally altered mud.

SITE: DD-2	**PRIORITY**: 2	**POSITION**: 48°27.35'N, 128°42.6'W
WATER DEPTH: 2425 m	**SEDIMENT THICKNESS**: 250 m	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: ODP Leg 139 survey data		

Objectives: To determine the structure, composition, and physical properties of the hydrothermal mound. To determine the temperature, structure, and pore fluid composition in the hydrothermal upflow zone. To sample the hydrothermal cap at the edge of the hydrothermal mound.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Hydrothermally altered mud.

SITE: DD-3	**PRIORITY**: 2	**POSITION**: 48°27.35'N, 128°42.55'W
WATER DEPTH: 2425 m	**SEDIMENT THICKNESS**: 250 m	**TOTAL PENETRATION**: 50 m
SEISMIC COVERAGE: ODP Leg 139 survey data		

Objectives: To determine the structure, composition, and physical properties of the hydrothermal mound. To determine the temperature, structure, and pore fluid composition in the hydrothermal upflow zone. To sample the potential hydrothermal cap at the edge of the hydrothermal mound. To complete the transect from Hole 858C to Hole 858G.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Hydrothermally altered mud.

SITE: BH-1	**PRIORITY**: 1	**POSITION**: 48°26.02'N, 128°40.85'W
WATER DEPTH: 2435 m	**SEDIMENT THICKNESS**: 200 m	**TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE: ODP Leg 139 survey data		

Objectives: To drill through the Bent Hill massive sulfide deposit to determine the composition and thickness, stratigraphy, depth to igneous basement, and sediment and basalt alteration. To constrain the paleo flow paths and the temperature of hydrothermal circulation.

Drilling Program: RCB and reentry.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: BH-2 **PRIORITY**: 1 **POSITION**: 48°26.02'N, 128°40.89'W
WATER DEPTH: 2440 m **SEDIMENT THICKNESS**: 200 m **TOTAL PENETRATION**: 220 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To constrain the geometry and composition of lateral massive sulfide mineralization and alteration. To examine the proximal sedimentary record of hydrothermal activity to constrain relative timing. Possibly to intersect the shallow portion of a normal fault.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered turbidite mud; ; hydrothermally altered diabase or basalt.

SITE: BH-3 **PRIORITY**: 1 **POSITION**: 48°26.02'N, 128°40.93'W
WATER DEPTH: 2450 m **SEDIMENT THICKNESS**: 200 m **TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To constrain the geometry and composition of lateral massive sulfide mineralization and alteration. To examine the proximal sedimentary record of hydrothermal activity to constrain relative timing. Possibly to intersect a normal fault at intermediate depth.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, and HEL and third party tools.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud.

SITE: BH-4 **PRIORITY**: 1 **POSITION**: 48°26.02'N, 128°41.02'W
WATER DEPTH: 2460 m **SEDIMENT THICKNESS**: 250 m **TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To constrain the geometry and composition of lateral massive sulfide alteration. To examine the distal sedimentary record of hydrothermal activity to constrain relative timing. Possibly to intersect a normal fault above basement.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered turbidite mud.

SITE: BH-5 **PRIORITY**: 1 **POSITION**: 48°26.02'N, 128°41.18'W
WATER DEPTH: 2465 m **SEDIMENT THICKNESS**: 400 m **TOTAL PENETRATION**: 400 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To constrain the geometry and composition of lateral massive sulfide alteration. To examine the distal sedimentary record of hydrothermal activity to constrain relative timing. To determine the stratigraphic relationship between the footwall and the Site 856 normal fault zone.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered turbidite mud.

SITE: BH-6 **PRIORITY**: 1 **POSITION**: 48°26.02'N, 128°41.39'W
WATER DEPTH: 2460 m **SEDIMENT THICKNESS**: 450 m **TOTAL PENETRATION**: 470 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To provide a normal reference section for the sedimentary sequence and physical properties outside of the thermal effects of the hydrothermal upflow zone. To complete the transect from Site 856 to Site 857. Possibly to intersect the Site 856 fault zone near the basement-sediment interface.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered turbidite mud; diabase sills.

SITE: BH-7 **PRIORITY**: 2 **POSITION**: 48°25.95'N, 128°40.9'W
WATER DEPTH: 2460 m **SEDIMENT THICKNESS**: 200 m **TOTAL PENETRATION**: 200 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To complete a N-S transect across the Bent Hill deposit. To constrain the geometry and composition of lateral massive sulfide mineralization and associated alteration. To examine the distal sedimentary record of hydrothermal activity to constrain relative timing. To provide a stratigraphic section on the footwall of the Site 856 fault block.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered turbidite mud.

SITE: BH-8 **PRIORITY**: 2 **POSITION**: 48°25.85'N, 128°40.9'W
WATER DEPTH: 2445 m **SEDIMENT THICKNESS**: 200 m **TOTAL PENETRATION**: 220 m
SEISMIC COVERAGE: ODP Leg 139 survey data

Objectives: To drill through the hydrothermally active sulfide deposit south of Bent Hill to determine the composition and thickness, stratigraphy, depth to igneous basement, and sediment and basalt alteration. To constrain the paleo flow paths, temperature, and composition of hydrothermal circulation.

Drilling Program: RCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: ET-1 **PRIORITY**: 1 **POSITION**: 41°00'N, 127°29'W
WATER DEPTH: 3240 m **SEDIMENT THICKNESS**: 100-600 m? **TOTAL PENETRATION**: 250 m
SEISMIC COVERAGE: USGS Bull. 2022 (1994)

Objectives: To drill through the Central Hill adjacent to the hydrothermally active massive sulfide deposit to determine the extent and composition of hydrothermal mineralization and alteration. To determine the footwall stratigraphy, depth to igneous basement, and magmatic and structural history. To constrain the paleo flow paths, temperature, and composition of hydrothermal circulation.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, and HEL and third party tools.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: ET-2 **PRIORITY**: 1 **POSITION**: 41°00'N, 127°29'W
WATER DEPTH: 3250 m **SEDIMENT THICKNESS**: 100-600 m? **TOTAL PENETRATION**: 220 m
SEISMIC COVERAGE: USGS Bull. 2022 (1994)

Objectives: To drill through the Central Hill adjacent to the hydrothermally active massive sulfide deposit to determine the extent and composition of hydrothermal mineralization and alteration. To determine the footwall stratigraphy, depth to igneous basement, and magmatic and structural history. To constrain the paleo flow paths, temperature, and composition of hydrothermal circulation.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: ET-3 **PRIORITY**: 1 **POSITION**: 41°00'N, 127°29'W
WATER DEPTH: 3255 m **SEDIMENT THICKNESS**: 100-600 m? **TOTAL PENETRATION**: 220 m
SEISMIC COVERAGE: USGS Bull. 2022 (1994)

Objectives: The west end of a transect across the hydrothermally active massive sulfide deposit to determine the extent and composition of hydrothermal mineralization and alteration. To determine the footwall stratigraphy, depth to igneous basement, and magmatic and structural history. To constrain the paleo flow paths, temperature, and composition of hydrothermal circulation.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: ET-4 **PRIORITY**: 1 **POSITION**: 41°00'N, 127°29'W
WATER DEPTH: 3260 m **SEDIMENT THICKNESS**: 100-600 m? **TOTAL PENETRATION**: 220 m
SEISMIC COVERAGE: USGS Bull. 2022 (1994)

Objectives: The west end of a transect across the hydrothermally active massive sulfide deposit to determine the extent and composition of hydrothermal mineralization and alteration. To determine the footwall stratigraphy, depth to igneous basement, and magmatic and structural history. To constrain the paleo flow paths, temperature, and composition of hydrothermal circulation.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: ET-5 **PRIORITY**: 1 **POSITION**: 41°00'N, 127°29'W
WATER DEPTH: 3250 m **SEDIMENT THICKNESS**: 100-600 m? **TOTAL PENETRATION**: 600 m
SEISMIC COVERAGE: USGS Bull. 2022 (1994)

Objectives: The west end of a transect across the hydrothermally active massive sulfide deposit to determine the extent and composition of hydrothermal mineralization and alteration. To determine the footwall stratigraphy, depth to igneous basement, and magmatic and structural history. To constrain the paleo flow paths, temperature, and composition of hydrothermal circulation.

Drilling Program: RCB and reentry.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Massive sulfide and hydrothermally altered turbidite mud; hydrothermally altered diabase or basalt.

SITE: ET-6	**PRIORITY**: 2	**POSITION**: 40°95'N, 127°30.5'W
WATER DEPTH: 3170 m	**SEDIMENT THICKNESS**: 500 m	**TOTAL PENETRATION**: 520 m
SEISMIC COVERAGE: USGS Bull. 2022 (1994)		

Objectives: The determine the structure and uplift history of a large sediment hill associated with massive sulfide formation. To determine the temperature and structural effects of a possible large igneous intrusion and the basement composition.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and hydrothermally altered diabase or basalt.

SITE: ET-7	**PRIORITY**: 2	**POSITION**: 40°57.5'N, 127°30.5'W
WATER DEPTH: 3340 m	**SEDIMENT THICKNESS**: 600 m	**TOTAL PENETRATION**: 650 m
SEISMIC COVERAGE: USGS Bull. 2042 (in press)		

Objectives: The provide a reference section through the sedimentary sequence for comparison with the hydrothermally-induced changes in physical properties and composition. To determine the temperature and structure, footwall stratigraphy, depth to igneous basement, and magmatic and structural history. To constrain the paleo flow paths, temperature, and composition of pore fluids. To determine the nature of the transparent seismic marker and its relationship to sea-level changes.

Drilling Program: APC and XCB.

Logging and Downhole Operations: Temperature, standard logs, and FMS.

Nature of Rock Anticipated: Turbidite mud and silt; hydrothermally altered diabase or basalt.

LEG 170

Costa Rica Accretionary Wedge

LEG 170

THE MIDDLE AMERICA TRENCH AND THE ACCRETIONARY COMPLEX OFF COSTA RICA

Modified from Proposal 400-Rev2 Submitted By

Eli Silver, Kirk McIntosh, Miriam Kastner, Terry Plank, Julie Morris, and Tom Shipley

To Be Named: Co-Chief Scientists and Staff Scientist

ABSTRACT

To gain a better understanding of the mechanical and chemical behavior of accretion and underplating and tectonic erosion and to determine how deformation and dewatering are distributed throughout an accretionary prism, it is essential to establish the flow pattern of materials through the subduction systems.

Leg 170 consists of a program of drilling at four primary sites (proposed sites CR-1 through CR-4) on the Costa Rica convergent margin to investigate mass- and fluid-flow patterns through the accretionary prism and will integrate structural analysis and sediment, fluid, and chemical mass-balance calculations. The objectives are to determine 1) the relative importance of frontal accretion, underplating, out-of-sequence thrusting, sediment subduction, and subduction erosion, 2) the timing, rate, and modes of the accretionary prism development, 3) the importance of fluids in both strengthening and weakening of the prism, particularly in the presence of underthrust carbonates, and 4) the fate of subcrustally subducted sediments and the associated fluxes.

Drilling on the Costa Rica margin could provide us with the first good estimates of the total material and chemical fluxes through a subduction system, because of the ideal conditions (the capping sediment apron and the lack of trench turbidites), extensive seismic imaging of the accretionary complex, and the opportunity to constrain the deeper parts of the sediment cycle, which are reflected in the forearc fluids and arc volcanics. Because of the global importance of understanding material and fluid fluxes through subduction zones, it is critical that these systems become well understood.

INTRODUCTION

Essential observations for establishing the mechanisms of accretion and underplating, tectonic erosion, and deformation and dewatering must include 1) the rate (positive and negative) of prism growth as a function of incoming sediment volume and type, 2) the partitioning of frontal offscraping, underplating, internal prism deformation, and subduction erosion, and 3) the effects of fluids. Excellent control is required of material mass balance and residence time in the prism, in addition to detailed structural geometry of the very complex interior regions of forearcs. Such control and imaging has not been well established in any convergent margin, despite a great amount of effort expended to understand these margins.

The scarcity of accurate mass balance estimates is due to the complexity of both sedimentary and structural processes at convergent margins, the poor structural imaging of the deeper parts of forearc regions, and the need for reliable age estimates that generally require drilling. The presence of trench turbidites, varying dramatically in thickness both spatially and temporally, is a major obstacle in estimating material influx. Erosion and redeposition of accreted material are additional complications that can not easily be taken into account. A first step in addressing these problems is to locate an experiment along a convergent margin that lacks trench turbidites, that has a slope cover preventing erosion of the accreted material, and that has clearly imaged deep and shallow structural control.

If the convergence rate is known, the incoming sediment flux can be closely estimated and prism size will reveal the relative importance of sediment accretion or bypassing. The case of subduction erosion may also be documented with additional structural, stratigraphic, or biostratigraphic data, to show subsidence or arcward retreat. The final requirement is that accurate emplacement dates for the accreted material must be available.

The Middle America Trench off Costa Rica satisfies all the requirements for accurate mass balance and flow estimation, except for knowledge of the age and residence time of the prism material. The trench is devoid of turbidites here and the convergence rate is known. Recently-acquired 2D and 3D seismic reflection data across the margin provide excellent control of the internal structure of the forearc, and they define boundaries between the accretionary prism and the overlying slope cover and between the prism and the subducting plate (Figure 1). These data show that the slope cover extends to within 3-5 km of the trench (Figure 2), so it protects the accreted mass from erosion and conserves its volume. Consequently, the growth rate of this prism can be calculated accurately when the emplacement age of the accreted material is determined by drilling through the basal slope cover and top of the prism.

This relatively closed system is also a superior environment to investigate the fluid and chemical fluxes in a subduction system. Comparison of physical (i.e., velocity and porosity) and chemical properties of sediments seaward of the trench with sediments that have been subducted or accreted can provide important information on the nature and rate of diagenetic processes in subduction zones. Aided by relatively rapid plate convergence and a stratigraphically-consistent, subducting sedimentary section, the sediment and pore-water chemistry can also be compared with the constituents of arc volcanic rocks using geochemical tracers. By their presence or absence in the volcanics, tracers such as ^{10}Be and Ba may be used to indicate amounts of sediment accretion, amounts of sediment recycling to the volcanic arc, and subduction into the mantle (Tera et al., 1986; Plank and Langmuir, 1993).

Prominent lithologic or structural boundaries that produce high-amplitude seismic reflectors in the interior of this moderately accreting prism are within reach through driling. The existing 3D seismic grid will allow exceptionally good correlation between seismic and borehole data due to accurate 3D imaging. Certain coherent intra-prism reflectors identified in the seismic data appear to be unrelated to offscraping but are interpreted as faults (Shipley et al., 1992), which formed during out-of-sequence thrusting and underplating. These and other faults are likely pathways along which fluids escape from the prism. Identifying the physical properties, lithologies, and geologic processes that produce these impedance contrasts will provide essential information for the structural interpretation of this margin and fundamental data about the nature of seismic reflections in accretionary prisms.

STUDY AREA

Geology and Seismic Data

Costa Rica is situated on the western edge of the Caribbean Plate (Figure 1). The Middle America Trench (MAT) is the surface trace of the convergent boundary between the Caribbean Plate and the subducting Cocos Plate. The convergence rate along this part of the MAT is estimated at 87 km/m.y. (computed using NUVEL-1, DeMets et al., 1990) with oceanic crust of late Oligocene-early Miocene currently being subducted (Hey, 1977).

The trench slope west of the Nicoya Peninsula of Costa Rica is relatively smooth. It is underlain by a sedimentary apron that reaches 2 km in thickness and generally decreases in thickness downslope. The apron is underlain by an accretionary complex which is separated from the apron by a set of irregular, high-amplitude reflectors. About 400 m of very uniform sediments are entering the trench, divided into an upper hemipelagic unit and a lower pelagic unit (Shipley and Moore, 1986). No turbidites occur along this section of the trench. This is probably a result of a subsiding, sediment-trapping, inner forearc region and a strong axial gradient along the trench, which was produced and maintained over the last several million years by underthrusting of the Cocos Ridge beneath Central America, 300 km to the southeast.

The accretionary wedge has been constructed and deformed by frontal offscraping, underplating, and out-of-sequence faulting. A décollement marks the base of the accretionary wedge (Figure 2). The apron is also faulted, by thrusts in the lower slope region and by normal faults in the upper slope. In addition, diapirs (whose source may be either the lower part of the apron or the prism) intrude the apron in the mid-slope and locally erupt onto the surface. DSDP Site 565 penetrated part way through the apron and bottomed in lowermost Pliocene mud.

Seismic reflection data acquired in the area off the Nicoya Peninsula include the high-resolution watergun survey (Shipley and Moore, 1986), conventional multichannel data (Shipley et al., 1982; Crowe and Buffler, 1983), and a combination 2D and 3D survey (Stoffa et al., 1991; Shipley et al., 1992). The conventionally acquired 2D seismic data show reflections that delineate the top of the subducting Cocos Plate from the trench to the shelf edge but do not clearly image the interior structure of the accretionary prism (Crowe and Buffler, 1983; Shipley and Moore, 1986; Moore and Shipley, 1988). Coltrin et al. (1989) found that much of the difficulty in producing accurate seismic images of prisms with conventional seismic techniques lies in the rapidly changing velocity fields and three-dimensional structural variation present in this environment.

3D Seismic Data

To improve the structural resolution within the Costa Rica accretionary prism, a 3D seismic survey has been acquired and processed (Stoffa et al., 1991). These data reveal unprecedented details of the interior of this prism, both because of the dense sampling of the 3D grid, and because the 3D processing techniques (sorting and migration) correctly position the seismic reflectors. These data confirm that certain features of the margin are regional in extent, while others are much more localized (Shipley et al., 1992). In particular, the high-amplitude reflection at the base of the slope apron and prominent, internal prism reflectors are mappable over much of the 3D grid. Conversely, structures near the prism toe and in the slope apron tend to vary rapidly and many are identifiable for only hundreds of meters along strike (Shipley et al., 1992).

Incoming Sediment and Offscraping

Active accretion has built up a mud-dominated prism along the Costa Rica convergent margin. Shipley and Moore (1986) observed that the trench axis lacks a turbidite wedge and that approximately 88 m of the incoming, 300-450-m-thick section is scraped off and accreted to the upper plate. In the study area, covered by more recent 2D and 3D seismic data, the amount of offscraping appears to be closer to 45 m (Shipley et al., 1990). Arcward of the frontal thrust ramp, Shipley and Moore (1986) imaged the décollement to study the effects of subducted basement structures. They demonstrated that, despite normal faults with relief of 300 m on the Cocos Plate, subduction erosion does not appear to be occurring beneath the lower slope. Another important result of this earlier work is that the underthrust section apparently dewaters rapidly in the first 3-5 km landward of the trench. Based on seismic velocities and thinning between prominent seismic reflections, Shipley et al. (1990) estimated that half the fluid initially contained in the incoming section may be expelled in this zone. This result is particularly interesting due to the fine grain size and low permeability expected for sediment in this area.

The incoming section has not been directly sampled in this area, but oceanic sections of the Cocos Plate drilled in DSDP Legs 9, 66, 67, and ODP Leg 138 suggest a two-layer interpretation. Legs 66 and 67, off the continental margins of Mexico and Guatemala, both encountered an upper hemipelagic layer and a lower carbonate-rich pelagic section in holes seaward of the Middle

America Trench (Watkins et al., 1982; von Huene et al., 1982). Leg 6 Sites 83 and 84, away from the continental margin, penetrated carbonate rich pelagic sediments before hitting basaltic basement (Hays, Cook, et al., 1972). Leg 138 recently drilled 175 m of silicic hemipelagic ooze overlying 115 m of carbonate ooze. Based on these drilling results, the top of the pelagic section off Costa Rica is expected to be middle to late Miocene.

Underplating

The 3D seismic reflection data extend the observations of Shipley and Moore (1986) and Shipley et al. (1990), who concluded that the upper hemipelagic sedimentary layer on the subducting Cocos Plate is accreted in part by offscraping and in part by underplating (Figure 2). In contrast to the upper layer, distinct seismic images show the basement and pelagic section apparently thrust intact beneath the lower slope. Analysis of the 3D data illustrates a variety of structural geometries inferred for the underplating process (McIntosh, 1992). Both duplexes and out-of-sequence thrusts prefer to nucleate at sites of lower plate-normal faulting.

Underplating begins 3-10 km arcward of the trench, coinciding with the first appearance of the high-amplitude reflector at the base of the slope apron and high-amplitude internal reflectors. The prism thickens significantly at a distance of 10-20 km from the trench, coinciding with an increased number of the high-amplitude internal reflectors (Figure 2).

A major enigma is the nature of the reflector at the top of the prism (Figure 2). Our initial interpretation of the 3D data (Shipley et al., 1992) suggests that this faulted surface probably marks the base of the depositional slope apron section and the top of the tectonically accreted prism material. One alternative explanation that cannot yet be ruled out is that this surface marks the boundary between offscraped sediments (above) and underplated sediments (below). These different interpretations are demonstrated by the two models shown in Figure 3.

Another important consideration is that a portion of the top-prism surface may represent a contact between the sedimentary apron and underlying ophiolitic rocks of the Nicoya complex. Despite the good quality of both the 2D and 3D seismic data, the seaward limit of the Nicoya complex basement, which crops out onshore near the coast, has not been identified. Two possible interpretations are that the ophiolitic basement may extend only a short distance seaward of the coast, or its seaward limit and contact with accreted material may extend beneath the slope apron but is poorly defined seismically. Our interpretation (Shipley et al., 1992) that the material beneath the apron section is composed of accreted sediments is based on sediment accretion at the toe, observed structure within the apron and prism (on seismic reflection data), migration velocities, refraction velocities (Crowe and Buffler, 1983), gravity data and interpretation (Ponce and Case, 1987), and lack of anomalies in magnetic data diagnostic of crystalline rock (Shipley, unpubl.). In contrast, other workers in the Costa Rica area interpret that the forearc is dominantly composed of ophiolite, based largely on comparisons to the Guatemala forearc (Azema et al., 1985; Corrigan et al., 1990; von Huene, pers. comm., 1993). Identifying the nature of the apron/prism boundary and its age distribution is fundamental to understanding the tectonic history of the Costa Rica margin and that of southern Central America but drilling is required to do so.

Out-of-Sequence Faulting

A first-order discovery of the 3D seismic data set has been the prominence of long, shallow reflectors within the wedge (Figure 2). Their length and smooth character far exceeds that expected from duplexes, which are themselves well-imaged on many lines about 3-10 km from the toe of the wedge. These long, smooth interior reflectors are interpreted as possible out-of-sequence thrusts (Shipley et al., 1992). The seismic data cannot fully resolve whether these faults are truly out-of-sequence or are old décollements that have been uplifted and gently folded by underplating. Drilling can distinguish these alternatives (Moore, Mascle, et al., 1990) and can therefore allow us to calibrate the seismic data and understand the strain partitioning within the wedge.

Subduction Erosion

Although the currently observed processes of the Costa Rica convergent margin suggest accretion accompanied by some unknown amount of sediment bypassing, the slope apron also records a possible period of erosion or non-accretion. At approximately 20-25 km seaward of the trench, there is a zone of severe disruption in the slope apron and upper prism (Figure 2). A thick apron section (1-2 km thick), displaying wel- layered, coherent reflections across the middle and upper slope, is segregated by this zone from the apron of the lower slope, which is abruptly thinner (generally <800 m thick) and characterized by discontinuous and frequently landward-dipping reflections.

The discrepancy in apron thickness across the disturbed zone may be explained by an extended period of non-accretion during which slope deposition continued, followed by renewed accretion to accumulate the present lower slope mass. Alternatively, truncation of the margin by transcurrent faulting or subduction erosion, followed by renewed accretion, may also explain the apron variations. If either of these explanations is valid, then the timing and cause of the event may be important for other parts of the Central America region, such as Guatemala.

Diapirism

At least four separate mud diapirs have erupted as mud volcanoes onto the surface of the apron within the 3D data volume. They occur generally in the mid-slope region of the wedge. The diapirs are elongate east-west, oblique to the slope contours (Shipley et al., 1992). Seismic data indicate that the diapirs root at, or near, the base of the apron. In some profiles, the high-amplitude surface of the accretionary wedge is displaced by faulting just beneath the diapirs, suggesting a relation between structure and diapirism.

Extension on the Upper Slope

The long 2D seismic lines crossing the Costa Rica margin have each imaged a wide zone of normal faulting cutting the upper slope segment of the sedimentary apron (Figure 2). This deformation contrasts with that observed in the middle and lower slope regions of all lines where the apron and prism are pervasively cut by thrust faults. The transition from convergence to extension in the apron occurs above a significant change in the dip of the décollement and is associated with thickening of the wedge. The normal faults may represent extension of a wedge that has become over-critically tapered (McIntosh et al., in review) due to underplating (as proposed by Platt, 1986), decreased strength of the basal detachment (e.g., Dahlen, 1984), deposition of the slope apron, or possible subduction erosion as mentioned above. We have measured approximately 1.5 km of extension in the zone of normal faulting (McIntosh et al., submitted).

Results of Submersible Observations off Costa Rica Using the *D/V Alvin*

Dive Results

During February, 1994, 20 dives were made with *D.S.R.V. Alvin* to investigate the surficial evidence for fluid flow and fault structure of the Costa Rica accretionary wedge. The nature and distribution of chemosynthetic communities and authigenic carbonates indicate present and paleo-fluid venting at the lower slope out-of-sequence-thrust (OOST) zone, one mid-slope mud diapir, and one upper slope canyon. No surficial evidence for venting is apparent at the deformation front.

A sharp 10° slope break marks the frontal thrust at the toe of the wedge at locations where large normal faults intersect the deformation front. Normal fault scarps are characteristic seaward of the trench, occurring as en echelon steps, ridges, and swales, and semi-lithified sediments crop out landward of the trench. Although remnant scatterings of small dead clams of unknown species were observed during one dive, no true surficial evidence of venting is apparent at the toe. Steep scarps with highly tectonized outcrop delineate a zone of out-of-sequence thrust faults, 5 km landward of the toe. Abundant paleo and present vents marked by small clusters of clams (*Calyptogena* sp., *Vesicamyid* sp., *Solemya* sp.) are localized at the tops and bases of numerous scarps. Although the live patches are generally $1/2$ m in diameter, we have not discovered any clear geometrical patterns of either the paleo or active vents at any particular site. Additionally, some vent sites are found in slight depressions.

Substantial and vigorous paleo- and present fluid expulsion are observed at one sizable mud diapir. An extensive covering of irregular carbonates surface the western flanks of the diapir, as massive blocks, slabs, and crusts are observed along the top flank and crest. Although it is not clear whether or not the carbonates are actively precipitating, their structure and vastness indicate strong, sustained flow at some point in time. Impressive vent communities mark the south and southeast portions of the crest. One site is composed of a 2-m live *Calyptogena* patch within a 5-m region of dead *Calyptogena*. Besides the extraordinary size of the community, the venting appears to be intense and sustained as the clams are covered with limpets, turban-type gastropods, galatheid crabs, rattailed fish, and egg mats. Two areas of vast, sustained active venting are marked by extensive *Vestimitiferan* sp. tube worms. One *Vestimitiferan* sp. site is composed of a 2-m-diameter patch densely packed in a circular depression, and the second site is a 60- to 100-m-long region with coexisting live *Calyptogena*. Three pockmarks align along the top flank of the diapir, increasing in size toward the crest. Additionally, one pockmark is evident at a second sizable diapir. Although the cause of the pockmarks is uncertain, it is possible that they indicate past instantaneous gaseous flow.

Two active vent sites are observed at one wall of one steep-walled canyon. The sites appear to be indicators of high permeability horizons, and thus stratigraphically controlled. They consist of one 4-m by 1.5-m bacterial mat, and two *Vestimitiferan* sp. tube worm sites, 1 to 2 m in diameter. One tube worm site has coexisting *Calyptogena*. Fracture permeability is likely responsible for fluid venting at the lower slope OOST zone.

Heat Flow Results

During the February 1994 cruise, we made 98 individual heat-flow measurements along 10 lines. A brief summary of the results appears below.

1) The lower slope region proved to be very difficult to penetrate with the heat-flow probe, suggesting (with the seismic data) that the lower slope is severely dewatered.

2) Of the 19 measurements made west of the deformation front, none exceeded 20 mW/m^2 and the mean of these measurements was about 14 mW/m^2. As the approximate age of the incoming crust is about 20 Ma, we expect heat-flow values to be in the range of 80 to 100 mW/m^2. The extraordinarily low values indicate non-equilibrium conditions and suggest widespread refrigeration of the crust by vigorous fluid flow at depth.

3) The deformation front forms a sharp geothermal boundary between the lower plate zone of very low heat flow (14 mW/m^2) and the toe of the slope, where heat-flow values range between 20 and 30 mW/m^2. The average value of heat flow on the slope is about 30 mW/m^2. The increase in heat flow at the toe of the wedge could be a result of a pervasive flow of somewhat warmer fluids from depth in the wedge. However, no signs of fluid venting were seen on the lower slope, which does not rule out diffuse fluid flow.

4) Slightly elevated heat flows (about 50 mW/m^2) were measured near sites of fluid venting.

SCIENTIFIC OBJECTIVES AND METHODOLOGY

Summary of Objectives

The goal of Leg 170 is to determine the mass- and fluid-flow paths through an accretionary prism. The drilling data will facilitate an integrated effort to understand these processes using structural data, and the physical and chemical properties of both the sediments and their pore fluids. The general objectives in pursuing this goal are to a) determine the sediment, chemical, and fluid mass balances within the accretionary prism and the larger subduction system (including the volcanic arc), b) test whether or not the prism is developing in equilibrium with the incoming sedimentary material and, if so, to quantify the partitioning of material into offscraped, underplated, internally shortened, and subducted, and c) determine the effects of fluids on prism deformation.

The specific objectives of the drilling program are to determine

1) The age and nature of the accretionary wedge beneath the slope apron.

2) The rate of accretion of the wedge.

3) The nature of the lower part of the apron and time sequence of formation.

4) The physical properties of the material above, within, and below the top-prism reflector.

5) The relative importance of underplating vs. out-of-sequence faulting.

6) The rate of fluid expulsion from the underthrust section and its structural and rheological effects.

7) The evidence of fluid stratigraphy and flow distribution within the wedge materials.

8) The nature of apron material relative to deep-sea hemipelagic sediment.

Specific Objectives and Methodology

The main focus of Leg 170 is determination of mass and fluid balances within an accretionary complex that is remarkably well constrained. Mass-balance estimates can play a key role in understanding structural, mechanical, and geochemical processes at convergent margins, but many convergent margins are not well suited for accurate mass balance calculations. A logical step is to pursue these types of studies in tectonic environments requiring fewer assumptions and posing fewer technical difficulties.

Material Mass Balance in the Accretionary Complex

Mass balance studies at convergent margins are useful for quantifying processes such as sediment underplating, sediment subduction, and subduction erosion that are not easily documented by seismic imaging. Off southern Mexico, mass-balance estimates strengthened the case for accretion by underplating and suggested that significant sediment bypassing also occurs. Seismic reflection profiles across this margin show dipping reflections indicative of offscraping accretion; however, by about 4 km from the trench, deformation of the offscraped sediments declines rapidly (as indicated by the lack of additional rotation of prominent reflectors), yet the prism continues to thicken with distance from the trench (Moore et al., 1982).

Platt et al. (1985) used a combination of field relations, seismic reflection data, and mass-balance calculations to interpret large-scale underplating in the Makran accretionary complex of Pakistan. Their mass balance calculations showed that with only frontal accretion of sediments since middle Miocene, 70% post-accretion shortening would be required to account for the present prism width of 180 km. However, because field relations allow only 30% shortening during this period, the mass-balance calculations strongly support an underplating mechanism to reconcile the sediment supply and the 7-27 km thickness of the Makran prism.

Recent interpretations of the Cascadia accretionary prism off Vancouver Island suggest that growth is occurring entirely by frontal accretion, and that nearly all of the incoming sediments are accreted (Davis and Hyndman, 1989). For the period since 1.8 Ma, the accreted mass is approximately equal to estimated sediment supply, suggesting that the current processes may have persisted through the Pleistocene.

A different type of mass balance analysis applies to the Peru-northern Chile convergent margin. This part of the South American margin lacks a significant accretionary complex (Schweller et al., 1981); instead, margin subsidence and a shortened gap between the trench and the Mesozoic magmatic arc indicate active subduction erosion. The type of mass-balance study applicable here is to determine the mass of material that has been tectonically eroded. Von Huene and Lallemand (1990) estimated subsidence and landward migration of the trench along the Lima Basin since 20 Ma and calculated an erosion rate of 31-55 km^3/m.y. per km of trench. Along the Chile margin (latitude 24°S-35°S), Stern (1991) estimated rates of subduction erosion of 50-500 km^3/m.y. per km of trench.

Material Mass Balance of the Costa Rica Accretionary Complex

Preliminary mass-balance calculations were made for the study area off the Nicoya Peninsula, Costa Rica (McIntosh et al., 1990; McIntosh, 1992). The emplacement age of material accreted beneath the lower slope is loosely constrained by DSDP Site 565. Site 565 penetrated 328 m of terrigenous mud in the slope apron section, bottoming in lowermost Pliocene sediments. This age indicates a mean sedimentation rate of 60 m/m.y. and suggests that the age of the prism below Site 565 could range from about 6 to over 10 Ma (Shipley et al., 1992). By graphing sediment accretion vs. time, we have estimated that, if all the incoming sediments were accreted, then the observed volume could be accumulated in about 1 m.y. However, if the amount accreted were 20-40% of the incoming sediments, then the time required to accrete the observed volume is 6-10 m.y., consistent with Site 565 age estimates.

The incoming section is roughly 40% hemipelagic and 60% pelagic, so 40% accretion beneath Site 565 implies accretion of the upper hemipelagic layer and underthrusting of the lower pelagic layer. This can be an important constraint for interpretation of the lower slope structure (Shipley et al., 1992) and rate of accretion through time. However, Site 565 does not adequately restrict the underlying prism emplacement age; if the accreted material is >10 Ma, it could imply episodic accretion or subduction erosion. Proposed site CR-3, located near Site 565, will sample the base of the slope apron and supply an emplacement age capable of tightly delimiting the lower slope rate of accretion.

Mass-balance calculations based on prism emplacement ages at proposed site CR-4 are also planned. This will allow study of accretion rates over a longer term. Combined with the results from proposed site CR-3, these calculations will quantify sediment bypassing or erosion, suggested by the abrupt change in slope apron thickness at 20-25 km from the trench.

Mass Balance at Costa Rica versus Other Convergent Margins

Two essential values must be determined or known to reconcile the sediment budget at a convergent margin. First, the incoming sediment flux must be determined, and, second, the amount of material accreted over a designated time span must be measured. Estimating the incoming sediment flux can be a difficult problem, especially with the presence of trench turbidites whose thickness can vary in both time and space along a margin. Another problem in estimating sediment influx is to determine the convergence rate; although plate convergence rates are generally known satisfactorily across most convergent boundaries, the rate of seaward advancement of the growing wedge must be taken into account in rapidly accreting margins such as Nankai, Cascadia, and parts of Barbados. For example, seaward advancement of the Cascadia accretionary complex just during the Pleistocene is estimated at 25 km (Davis and Hyndman, 1989). This calculates to a rate of advancement of about 14 mm/yr, or 31% of the 45 mm/yr convergence rate. To avoid serious inaccuracy in the effective convergence rate, the age of the accreted material must be controlled, and shortening or extension in the older part of the wedge must be well known or negligible. Seaward advancement of the deformation front in Costa Rica, however, is negligible compared to the convergence rate. Estimates of advancement rate are 1.4-2.3 mm/yr or less than 3% of the 87 mm/yr plate convergence.

The Costa Rica prism is also better suited than most for accurately identifying and measuring the accreted volume. The top of prism reflector gives Costa Rica a demonstrably closed and bounded system, free from the effects of surface erosion. This unusual feature differs from many margins where erosion of accreted material is common. Furthermore, the moderate rate of accretion off Costa Rica has resulted in a relatively thin prism beneath the middle and lower slope. This geometry, combined with the 2D and 3D seismic reflection data, allow for good interpretations of the internal structure of the prism and consequently good estimates of the geometry of the accreted mass. Other mass balance estimates, such as off southern Mexico (Watkins et al., 1982), are subject to considerable uncertainty due to difficulty in measuring the geometry of the accreted mass.

Fluid Effects

It is estimated that a volume of fluid roughly equal to the mass volume of the accretionary prism passes through the prism during accretion (Carson, 1977). Numerous studies have indicated that the décollement, intraprism faults, highly permeable (sandy) layers, and mud volcanoes provide conduits for water flow to escape. Detailed studies of the Barbados (Foucher et al., 1990; Fisher and Hounslow, 1990), Oregon-Washington (Moore et al., 1990), and Japan (Henry et al., 1989) accretionary wedges have documented that rates of fluid expulsion from vents and mud volcanoes can be as great, as or significantly greater than, the total rate of fluids entering the subduction zone, implying that fluid vents and mud volcanoes are transient features. The Costa Rica margin probably has few sandy layers, so any elevated permeability is likely to be fracture permeability. As noted above, we have discovered four mud volcanoes in the 3D grid. These and numerous through-prism faults, many of them out-of-sequence thrusts, may play a significant role in dewatering the prism.

An additional process of great importance in fluid and mass transport within accretionary wedges is dissolution and precipitation of carbonates. Kulm and Suess (1990) have mapped a very large area of probable carbonate outcrop off Oregon-Washington. Sample (1990) carried out experiments on the stability of carbonate cementation in subduction zones and discussed the importance of such cementation to the physical properties and therefore the structural development of the prism. His results suggest that carbonate cementation within underthrust sediments may lead to accretion of coherent duplexes rather than diffuse underplating of sedimentary melange.

We are interested in carbonate sedimentation with respect to the Costa Rica margin because the lower pelagic sediments on the subducting Cocos Plate are carbonate rich. Cementation of the accreted material by carbonate released from the dewatering underthrust section is a possible explanation for the major change in seismic velocity marking the top of the prism. If so, it may result in significant differences in rock strength between the top of the prism and base of the apron. Cementation in the underthrust section itself may allow deeper sediment underthrusting and, if eventually accreted, these sediments may remain in coherent underplated blocks (e.g., Sample, 1990). Early cementation will also increase the importance of fracture permeability in dewatering, possibly concentrating fluid flow along fault zones. These speculations must be tested by drilling. The total volume of internal fluids available in the Costa Rica subduction zone could be estimated by assuming steady-state sediment mass conservation, by thoroughly characterizing the amount and nature of the incoming sediments, and by establishing the degree and nature of alteration of the uppermost oceanic basement (plus extrapolation to greater depths).

Fluid expulsion at the seafloor is an important consequence of porosity reduction, subduction-induced sediment diagenesis and metamorphic deformation. It is well established that fluids affect virtually all aspects of the geologic evolution of subduction zones, and that fluids play a central role in the deformational, thermal, and geochemical evaluation of this environment (Von Huene, 1984; Bray and Karig, 1985; Moore et al., 1990 and references therein). Here extensive fluid-solid diagenetic and metamorphic reactions take place (Ritger et al., 1987; Peacock, 1990; Gieskes et al., 1990; Kastner et al., 1990, 1991) and significant fluid volumes are expelled (Kulm et al., 1986; Carson et al., 1990; von Huene and Scholl, 1991; Le Pichon et al., 1990, 1991). These fluids contain key information on the relative mobility of important elements for mass-balance calculations, and on the degree to which these fluid flow regimes influence global geochemical and heat budgets. It is clear from the data presently available from Barbados, Nankai, Peru, and Cascadia that the fluid compositions are chemically and isotopically very different from those of present day seawater. Therefore, the chemical and isotopic fluxes are potentially significant. It is imperative to document and compare the incoming sediment and pore-fluid chemistry and isotopic compositions at a reference site with those that have been modified by diagenesis and metamorphism throughout the subduction zone.

Typically, sediments entering subduction zones have porosities of approximately $50 \pm 10\%$ (e.g., Hamilton, 1976), while subaerially exposed accretionary complex sediments have porosities of less than 5% to 10%. Expulsion of fluids through porosity reduction and by devolatilization reactions (e.g., dehydration and thermal decomposition of hydrous minerals and organic matter and decarbonation of calcareous minerals) occurs through the décollement and other major and minor faults and by flow dispersed through the sediments. Determining the relative importance of channelized versus dispersed (diffuse) fluid flow is critical for understanding the hydrogeology of subduction zones. Thus capturing and analyzing the fluids in the décollement, across faults, and within the sediment pore space is a primary objective.

Studies of the pore fluid and sediment geochemical and isotopic compositions would also permit evaluating the types and extent of fluid-rock reactions that have occurred and possibly even detecting mixing with external fluids (principally with meteoric water?). Modeling the pore fluid chemical and isotopic depth profiles together with the temperature profiles would give solute fluxes into seawater. In order to determine the origin of the pore fluids, to establish the contributions from each of the possible internal devolatilization processes, and to assess the possibility of external fluid sources, these fluids must be analyzed not only for their major components (carried out onboard the ship) but also for a number of diagnostic minor and trace components that would provide insights into the above mentioned key recycling processes (e.g., for oxygen, hydrogen, and carbon isotopic ratios, Ba concentrations and for Li, Be, B, Cl, Sr, and REE concentrations and isotopic ratios). The need for multi-isotopic analyses arises because some record important but non-unique environmental physical-chemical conditions, while the others are controlled by the sources and sinks involved.

Mass Balance Constraints From Arc Volcanics

Volumes of sediments underplated at depth, eroded or subcrustally subducted are necessarily estimated by difference in the physical mass-balance calculations described above. Chemical mass- balance calculations, in contrast, measure the percentage of subducted sediment-hosted elements that are recycled in arc volcanism and so permit minimum estimates of the amount of sediment bypassing the accretionary margin altogether. Volcanic recycling thus provides important limits on processes in the deep accretionary prism not attainable by other imaging techniques. Incorporating these estimates of subduction recycling highlights the inherent difficulties of studying the accretionary prism as an integrated whole; material in the different parts of the prism have been in the system for different lengths of time and comparison implicitly requires an assumption of steady state. The sediments now beneath the volcanoes generally were supplied to the trench some 2-4 m.y. ago and, to be rigorous, steady state must apply over this interval.

Assuming steady state, cosmogenic ^{10}Be is particularly useful in partitioning the incoming sediments into those accreted, underplated, diluted by erosion, or deeply subducted. Made by cosmic rays in the atmosphere, strongly adsorptive on settling sediment particles in the oceans, and with a half life of 1.5 m.y., ^{10}Be tags only the uppermost part of the sediment column (Lal and Peters, 1967; Anderson et al., 1990; Yiou and Raisbeck, 1972). This is shown by measurements for DSDP Site 495, outboard of Guatemala (Figure 4a). Efficient subduction of these sediments is indicated by the ^{10}Be recycled in the volcanic arc of Guatemala. It is also important to note that erosion of old material from the deep prism will dilute the ^{10}Be in the oceanic column, so the presence of ^{10}Be in the volcanoes may also place limits on the amount of permissible subduction erosion.

The situation is different in Costa Rica; the arc volcanoes do not have measurable quantities of ^{10}Be. Measurement of ^{10}Be at proposed site CR-1 will provide a detailed picture of the ^{10}Be distribution in the sediment column, which can be combined with physical mass-balance models and the absence of recycled ^{10}Be to further quantify estimates of accretion and underplating. This situation is shown in Figure 4b, where the expected age-depth-lithology relations are shown. If only 44 m (~10-15% of the sediment column) is accreted frontally, then much of the remaining hemipelagic sediments must be underplated or diluted by subduction erosion; these masses can be determined when the distribution of ^{10}Be at CR-1 is known.

Proposed sites CR-2 and CR-3 provide opportunities to assess the amount of ^{10}Be stored in the forearc, a quantity that is important for mass balance. In addition, a model of episodic accretion or erosion is indicated if sediments too old to contain ^{10}Be (>12-15 Ma) are recovered at these sites. If the sediments are young enough, the ^{10}Be distribution may help to distinguish between different proposed origins for the coherent intra-prism reflectors seen near this site. The column labeled "hypothetical CR-2 core" (Figure 4b) shows the pattern of ^{10}Be distribution with depth to be expected if the reflectors are old, gently folded décollements; out-of-sequence thrusting would not be expected to preserve simple age-depth ^{10}Be patterns. For any of these approaches to work, ^{10}Be in the sediment column cannot be significantly redistributed by diagenesis or fluid flow. Experimental studies in simple water-sediment systems suggest that ^{10}Be (with Kd sediment/water

~104-105) is relatively immobile (Nyffeler et al., 1984; You et al., 1989). However, recent results (You et al., 1989) indicate that this question should be investigated carefully in natural systems; this can be done in the context of fluid flow and chemical studies at the proposed drill sites.

The geochemical stratigraphy of the incoming sediment column may be an important aid in constraining the accretionary processes. Like ^{10}Be, elements can also be traced through the subduction zone (Plank and Langmuir, 1993), and because elements do not decay like ^{10}Be, they can potentially tell us about processes affecting the entire sedimentary column. For example, although northern Costa Rican volcanics have no ^{10}Be, they have roughly the same enrichment in Ba as Guatemalan volcanics. Because Ba in Central American volcanics appears to originate in subducted sediment, similarity in the volcanics suggests similar mass fluxes of subducted Ba. This is perhaps surprising given the different accretionary styles along the margin. Almost no net accretion has occurred at the Guatemala margin throughout the Neogene, and so the entire sedimentary package is apparently subducted (von Huene and Aubouin, 1982). On the other hand, frontal accretion at the Costa Rica margin should reduce the flux of subducted Ba available to the arc. Figure 5 shows the effect of accretion on the flux of subducted Ba for a 450 m incoming sediment section with the same density and Ba concentration as Site 495 sediments (off Guatemala). For these parameters, 50 m of offscraping would bring Costa Rica into line with the global trend. Although there is uncertainty in the global trend, this type of calculation demonstrates, at least conceptually, how the chemical fluxes can help to constrain physical processes. This example also underscores the importance of integrating trace element and isotope studies. This is especially true for Costa Rica because the trace element and isotopic composition of the volcanics seems to require a delicate balance between sediment accretion and subduction; enough of the uppermost sediment must be accreted or underplated to remove the ^{10}Be, but not so much as to deplete the Ba flux to the arc. This balance can be determined once actual ^{10}Be and Ba measurements are made (at the reference site CR-1 and within the prism).

Global Sediment Budgets

Von Huene and Scholl (1991) have examined convergent margins around the world in an attempt to study the global sediment budget and to make corollary estimates of the volume of terrestrial crust through time. They characterized convergent margins by either the presence (Type-1) or the absence (Type-2) of an accretionary prism. They further subdivided Type-1 margins into those with small to medium-sized (5-40-km-wide) accretionary prisms and those with large (>40 km-wide) prisms. Based on mass balance estimates and direct observations at several "best-controlled" margins, they estimated that for Type-1 small-prism margins, more than half of the incoming sediment bypasses the accretionary complex, whereas for Type-1 large-prism margins, only about 10% of the incoming sediment bypasses the accretionary complex. At Type-2 margins, von Huene and Scholl (1991) assumed that virtually all of the incoming sediment is subcrustally subducted.

By extrapolating these sediment bypassing estimates world wide (incorporating convergence rates and observed sediment thicknesses) and adding products of subduction erosion, von Huene and Scholl (1991) calculated that approximately 1.6 km^3/yr of terrestrial material is subcrustally subducted. This rate compares closely with the 1.65 km^3/yr estimated addition of new igneous continental and island arc crust (Reymer and Schubert, 1984). This apparent balance of crust/mantle mass exchange suggested to von Huene and Scholl (1991) that the volume of terrestrial crust may have remained fairly constant over the last 100-200 m.y.

Continuous injection of crustal material into the mantle at subduction zones can have a profound effect on the chemical and physical evolution of the continents and mantle over the history of the earth. This topic was appreciated long ago by Armstrong (1968), but few precise estimates of subducted fluxes have been made since then. The recent calculations by von Huene and Scholl (1991) show that the flux of sedimentary material into the mantle is potentially large -- similar to modern crustal growth rates. Although their calculations provide a good estimate for the global flux of subcrustally-subducted sediment, this flux is an upper limit because some material is recycled to the arc crust. It is a common misconception that the sediment contribution to the arc is trivial (around 1%), based on isotopic mixing arguments which constrain only the proportion of sediment to the mantle and not the proportion of the total subducting budget that contributes to the arc. In order to calculate the latter, estimates of input fluxes (sediment) and output fluxes (volcanic) are required. Earlier flux balances by Karig and Kay (1981) for the Marianas suggested that 10% of the sedimentary section contributes elements to the arc. More recent calculations by Plank and Langmuir (1993) suggest that the value might be closer to 20% globally, and uncertainties in mobile components could increase this figure even further. These studies, however, do not consider underplating or erosion at the forearc. Thus in order to determine the return flux of crustal material into the deep mantle at subduction zones, we need to consider the sediment cycle through the entire subduction zone -- from trench to volcanic arc (Figure 6).

A total mass balance of a subduction zone would involve estimating inputs and outputs from each level in the system (Figure 6). The material balance in the accretionary complex reveals sediment inputs to the mantle (subducted and eroded components) and sediment outputs that are recycled to the forearc (accreted and underplated components). Pore-fluid chemical and isotopic compositions provide important limits on fluid-rock processes in the shallow to intermediate portions of the accretionary complex, and volcanic recycling provides important limits on processes in the deeper portions of the accretionary complex. Finally the mineralogy, chemistry, and isotopic compositions of the accreted and underplated sediment provide key complementary information on both the residual non-recycled components and on the redistribution of components within the system. This combined information is essential for estimating the amount of accretion and underplating, for identifying sources and sinks of recycled components, and for chemical and isotopic flux calculations. The pore fluids and sediments will be recovered through drilling and the volcanic recycling has been documented.

This total chemical mass balance for a subduction zone has not been possible previously because it requires good control of so many factors: bulk sediment dynamics within the accretionary complex, fluid flow through the shallow subduction zone, and recycling fluxes to the volcanic arc (Figure 6). Drilling on the Costa Rica margin could provide us with the first good estimates of the total chemical fluxes, partly because of the ideal conditions (the capping sediment apron and the lack of trench turbidites) and extensive seismic imaging of the accretionary complex, and partly because of the opportunity to constrain the deeper parts of the sediment cycle, which are reflected in the forearc fluids and arc volcanics.

The Costa Rica subduction zone is ideally amenable for chemical and isotopic mass-balance calculations mainly for the following reasons.

1) Here it is feasible to drill a reference site through the sediment into the oceanic basement (>50 m) to provide the chemical and isotopic stratigraphy and the amount of volatiles entering the subduction zone.

2) The sediment dynamics, including the approximate percentage of sediment accreted per unit time, can be well determined through drilling, and the convergence rate is well known; there are no mass balance complications from trench turbidites.
3) The subduction rate is significantly higher than at Barbados, Nankai, and Cascadia subduction systems, thus providing significant volumes of fluids and solute fluxes.
4) The active volcanic arc is one of the most thoroughly studied in the world (Carr and Rose, 1987; Carr et al., 1990), and thus a vast and comprehensive chemical data set exists for the volcanic output with which to compare to sediment inputs.
5) The sediment signal in the arc is demonstrably high; sediment input affects arc output for many elements, and the fluxes into the Middle America Trench are extreme for some of these elements (Plank and Langmuir, 1993). For example, the anomalously high Ba and Sr in Central American volcanics (from Guatemala to Costa Rica) are explained well by the Ba and Sr sediment fluxes into the Middle America Trench, which are among the highest in the world (based on DSDP Site 495; see Figure 5).
6) The incoming sediments have a distinctive composition. The high proportion of biogenic to detrital phases leads to the high Ba and Sr (which are associated with biogenic opal and carbonate, respectively), but low K and Th is a signal that is easy to pick up at the arc because these four elements are not easily fractionated by igneous processes.

All of these factors combine to make Central America an ideal place to mass balance the sediment fluxes through the entire subduction zone.

PROPOSED SITES

Leg 170 will consist of a set of four drill sites (proposed sites CR-1 through CR-4) and one alternate drill site (proposed site CR-5) to carry out the drilling objectives for the Costa Rica convergent margin (Figure 1 and Table 1). The depth requirements for some of the sites may require multiple holes for adequate sampling.

Proposed site CR-1 (Middle America Trench Axis) is located on Swath Line 20, seaward of the Middle America Trench to act as a reference for the age, thickness, lithology, physical properties, and fluid composition of the incoming sedimentary section. The planned depth of penetration is 600 m (sub-bottom), including up to 200 m into oceanic basement. This site has taken on greater significance as a result of the discovery of regional, extremely low heat flow on the lower plate during the February 1994 cruise of the *A2/Alvin*. A minimum depth of 200 m is necessary to understand the fluid-flow regime in the uppermost part of the oceanic crust. Deeper drilling would certainly be helpful but would seriously impact other major objectives. Standard logging will be done at this site as well as careful downhole temperature measurements.

Proposed site CR-2 is located on Swath Line 20, 1.5 km from the toe of the accretionary wedge, near the base of the slope. The objective of drilling this site is largely fluid oriented, and the targets include drilling through the accretionary wedge and the décollement, and an additional 150 m beneath the décollement. Objectives include obtaining an understanding of the rate of dewatering of wedge sediments, the hydrogeology of the décollement, and constraining the amount of dewatering occurring in the underthrust strata. In addition to coring and standard logging, we will measure downhole temperature and possibly utilize an in-situ pore-water sampler. We will also use the formation microscanner (FMS) for structural control of the site. A CORK borehole seal will be emplaced at this site to investigate longterm changes of temperature, pressure, permeability, and fluid chemistry in the décollement zone. The U.S.-Canadian string will be used (the Keir Becker-Earl Davis string). Two osmotic pumps have been installed in the Barbados CORKed site. One is a continuous sampler. The second sampler is gas-tight, using Ti syringes to collect fluid at a pre-set time sequence (approximately once every two weeks). The samplers will be taken out after two years and analyzed for major and minor components, and the gas tight samples for various isotopes, especially Sr, O, H, B, and possibly Li (depending on concentrations). After one year, a follow-up diving cruise will permit us to read the T-P, conduct pressure experiments, and also pump fluid from the CORKs for geochemistry, including methane concentrations. Before the string is deployed and the CORK sealed, in-situ VSP and packer experiments will be conducted. The VSP data is needed for ground truthing the seismic profiles.

Proposed site CR-3 (lower trench slope) is located on Line CR3D-177, 14 km landward of the trench where it can penetrate the slope apron, the high-amplitude reflector at the base of the apron, and one or more of the interpreted fault zone reflectors. This key site will constrain age, lithology (hemipelagic or carbonate), structure, and physical properties of the slope apron, the prism, and the important boundaries. It will allow us to utilize geochemical markers in determining the significance of fluid flow along the décollement as well as through other fault zones within the wedge. This site also has the potential for providing some input on the concept of a flow channel, proposed by Cloos and Shreve (1988a, b), though the drilling depths will be too shallow to fully test the idea. In addition to standard logging at this site, we plan to carry out downhole temperature measurements, and conduct FMS runs and packer experiments for permeability measurements (if time permits). Also, if time permits, a VSP may be run to obtain better structural control and velocity determinations at the site.

Proposed site CR-4 (middle trench slope) is located on 3D line 132, 23 km landward of the trench. This site will sample a portion of the slope apron that is thicker and less deformed than at proposed sites CR-2 or CR-3 and also penetrate the high-amplitude reflector. The purpose of sampling the slope apron is to date regionally-correlatable seismic sequences and thereby constrain a large portion of the upper slope. Additional penetration of the apron-prism boundary is important to confirm the nature of this seismic impedance boundary and in calculating the growth rate of a larger portion of the accretionary complex. This site is upslope from a major structural disturbance and change in thickness of the slope apron. Proposed site CR-4 will allow us to calibrate the seismic stratigraphy, which is well-developed in the middle and upper slope regions of the margin, but more poorly developed on the lower slope. Penetration of the apron-prism boundary will provide the second datum for determining an age gradient for the rate of underplating (if that process is documented) and information on variation in material properties of the sub-apron prism. Are the underlying rocks recently underplated, or are they older, basement rocks like those found off Guatemala? Is the apron-prism boundary reflector explained entirely by the contrast in materials on either side, or have precipitates along this interface "brightened" the reflector? If the lower units are indeed recently underplated, what makes them of sufficiently high velocity contrast with the overlying apron sediments -- extensive cementation?

Proposed site CR-5 (lower trench slope) is located on 3D seismic line 172, 5.5 km landward of the base of the trench slope, and is designed to intersect a major out-of-sequence thrust which showed abundant fluid vents where it cropped out at the surface. Because of time constraints of the program, proposed site CR-5 is considered an alternate site to be drilled if one of the other sites (CR-2 or CR-3) cannot be drilled. Our plan would be to drill to a depth of 1150 m, which would cross the OOST and penetrate into the décollement.

REFERENCES

Anderson, R.F., Lao, Y., Broecker, W.S., Trumbore, S.E., Hoffman, H.J., et al., 1990. Boundary scavanging in the Pacific Ocean: a comparison of ^{10}Be and ^{231}Pa. *Earth Planet. Sci. Lett.*, 96:287-304.

Armstrong, R.L., 1968. A model for Sr and Pb isotopic evolution in a dynamic earth. *Rev. Geophys.*, 6:175-199.

Azema, J., Bourgois, J., Baumgartner, P.O., Tournon, J., Desmet, A., and Aubouin, J., 1985. A tectonic cross-section of the Costa Rican Pacific Littoral as a key to the structure of the landward slope of the Middle America Trench off Guatemala. *In* von Huene, R., Aubouin, J., et al., *Init. Repts., DSDP*, 84: Washington (U.S. Govt. Printing Office), 831-850.

Bray, C.J., and Karig, D.E., 1985. Porosity of sediments in accretionary prisms and some implications for dewatering processes. *J. Geophys. Res.*, 90:768-778.

Brown, L., Klein, J., Middleton, R., Sachs, I.S., and Tera, F., 1982. ^{10}Be in island arc volcanoes and implications for subduction. *Nature*, 299:718-720.

Carr, M.J., Feigenson, M.D., and Bennet, E.A., 1990. Incompatible element and isotopic evidence for tectonic control of source mixing and melt extraction along the Central American arc. *Contrib. Mineral. Petrol.*, 105:369-380.

Carr, M.J., and Rose, W.I., 1987. CENTAM - A data base of Central American volcanic rocks. *J. Volcanol. Geotherm. Res.*, 33:2239-240.

Carson, B., 1977. Tectonically induced deformation of deep-sea sediments off Washington and northern Oregon: Mechanical consolidation. *Mar. Geol.*, 24:287-307.

Carson, B., Suess, E., and Strasser, J.C., 1990. Fluid flow and mass flux determinations at vent sites on the Cascadia margin accretionary prism. *J. Geophys. Res.*, 95:8891-8897.

Cloos, M., and Shreve, R.L., 1988a. Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins: 1. Background and description. *Pageoph.*, 128:455-500.

Cloos, M., and Shreve, R.L., 1988b. Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins: Implications and discussion. *Pageoph.*, 128:501-545.

Coltrin, G., Backus, M., Shipley, T.H., and Cloos, M., 1989. Seismic reflection imaging problems resulting from a rough surface at the top of the accretionary prism at convergent margins. *J. Geophys. Res.*, 94:17,485-17,496.

Corrigan, J., Mann, P., and Ingle, J.C., Jr., 1990. Forearc response of the Cocos Ridge, Panama-Costa Rica. *Geol. Soc. Am. Bull.*, 102:628-652.

Crowe, J.C., and Buffler, R.T., 1983. Regional seismic reflection profiles across the Middle America Trench and convergent margin of Cost Rica. *In* Bally, A.W. (ed.) *Seismic expression of structural styles - A picture and work atlas* (Volume 3): AAPG Studies in Geology, 15.

Dahlen, F.A., 1984. Noncohesive critical Coulomb wedges; an exact solution. *J. Geophys. Res.*, 89:10,125-10,133.

Davis, E.E., and Hyndman, R.D., 1989. Accretion and recent deformation of sediment along the northern Cascadia subduction zone. *Geol. Soc. Am. Bull.*, 101:1465-1480.

DeMets, C., Gordon, R.G., Argus, D.F., and Stein, S., 1990. Current plate motions. *Geophys. J. Int.*, 101:425-478.

Fisher, A.T. and Hounslow, M.W., 1990. Transient fluid flow through the toe of the Barbados accretionary complex: Constraints from Ocean Drilling Program Leg 110 heat flow studies and simple models. *J. Geophys. Res.*, 95:8845-8858.

Foucher, J.P., Le Pichon, X., Lallemant, S., Hobart, M.A., Henry, P., Benedetti, M, Westbrook, G.K., and Langseth, M.G., 1990. Heat flow, tectonics, and fluid circulation at the toe of the Barbados Ridge accretionary prism. *J. Geophys. Res.*, 95:8859-8867.

Gieskes, J.M., Blanc, G., Vrolijk, P., Elderfield, H., and Barnes, R., 1990. Interstitial water chemistry - major constituents. *In* Moore, J.C., Mascle, A., et al., *Proc. ODP, Sci. Results*,110: College Station, TX (Ocean Drilling Program),155-178.

Hamilton, E.L., 1976. Variations of density and porosity with depth in deep-sea sediments. *J. Sediment. Petrol.*, 46:280-300.

Hays, J.D., Cook, H.E., et al., 1972. *Init. Repts. DSDP*, 9: Washington (U.S. Govt. Printing Office).

Henry, P., Lallemant, S.J., Le Pichon, X., and Lallemand, S.E., 1989. Fluid venting along Japanese trenches, tectonic context and thermal modeling. *Tectonophysics*, 160:277-292.

Hey, R., 1977. Tectonic evolution of the Cocos-Nazca spreading center. *Geol. Soc. Am. Bull.*, 88:1404-1420.

Karig, D.E., and Kay, R.W., 1981. Fate of sediments on the descending plate at convergent margins. *Philos. Trans. R. Soc. London*, 301:233-251.

Kastner, M., Elderfield, H., Martin, J.B., Suess, E., Kvendholden, K.A., and Garrison, R.E., 1990. Diagenesis and interstitial water chemistry at the Peruvian continental margin - major constituents and strontium isotopes. *In* Suess, E., von Huene, R., et al., *Proc. ODP, Sci. Results*, 112B: College Station, TX (Ocean Drilling Program), 413-440.

Kastner, M., Elderfield, H., and Martin, J.B., 1991. Fluids in convergent margins: what do we know about their composition, origin, role in diagenesis and importance for oceanic chemical fluxes. *Philos. Trans. R. Soc. London (A)*, 335:243-259.

Kulm, L.D., Suess, E., Moore, J.C., Carson, B., Lewis, B.T., Ritger, S.D., Kadko, D.C., Thornburg, T.M., Embley, R.W., Rugh, W.D., Massoth, G.J., Langseth, M.G., Cochrane, G.R., and Scamman, R.L., 1986. Oregon subduction zone: venting, fauna and carbonates. *Science*, 231:561-566.

Kulm, L.D., and Suess, E., 1990. Relationship between carbonate deposits and fluid venting: Oregon accretionary prism. *J. Geophys. Res.*, 95, 8899-8915.

Lal, D., and Peters, B., 1967. Cosmic-ray-produced radioactivity on the Earth. *In Handbuch der Physik*, 4/2: Berlin (Springer-Verlag), 551-612.

Langseth, M.G., and Moore, J.C., 1990. Special section on the role of fluids in sediment accretion, deformation, diagenesis, and metamorphism in subduction zones. *J. Geophys. Res.*, 95:8737-9147.

Le Pichon, X., Henry, P., and Kaiko scientific crew, 1991. Water budgets in accretionary wedges: A comparison. *Philos. Trans. R. Soc. London (A)*, 335:315-330.

Le Pichon, X., Henry, P., and Lallemant, S., 1990. Water flow in the Barbados accretionary complex. *J. Geophys. Res.*, 95:8945-8967.

McIntosh, K.D., 1992. Geologic structure and processes of the eastern Pacific margin; California and Costa Rica [Ph.D. dissert.]. University of California, Santa Cruz, CA.

McIntosh, K.D., Silver, E.A., and Shipley, T.H., 1990. Growth processes and volume constraints of the accretionary wedge off the southwestern margin of Costa Rica. *Am. Geophys. Union Trans.*, 71:1562 (Abstract).

Monaghan, M.C., Klein, J., and Measures, C.I., 1988. The origins of ^{10}Be in island arc volcanic rocks. *Earth Planet. Sci. Lett.*, 89:288-298.

Moore, J.C., Mascle, A., et al., 1990. *Proc. ODP, Sci. Results*, 110: College Station, TX (Ocean Drilling Program).

Moore, J.C., and Shipley, T.H., 1988. Mechanisms of sediment accretion in the Middle Trench off Mexico. *J. Geophys. Res.*, 93:8911-8927.

Moore, G. F., Shipley, T.H., Stoffa, P.L., Karig, D.E., Taira, A., Kuramoto, S., Tokuyama, H., and Suchiro, K., 1990. Structure of the Nankai Trough accretionary zone from multichannel seismic reflection data. *J. Geophys. Res.*, 95:8753-8765.

Moore, J.C., Watkins, J.E., Shipley, T.H., McMillen, K.J., Bachman, S.B., and Lundberg, N., 1982. Geology and tectonic evolution of a juvenile accretionary terrain along a truncated convergent margin: Synthesis of results from Leg 66 of the Deep Sea Drilling Project, southern Mexico. *Geol. Soc. Am. Bull.*, 93:47-861.

Morris, J.D., Leeman, W.P., and Tera, F., 1990. The subducted component in island arc lavas: constraints from Be isotopes and B-Be systematics. *Nature*, 334:31-36.

Morris, J.D. and Tera, F., 1989. ^{10}Be and ^{9}Be in mineral separates and whole rocks from volcanic arcs: implications for sediment subduction. *Geochim. Cosmochim. Acta*, 53:3197-3206.

Nyffeler, U.P., Li, Y.-H., Santschi, P.H., 1984. A kinetic approach to describe trace-element distribution between particles and solution in natural aquatic systems. *Geochim. Cosmochim. Acta*, 48:1513-1522.

Peacock, S.M., 1990. Fluid processes in subduction zones. *Science*, 248:329-337.

Plank, T., and Langmuir, C.H., 1993. Tracing trace elements from sediment input to volcanic output at subduction zones. *Nature*, 362:739-743.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. *Geol. Soc. Am. Bull.*, 97:1037-1057.

Platt, J.P., Leggett, J.K., Young, J., Raza, H., and Alam, S., 1985. Large-scale sediment underplating in the Makran accretionary prism, Southwest Pakistan. *Geology*, 13:507-511.

Ponce, D.A., and Case, J.E., 1987. Gravity anomalies of Costa Rica and their relations to crustal structure and mineralization. *In* Brennan, E. (ed.), *Pacific Rim Congress 87*. Australas. Inst. Min. Metall., 369-372.

Reymer, A., and Schubert, G., 1984. Phanerozoic addition rates to the continental crust and crustal growth. *Tectonics*, 3:63-77.

Ritger, S., Carson, B., and Suess, E., 1987. Methane-derived authigenic carbonates formed by subduction-induced pore-water expulsion along Oregon/Washington margin. *Geol. Soc. Am. Bull.*, 98:147-156.

Sample, J., 1990. The effect of carbonate sedimentation of underthrust sediments on deformation styles during underplating. *J. Geophys. Res.*, 95:9111-9121.

Schweller, W.J., Kulm, L.D., and Prince, R.A., 1981. Tectonics, structure, and sedimentary framework of the Peru-Chile trench, in Nazca Plate: Crustal Formation and Andean Convergence. *Mem. Geol. Soc. Am.*, 154:232-349.

Shipley, T.H., Ladd, J.W., Buffler, R.T., and Watkins, J.S., 1982. Tectonic processes along the Middle America Trench inner slope. *Geol. Soc. Spec. Publ. London*, 10:95-106.

Shipley, T.H., McIntosh, K.D., Silver, E.A., and Stoffa, P.L., 1992. Three-dimensional seismic imaging of the Costa Rica accretionary prism: structural diversity in a small volume of the lower slope. *J. Geophys. Res.*, 97:4439-4459.

Shipley, T.H., and Moore, G.F., 1986. Sediment accretion, subduction, and dewatering at the base of the trench slope off Costa Rica: A seismic reflection view of the décollement. *J. Geophys. Res.*, 91:2019-2028.

Shipley, T.H., Stoffa, P.L. and Dean, D.F., 1990. Underthrust sediments, fluid migration paths and mud volcanoes associated with the accretionary wedge off Costa Rica: Middle America Trench. *J. Geophys. Res.*, 95:8743-8752.

Stern, C.R., 1991. Role of subduction erosion in the generation of Andean magmas. *Geology*, 19:78-81.

Stoffa, P.L., Shipley, T.H., Dean, D.F., Kessinger, W., Rigmor, E., Silver, E.A., Reed, D.L., and Aguilar, A., 1991. Three-dimensional seismic imaging of the Costa Rica accretionary wedge: Field program and migration examples. *J. Geophys. Res.*, 96:21,693-21,721.

Tera, F., Brown, L., Morris, J.D., Sacks, I.S., Klein, J., and Middleton, K., 1986. Sediment incorporation in island-arc magmas: inferences from ^{10}Be. *Geochim. Cosmochim. Acta*, 50:535-550.

von Huene, R., 1984. Tectonic processes along the front of modern convergent margins - research of the past decade. *Ann. Rev. Earth Planet. Sci.*, 12:359-381.

von Huene, R., and Aubouin, J., 1982. Summary -- Leg 67, Middle America Trench transect off Guatemala. *In* Aubouin, J., von Huene, R., et al., *Init. Repts., DSDP*, 67: Washington (U.S. Govt. Printing Office).

von Huene, R., Aubouin, J., Azema, J., Blackinton, G., Carter, J.A., Coulbourn, W.T., Cowan, D.S., Curiale, J.A., Dengo, C.A., Faas, R.W., Harrison, W.H., Hesse, R., Hussong, D.M., Ladd, J.W., Muzylov, N., Shiki, T., Thompson, P.R., and Westberg, J., 1982. *In* Leggett, J.K. (ed.) *A summary of Deep Sea Drilling Project Leg 67 shipboard results from the Mid-America Trench transect off Guatemala, Trench-Forearc Geology*. Spec. Publ. - Geol. Soc. London, 10:121-129.

von Huene, R., and Lallemand, S., 1990. Tectonic erosion along the Japan and Peru convergent margins. *Geol. Soc. Am. Bull.*, 102:704-720.

von Huene, R., and Scholl, D., 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental crust. *Rev. Geophys.*, 29:279-316.

von Huene, R., and Scholl, D.W., 1993, The return of sialic material to the mantle indicated by terrigenous material subducted at convergent margins. *Tectonophysics*, 219:163-175.

Watkins, J.S., McMillen, K.J., Bachman, S.B., Shipley, T.H., Moore, J.C., and Angevine, C., 1982. Tectonic synthesis, Leg 66: Transect and Vicinity. *In* Watkins, J.S., Moore, J.C., et al., *Init. Repts., DSDP*, 66: Washington (U.S. Govt. Printing Office), 837-849.

Yiou, F., and Raisbeck, G.M., 1972. Half-life of ^{10}Be. *Phys. Rev. Lett.*, 29:372-375.

You, C.F., Lee, T., Li, Y.-H., 1989. The partition of Be between soil and water. *Chem. Geol.*, 77:105-118.

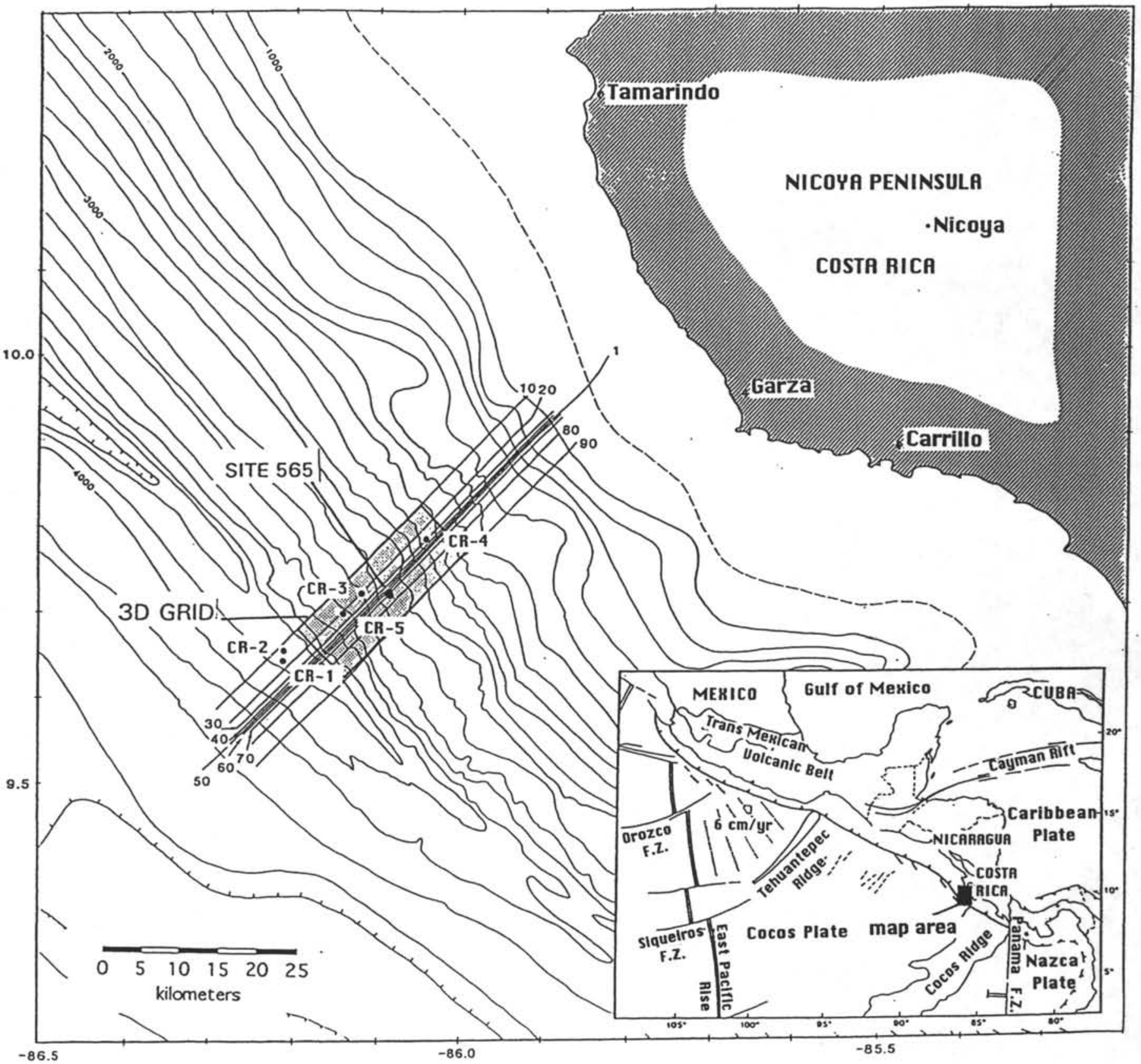


Figure 1. Location of 2D and 3D seismic profiles from 1987 cruise of *R/V Fred Moore*. Inset shows map of Central America and major tectonic features on the adjacent seafloors. Nicoya Peninsula is located just below the "C" in Costa Rica on the inset drawing. The stippled rectangle shows the location of the 3D seismic grid. The longer, labeled lines are 2D profiles.

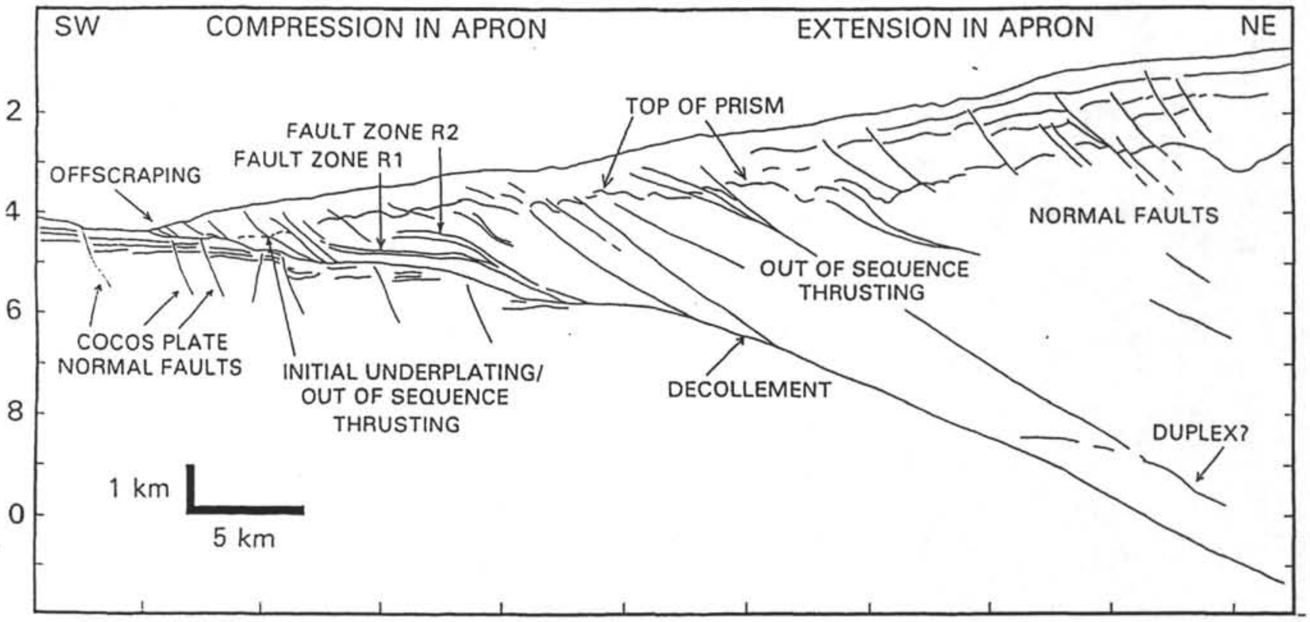


Figure 2. Simplified interpretation of a section through the lower and middle slope region of the Costa Rica continental margin.

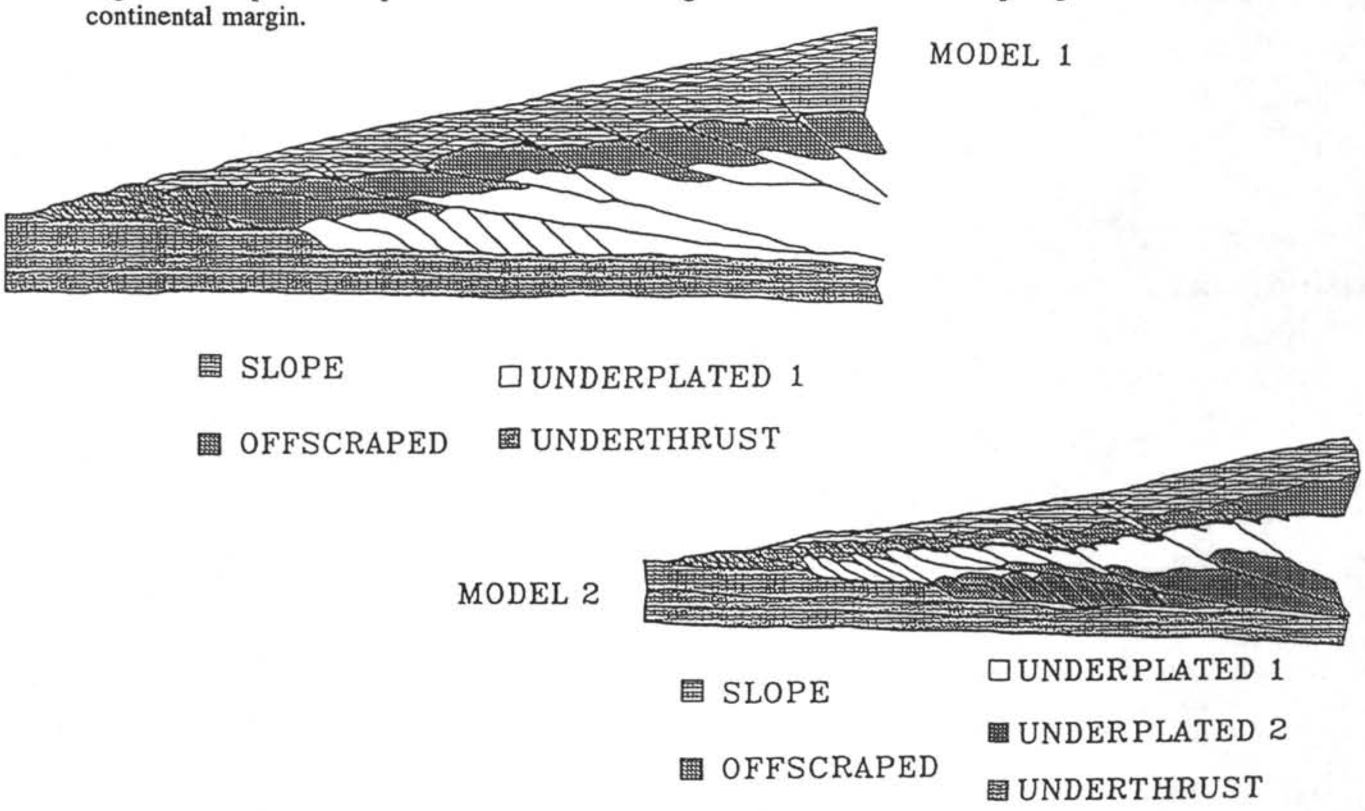


Figure 3. Model from Shipley et al. (1992) illustrating offscraping, underplating, and out-of-sequence thrusting. Model 1 makes the assumption that the high-amplitude reflector at the prism top is the boundary between apron sediments and offscraped rocks. In Model 2, this boundary separates offscraped from underplated rocks.

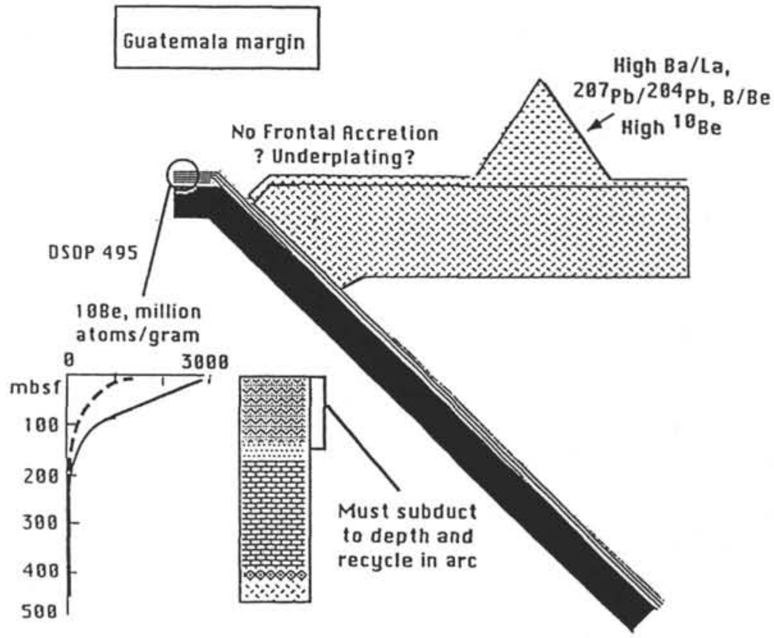


Figure 4a. Lithology and ^{10}Be (half-life = 1.5 m.y.) concentrations vs. depth (data from Zheng and Morris, unpubl.) in DSDP Site 495, outboard of Guatemala. The solid ^{10}Be profile emphasizes the high measured concentrations of ^{10}Be in near surface sediments, and the exponential decay to unmeasurable values at about 200 m (approximately 12 Ma). For the volcanoes to contain ^{10}Be, greater than 90% of these uppermost sediments must subduct to the arc source region. The dashed curve indicates the distribution of ^{10}Be in the sediments after correcting for radioactive decay during the roughly 2 m.y. required to subduct them from the trench axis to a point beneath the present volcanic front. (See Brown et al., 1992; Tera et al., 1986; Monaghan et al., 1988; Morris and Tera, 1989; Morris et al., 1990; and Morris et al., in prep. for discussion of the ^{10}Be systematics and results from volcanic arcs and oceanic sediments).

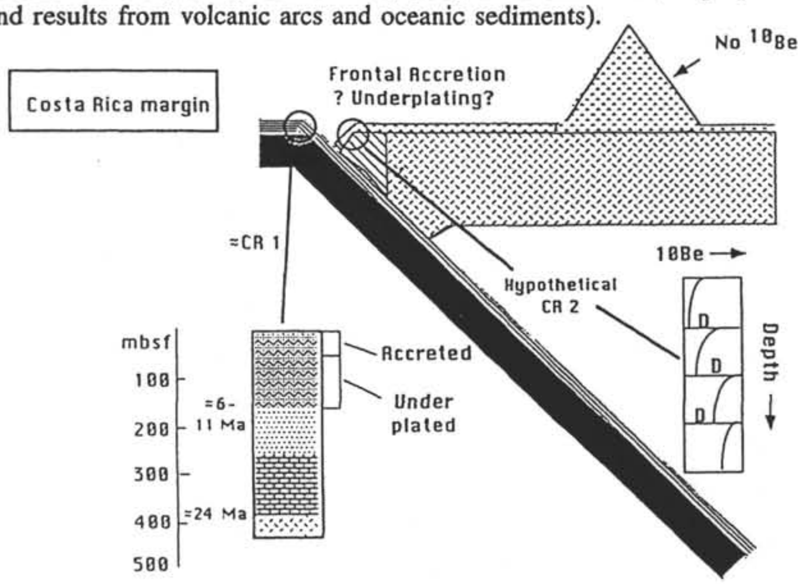


Figure 4b. The equivalent diagram for Costa Rica, showing the approximate age-depth-lithology relations in the incoming sediment column. The absence of ^{10}Be in the volcanoes indicates that this uppermost part is accreted and/or underplated. The column labeled "hypothetical CR-2 core" shows the distribution of ^{10}Be with depth to be expected if the intra-prism reflectors are older gently folded décollements (labeled D) separating a younging downward sequence of sedimentary packets, each packet of which is youngest at the top. ^{10}Be concentrations will be at measurable levels if younger than about 12 Ma. An absence of ^{10}Be at CR-2 implies older ages, consistent with episodic erosion or subduction erosion as discussed.

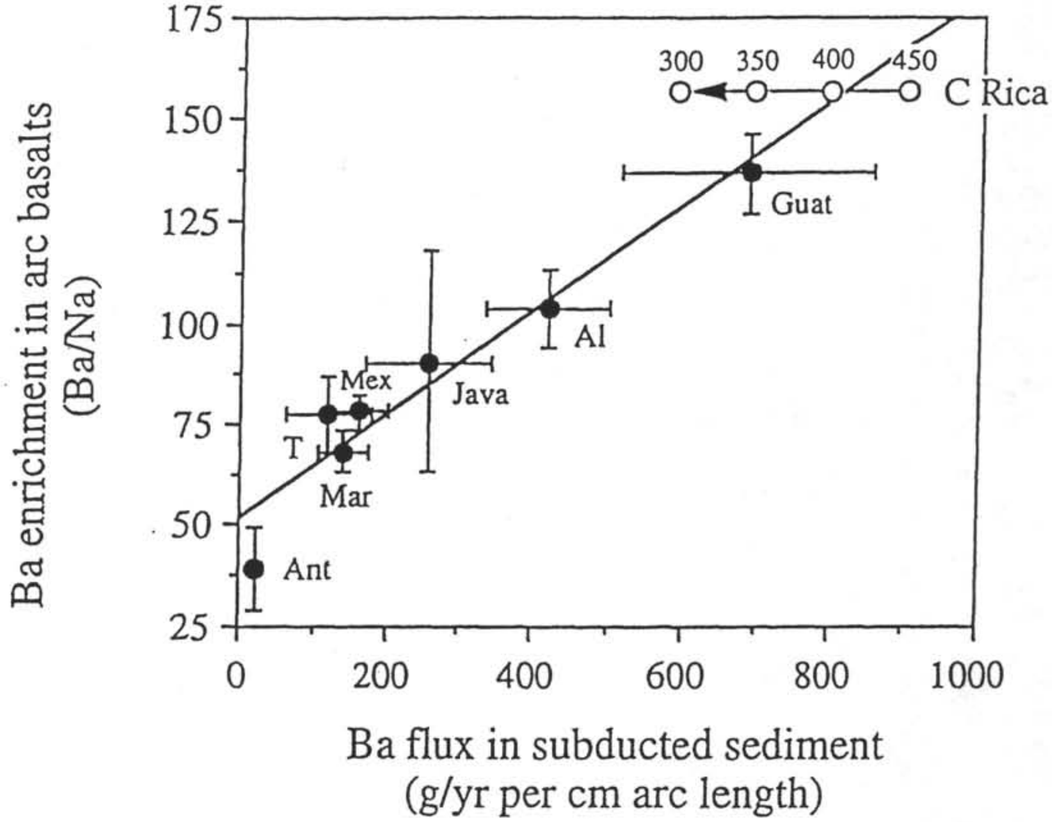
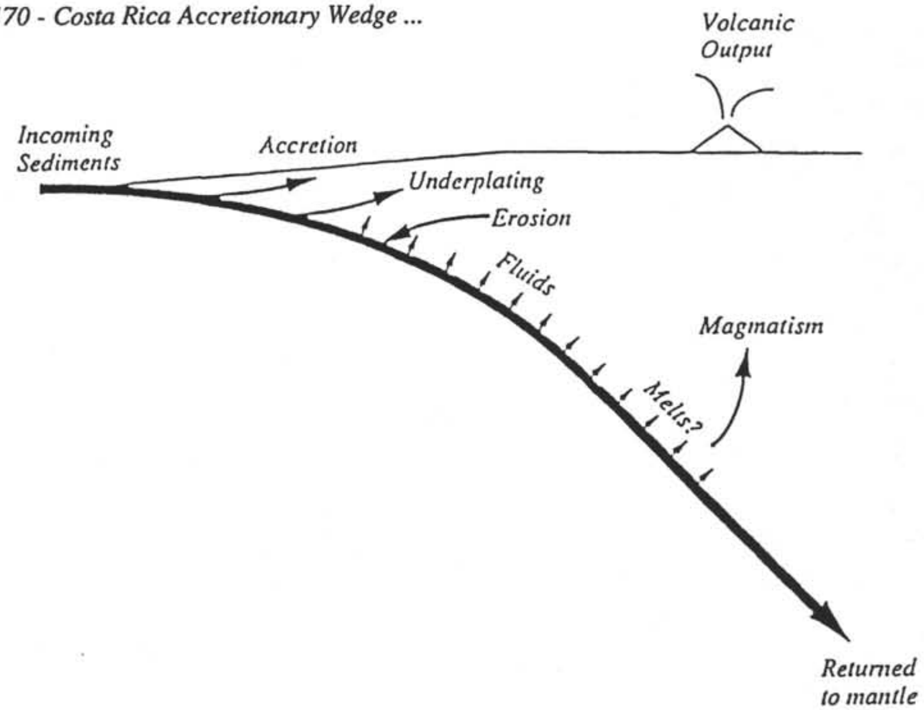


Figure 5. Correlation between Ba flux in subducted sediment and Ba enrichment of arc basalts, for the Northern Antilles, Marianas, Tonga, Mexico, Java, Aleutians, and Guatemala arcs (after Plank and Langmuir, 1993). These types of correlations, which are present for other elements as well, suggest that volcanic output is linked to sediment input in subduction zones. Line is best fit of solid points; vertical error bars are + one standard deviation of the mean of volcanoes within each arc; horizontal error bars represent uncertainties in the thickness of sediment being subducted due to variable supply, underplating and erosion (generally + 100 m). Input fluxes do not include accreted material, however (see Plank and Langmuir, 1993). Open circles are for the Costa Rica subduction zone. Ba/Na ratios are for Arenal and Rincon volcanoes (data from Carr and Rose, 1987), which are the closest of the Costa Rican volcanoes to the proposed drilling transect (these northern Costa Rican volcanoes are also chemically distinct from the alkalic southern Costa Rica volcanoes, as noted by Carr et al., 1990). The Ba fluxes for Costa Rica are calculated from the composition and density of the sedimentary column at Site 495, off Guatemala. The arrow shows the effect of frontal accretion on the subducted flux, where increasing amounts of the upper hemipelagic mud unit are removed (total meters of sediment subducted as indicated). Fifty meters of offscraping would bring the Ba flux for Costa Rica in line with the global trend. This is an illustrative example of how chemical fluxes might help to constrain accretionary processes. Accurate estimates require better control of the global trend (from improved constraints on the accretionary dynamics at other subduction zones), and Ba data on the incoming sedimentary column off Costa Rica (e.g., proposed site CR-1).



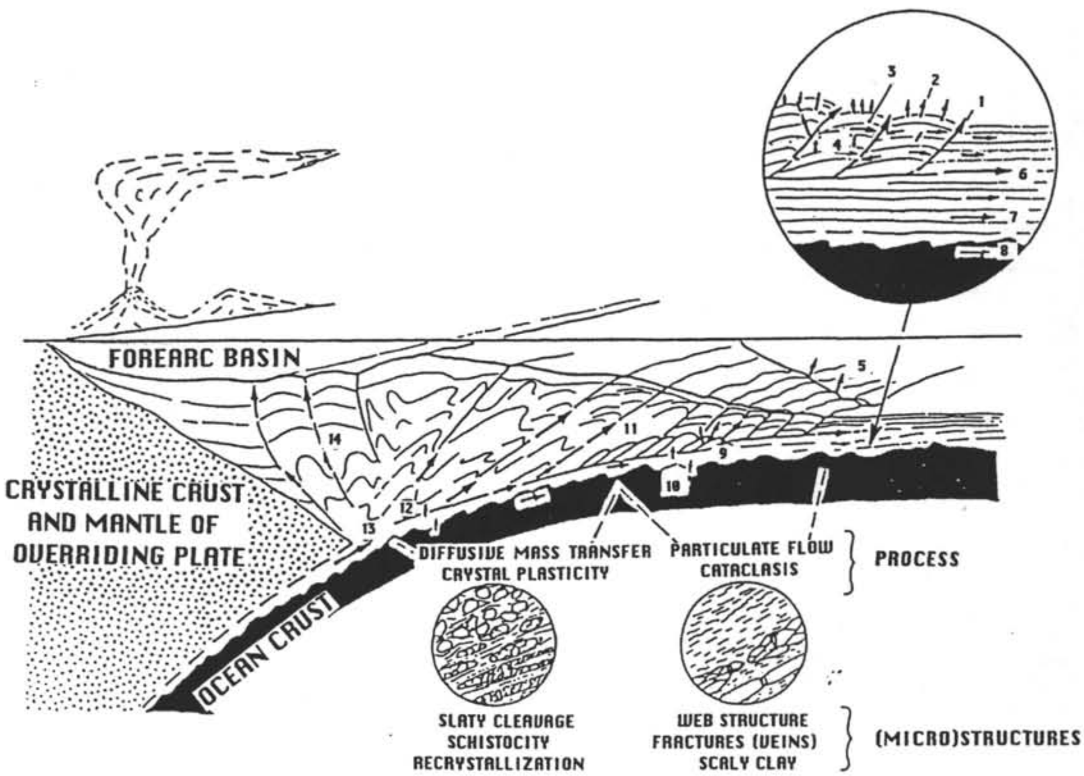


Figure 6. Top: The sediment cycle through a subduction zone (after von Huene and Scholl, 1993). The return flux of sediment to the mantle, which affects crustal growth, depends on many other fluxes -- the partitioning of bulk sediment in the shallow part of the subduction zone (by accretion, underplating and erosion), the chemical and fluid fluxes due to sediment dehydration and melting, and the chemical fluxes to the volcanic arc. Bottom: Fluid migration paths and deformation mechanisms in an accretionary prism. Small black arrows show possible paths of fluid migration (from Langseth and Moore, 1990).

TABLE 1

PROPOSED SITE INFORMATION and DRILLING STRATEGY

SITE: CR-1	**PRIORITY**:	**POSITION**: 9°38.4'N, 86°12'W
WATER DEPTH: 4350 m	**SEDIMENT THICKNESS**: 450 m	**TOTAL PENETRATION**: 750 m
SEISMIC COVERAGE: Swath Line 20		

Objectives: To serve as a reference site on the lower plate to study lithology, geochemistry, fluid composition and to determine the age and physical properties in an undeformed state.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: LWD, quad combo, GLT, FMS, and temperature.

Nature of Rock Anticipated: Hemipelagic siliceous mud and carbonate-rich pelagic mudstone.

SITE: CR-2	**PRIORITY**:	**POSITION**: 9°39.7'N, 86°12'W
WATER DEPTH: 4160 m	**SEDIMENT THICKNESS**: 750 m	**TOTAL PENETRATION**: 750 m
SEISMIC COVERAGE: Swath Line 20		

Objectives: To examine the structure of the accretionary wedge and the fluid stratigraphy of the wedge, décollement, and underthrust sediment section to determine mass balance and fluid-flow paths.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: LWD, VSP, CORK, and packer.

Nature of Rock Anticipated: Deformed hemipelagic mudstone and carbonate-rich pelagic mudstone.

SITE: CR-3	**PRIORITY**:	**POSITION**: 9°43.8'N, 86°7.2'W
WATER DEPTH: 3320 m	**SEDIMENT THICKNESS**: 1400 m	**TOTAL PENETRATION**: 1400 m
SEISMIC COVERAGE: 3D Line 177		

Objectives: To constrain the age, stratigraphy, and structure of the apron and prism to determine mass balance and fluid-flow paths.

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

Logging and Downhole Operations: LWD, VSP, temperature, and packer.

Nature of Rock Anticipated: Hemipelagic mudstone and carbonate-rich pelagic mudstone.

SITE: CR-4	**PRIORITY**:	**POSITION**: 9°46.8'N, 86°2.4'W
WATER DEPTH: 2200 m	**SEDIMENT THICKNESS**: 5000 m	**TOTAL PENETRATION**: 1000 m
SEISMIC COVERAGE: 3D Line 132		

Objectives: To constrain the age, stratigraphy, and structure of the slope, apron, and top of the prism to determine the seismic stratigraphy, material properties, and mass balance fluid-flow paths.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations:LWD, quad combo, GLT, and FMS.

Nature of Rock Anticipated: Hemipelagic mudstone/sandstone.

SITE: CR-5	**PRIORITY**: Alternate to CR-2 or CR-3	**POSITION**: 9°42'N, 86°8.4'W
WATER DEPTH: 3580 m	**SEDIMENT THICKNESS**: 1150 m	**TOTAL PENETRATION**: 1150 m
SEISMIC COVERAGE: 3D Line 172		

Objectives: To constrain the age, stratigraphy, and structure of the apron and prism to determine mass balance and fluid-flow paths.

Drilling Program: APC, XCB, and RCB.

Logging and Downhole Operations: Quad combo, GLT, FMS, and temperature.

Nature of Rock Anticipated: Hemipelagic mudstone and carbonate-rich pelagic mudstone.