WORKSHOP TO DEVELOP SCIENTIFIC OCEAN DRILLING INITIATIVES IN THE SOUTH ATLANTIC AND ADJACENT SOUTHERN OCEAN

APRIL 6-8, 1987

WOODS HOLE OCEANOGRAPHIC INSTITUTION
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SUMMARY

This report represents the product of a workshop designed to consider scientific ocean drilling priorities in the South Atlantic and adjacent Southern Ocean, an area defined broadly as extending from the large-offset fracture zones of the equatorial Atlantic and the associated translational/sheared margins of western Africa/northeastern South America to the passive continental margins of the Atlantic portion of the Antarctic. The workshop was held April 6-8, 1987, at Woods Hole Oceanographic Institution, Woods Hole, Massachusetts. The list of participants included approximately 50 representatives from 9 countries.

The goals of the workshop were two-fold: 1) To develop suites of drilling objectives in the South Atlantic from global, regional and topical perspectives by stressing themes, not individual drilling proposals; and 2) To broaden the base of expertise on which ODP efforts are based by including scientific input from non-ODP members. The three-day workshop began with a plenary session during the morning of the first day at which general overviews of various aspects of current South Atlantic research were presented. Then the participants split into the following topical groups for further discussions:

I. evolution of oceanic lithosphere/tectonics
II. biostratigraphy
III. physical stratigraphy/development of the sedimentary record
IV. geochemistry

Once major themes had been developed, each group went on to consider where they could be addressed optimally by drilling and what drilling strategies were necessary for each target area or areas.

The tectonics working group recognized that the South Atlantic provides a unique opportunity for studying the lithospheric evolution of a well-defined ocean basin system where many of the important tectonic elements are not overprinted by later events, subducted, or broadly linked to other ocean systems. This group proposed and developed the following set of themes as they pertain to the South Atlantic: 1) Tectonic segmentation and the evolution of oceanic crust; 2) Evolution of conjugate rift margins; 3) Evolution of transform-shear margins; 4) Tectonic controls on paleoceanographic gateways; 5) Evolution of the Scotia Sea: microplate evolution along a transpression plate-boundary system; and 6) Absolute plate motions: hot spot evolution and shifting plate boundaries.

The biostratigraphy working group based their deliberations on the fact that the South Atlantic is probably the most stable ocean basin with respect to atmospheric circulation, and therefore is probably the best place to study long-term climate stability. They identified and summarized the following set of themes: 1) Water mass distribution in space and time; 2) Climatic history; 3) Sea level history and effects; 4) Mesozoic black shale paleoceanography; 5) Biochronology; 6) Stratigraphy in carbonate-poor sediments; and 7) Nature of biogeographic change in surface to deep waters.

The physical stratigraphy working group summarized its discussions concerning the evolution of the sedimentary record in the South Atlantic by identifying five major themes: 1) Gateways; 2) History of deep circulation; 3) Fan growth and evolution as keys to equatorial climate and continental denudation; 4) Coastal upwelling and the history of shallow circulation; and 5) Definition of eustatic sea level changes.

The geochemistry working group considered a variety of problems which were grouped into two broad categories: 1. Sediment geochemistry; and 2. Igneous petrology and geochemistry. The group considered that geochemical investigations of the long sedimentary records present in the major basins of the South Atlantic were crucial for understanding the long-term development of surface/deep circulation patterns, the accompanying changes in seawater chemistry, the production and preservation of biogenic sediments, and the diagenetic consequences of those factors. Furthermore, interbasin comparisons could provide opportunities not equaled anywhere else in the world's oceans. The South Atlantic also provided an opportunity to address a number of intraplate and plate boundary processes that are fundamental to an improved understanding of the processes that affect volcanism, mantle dynamics and crustal structure in ocean basins.

The following report summarizes these group discussions, and should provide a partial template for planning as the *JOIDES Resolution* prepares to return to the Atlantic Ocean in the 1990's.

BACKGROUND AND INTRODUCTION

Even before the *JOIDES Resolution* completed drilling off Barbados in the summer of 1986, thereby concluding the first phase of Ocean Drilling Program (ODP) operations in the Atlantic, the JOIDES Atlantic Regional Panel (ARP) was considering important scientific objectives for the next cycle of ODP activities in the Atlantic, Mediterranean, Caribbean and Gulf of Mexico. After repeated discussions, ARP decided to endorse a series of international workshops whose primary goal was to develop a long-term, scientifically justified and geophysically supported drilling plan for these ocean basins which would be ready for implementation in the 1990's. This report represents the product of the first of these workshops, which was convened April 6-8, 1987, at the Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, in order to consider ocean drilling priorities in the South Atlantic and adjacent Southern Ocean. For the purposes of the workshop, the bounds of the "South Atlantic" were defined broadly as extending from the large-offset fracture zones of the equatorial Atlantic and the associated translational/sheared margins of western Africa/northeastern South America to the adjacent Southern Ocean and related passive margins of the Antarctic.

Within this enormous area, all of the "top priority" scientific problems identified by the first Conference on Scientific Ocean Drilling (COSOD, 1982) can be addressed effectively: tectonic evolution of plate margins, origin and evolution of oceanic crust, origin and evolution of marine sedimentary sequences, and the various controls on long-term changes in the atmosphere, hydrosphere, cryosphere, biosphere and magnetic field.

1. Tectonic evolution of plate margins: The South Atlantic as defined above contains all of the major classes of plate edges:

    a. translational, e. g. western Africa/northeastern South America continental edges associated with the large-offset equatorial Atlantic fracture zones (Emery et al., 1975a; Mascle and Blarez, 1987), and the north side of the Falkland Plateau/southeast Africa continental margin (Rabinowitz and LaBrecque, 1979; Barker, 1979);

    b. conjugate passive, e. g. east coast of South America/west coast of Africa south of the equator (Rabinowitz and LaBrecque, 1979; Austin and Uchupi, 1982); and

    c. active/convergent, e. g. Scotia Arc (Barker and Dalziel, 1983) and the North Scotia Ridge (Ludwig and Rabinowitz, 1982). The translational margins mentioned above are perhaps the best-developed anywhere in the world, while passive margin structures and continent-ocean crustal transitions should be more consistently accessible to the drill in the South Atlantic than they are in the North Atlantic, where overlying drift sediments are often substantially thicker (compare sediment thickness distributions for the two areas compiled by Emery and Uchupi, 1984).

2. Origin and evolution of oceanic crust: The mid-ocean ridge of the South Atlantic south of the equator is characterized by intermediate spreading rates (Ladd et al., 1973; Pitman et al., 1974). Recent collection of Sea Beam, magnetic and gravity data over portions of this ridge suggests that its structure also represents a transition, exhibiting characteristics of both the faster-spreading East Pacific Rise and the slower-spreading Mid-Atlantic Ridge (MAR) in the North Atlantic (Fox et al., 1985; Macdonald et al., 1985). The South Atlantic may therefore represent an important "middle-ground" in the continuum of tectonic controls governing the

generation and structure of oceanic crust, and knowledge of all aspects of this continuum is essential for a complete understanding of the evolution of oceanic lithosphere. Furthermore, "natural laboratories" have already been established on a slow-spreading mid-ocean ridge in the North Atlantic (MARK area, ODP Legs 106/109) and a faster spreading ridge in the eastern Pacific (Hole 504B, ODP Leg 111). The logical next step is to continue to establish more of these deep windows into oceanic crust, one or more of which could certainly be located in the South Atlantic.

The South Atlantic is also the site of the most widely recognized example of paired aseismic ridges. The Walvis Ridge-Rio Grande Rise system, presently thought to have been generated by a mantle plume underlying the mid-ocean ridge, has been the focus of both geophysical studies (Goslin and Sibuet, 1975; Detrick and Watts, 1979; and others) and drilling transects (Barker, Carlson, and Johnson, et al., 1983; Moore, Rabinowitz, et al., 1984). However, much more needs to be learned concerning its cause/evolution/ composition/structure, and its long-term effects on deep and intermediate circulation in the South Atlantic. A second pair of aseismic ridges, the Meteor/Islas Orcadas rises, exists south of the Agulhas/Falkland fracture zone system. Recent plate tectonic reconstructions suggest that these structural features have at least intermittently controlled the depth of the interbasin connection between the Southern Ocean and South Atlantic (J. LaBrecque, pers. comm.), but their role can only really be elucidated through drilling (an effort which has recently been inaugurated during ODP Leg 114).

3. Origin and evolution of marine sedimentary sequences: The South Atlantic can play a pivotal role in many aspects of this important initiative:

    a. Origin and volume of evaporites: The existence of conjugate diapiric fields composed of evaporites in the South Atlantic has been confirmed by drilling (Bolli, Ryan, et al., 1978) and used successfully in plate tectonic reconstructions of this region (Rabinowitz and LaBrecque, 1979). However, as with other instances of diapirism along passive continental margins, the relationship of the evaporites to underlying and adjacent crustal structure is complicated and still largely unknown (e.g. Hinz, Winterer, et al., 1984; Dauzacker et al., 1985). In addition, the presence of these evaporites has both environmental and geochemical implications which only drilling (following intensive geophysical site surveys) can resolve.

    b. Deep basin stratigraphy/tectonic gateways: Unlike the North Atlantic, the South Atlantic is characterized by four deep but semi-isolated basins: Brazil, Argentina, Cape and Angola. In all likelihood, these basins have experienced unique paleoceanographic and CCD histories during the continuing separation of Africa and South America. Because these basins are silled, the narrow "gateways" between them have played fundamental roles in controlling the intermediate/deep circulation of the South Atlantic and its attendant depositional patterns. While transects of drill-holes across and near such "gateways" have already paid dividends in understanding the interactions between water masses and sedimentation (e.g. Barker, Carlson, Johnson et al., 1983), the basins themselves are very poorly sampled and consequently their sedimentation histories are largely unknown. Complete reference sections must be obtained in each of these basins in order to understand the "compartmentalized" stratigraphic development of the South Atlantic.

c. Deltaic sedimentation: The northern South Atlantic receives the terrigenous detritus from two of the world's great rivers: the Niger and the Amazon. These deltaic systems have been studied for many years (Delteil et al., 1974; Milliman, 1979; and many others), but only the proximal portions have been drilled for potential hydrocarbon resources. Their relationships to underlying crustal structure, and their unparalleled record of the geologic histories of the continental interiors of Africa and South America, await further geophysical surveying and deep-ocean drilling activities.

Other deltaic accumulations in the South Atlantic are also worthy of study, e. g. the Orange River cone off southwestern Africa, which contains a complete record of interior drainage from the southern part of the African continent during the Cretaceous and early Tertiary (Emery et al., 1975b; Dingle, 1980; Austin and Uchupi, 1982).

4. Long-term changes in the earth's atmosphere, hydrosphere, cryosphere, biosphere and magnetic field: The potential for understanding these changes by drilling in the South Atlantic is high. Many important questions remain to be answered, only some of which are summarized here:

   a. Atmosphere: What role do aerosols (e. g. from the Sahara and Namib deserts) play in marine sedimentation? What do the presence of significant quantities of evaporites signify about climatic regimes during the Early Cretaceous opening of the South Atlantic?

   b. Hydrosphere:

      1) What is the history of Antarctic Bottom Water? How did the formation of cold bottom water in the Southern Ocean off Antarctica affect South Atlantic circulation, and how was it related in space and time to the formation of North Atlantic (Arctic-derived) bottom water?

      2) What is the history of lateral migration of the Polar Front? How has it affected sedimentation and circulation patterns in the subantarctic South Atlantic?

      3) What are the geologic histories of the Drake Passage and Vema Channel gateways? When was circum-Antarctic circulation finally established? Once again, how did these events affect South Atlantic circulation?

      4) What is the evolution of the connection between the North and South Atlantic? When was this connection first established? What are the sedimentary facies associated with it, e. g. "black shales", and how are they distributed? How did the widening central Atlantic seaway affect Atlantic-wide circulation patterns in the Cretaceous?

      5) What is the history of surface water masses in the South Atlantic? For example, what is the history of the Benguela Current? How is it related to the development of the Antarctic ice cap and southern hemisphere trade winds? What are the glacial/interglacial variations in its intensity and positioning, and how do these relate to the upwelling phenomena off southwestern Africa that control the deposition of organic-rich sediments and phosphorites there?

c. Cryosphere: What initiated the growth of ice in the Southern Ocean? When did the process begin? How does its timing compare with the growth of ice in the Arctic?

d. Biosphere: How has the "compartmentalized" nature of the South Atlantic affected the development of marine organisms within its component basins? Is each basin's biostratigraphic history unique?

e. Magnetic field: How can an improved understanding of magnetic lineations vs. basement age help unravel the long-term tectonic evolution of the South Atlantic and adjacent Southern Ocean?

WORKSHOP GOALS

1. **To develop suites of drilling objectives in the South Atlantic from global, regional and topical perspectives. The focus of the workshop was on themes, not individual drilling proposals.** Past experience in scientific ocean drilling suggested that 3-5 years were required for adequate completion of geophysical surveying and compilation necessary for integration of drilling results with previous knowledge. Unfortunately, such advance planning was only been rarely accomplished during the Deep Sea Drilling Project (DSDP), and has only recently become an important part of ODP activities. Many participants brought geophysical data to the workshop in order to define important problems for either further geophysical analysis (i. e., regional and site-specific surveys) or drilling. The anticipated advent of riser drilling in the 1990's, an important topic to be discussed at COSOD II, made considerations of pre-drilling site preparation more critical than ever, particularly on continental margins around the South Atlantic.

2. **To broaden the base of scientific expertise on which ODP efforts are based.** The present JOIDES community is concentrated in Europe and North America, and yet both academic and industrial groups in Brazil, Argentina, Chile and the Republic of South Africa actively acquire and interpret geophysical data in the South Atlantic. The workshop attracted knowledgeable marine researchers from nine countries, including Brazil, Argentina and South Africa (see participants list). Their active participation was a prominent reason for the success of the planning effort.

WORKSHOP ORGANIZATION

The three-day workshop began with a plenary session during the morning of the first day at which five general overviews of various aspects of South Atlantic research were presented (see below).

These oral presentations were as follows:

A) S. Cande: "Plate tectonic evolution of the South Atlantic".
B) D. Hayes: "Depth anomalies and tectonic corridors in the South Atlantic".
C) W. Hay: "Sediments and water masses in the South Atlantic".
D) W. Dean: "Geochemistry of black shale: What have we learned from the North Atlantic?".
E) P. Barker: "Results of ODP Leg 113".

Then, the participants split into topical groups for further discussions:

I. evolution of oceanic lithosphere/tectonics
II. biostratigraphy
III. physical stratigraphy/development of the sedimentary record, and
IV. geochemistry.

In the middle of the third day, these groups reconvened to hear summaries of group deliberations (summarized below) and to consider workshop report format and dissemination.

TOPICAL WORKING GROUP REPORTS

I. EVOLUTION OF OCEANIC LITHOSPHERE/TECTONICS

RAPPORTEURS: Kim D. Klitgord, Dale S. Sawyer

MEMBERS:

P. Barker
H. Bergh
S. Cande
I. Dalziel
P. Dauphin
C. Hartnady
D. Hayes
J. Jones
J. Lorenzo
J. Mascle
G. Schuster
P. Shaw
D. Smythe

INTRODUCTION

The deep ocean basins and adjacent margins of the South Atlantic (Fig. I.1.1) provide an environment in which many of the major tectonic objectives of the Ocean Drilling Program (ODP) can be successfully pursued. These objectives include the evolution of continental margins, origin and evolution of oceanic crust, and development of marine sedimentary sequences. In particular, the South Atlantic provides a unique opportunity for studying the lithospheric evolution of a well-defined ocean basin system where many of the important tectonic elements are not overprinted by later events, subducted, or broadly linked to other ocean systems. Equally important, sediments of the older adjacent ocean basins (central Atlantic and southwest Indian Ocean) record the influences of South Atlantic rifting and early sea floor spreading on paleocirculation and paleoenvironment. In order to focus these diverse objectives as they pertain to the South Atlantic, the tectonics working group proposed and developed the following:

I.1 Tectonic segmentation and the evolution of oceanic crust.

I.2 Evolution of conjugate rift margins.

I.3 Evolution of transform-shear margins.

I.4 Tectonic controls on paleoceanographic gateways.

I.5 Evolution of the Scotia Sea: microplate evolution along a transpression plate-boundary system, and

I.6 Absolute plate motions: hot spot evolution and shifting plate boundaries.

I.1. TECTONIC SEGMENTATION AND THE EVOLUTION OF OCEANIC CRUST

BACKGROUND

There is clear evidence that the characteristics of oceanic crust formed by sea floor spreading are variable along the strike of the mid-ocean ridge system These variations appear to be systematic in both space and time, and therefore serve to define a segmentation of the oceanic lithosphere. Segmentation exists with at least three identifiable scales:

1. **The smallest scale, typically <50 km**, corresponds to the probable size of magma chambers. The associated segmentation has been well documented in selected parts of the central Atlantic and eastern Pacific on the basis of variations in "mid-ocean ridge crest bathymetry", magnetic anomaly patterns, SEASAT-derived gravity data and geochemistry (?) (Schouten and others, 1985, 1987; Lonsdale, 1985; Haxby and Weissel, 1986; Langmuir and others, 1986). A similar segmentation postulated for the South Atlantic has recently been documented using Sea Beam (Fox et al., 1985).

2. **The intermediate scale, ranging from perhaps 100 to 300 km in the South Atlantic**, corresponds to the spacing of large, recognizable fracture zones. Many of these fracture zones can be traced across the entire South Atlantic using SEASAT-derived gravity data. These large fracture zones bound broad regions on both flanks of the mid-ocean ridge which often have distinctive morphology and geophysical signatures.

These crustal characteristics may represent the "aged" and transported products of ancient magma chamber imprints which have persisted for >100 m.y. They also may represent the influences of convective flow patterns in the upper mantle on plate accretion. The locations of certain fracture zones may in fact control the locations and along-axis distribution of individual magma chambers or groupings of magma chambers. These corridors may or may not have identifiable geochemical signatures recorded within the uppermost portion of the oceanic crust.

3. **The largest scale of tectonic segmentation is associated with corridors which are roughly 500-1000 km wide.** These corridors appear to be bounded by large morphologic-tectonic features (e. g. the equatorial fracture zone system, Rio Grande Rise-Walvis Ridge, Falkland-Agulhas escarpments). It has been demonstrated that at least 3 or 4 of these corridors exist in the South Atlantic and that they exhibit systematically different subsidence histories (Fig. I.1.1; Hayes, in prep.). The subsidence characteristics within each corridor are consistent with the linear relationships between crustal depth and square root of age predicted by simple, one-dimensional lithospheric cooling models. Differences in the subsidence history of relatively young ocean crust have been documented for several portions of the world mid-ocean ridge system. These subsidence differences have been largely attributed to inferred differences in the temperature (~1000°-1300°C) of the magma at the time the oceanic lithosphere first begins to form at the ridge axis. This is a plausible explanation for the observed differences in most corridors. However, some corridors are known to exhibit dramatic asymmetries in their depth vs. age subsidence characteristics. The corridor roughly bounded by 35°-45°S in the South Atlantic subsides asymmetrically, with oceanic crust on the African plate subsiding much more slowly than crust on the South American plate.

DRILLING OBJECTIVES

Basic objectives of a drilling program to investigate the segmentation of ocean crust would be to calibrate the observed geophysical signatures associated with that segmentation. We must be able to identify both the temporal and spatial character as well as the source of these signatures. This requires both basement rock sampling and complete stratigraphic records in order to understand the crustal subsidence history.

Basement samples are essential for establishing the associations between geophysical-morphologic properties and geochemical-petrologic properties of oceanic crust. These studies would be aimed towards understanding the depth, spatial influence and timing of crustal modification processes which control the various scales of crustal segmentation. In particular,

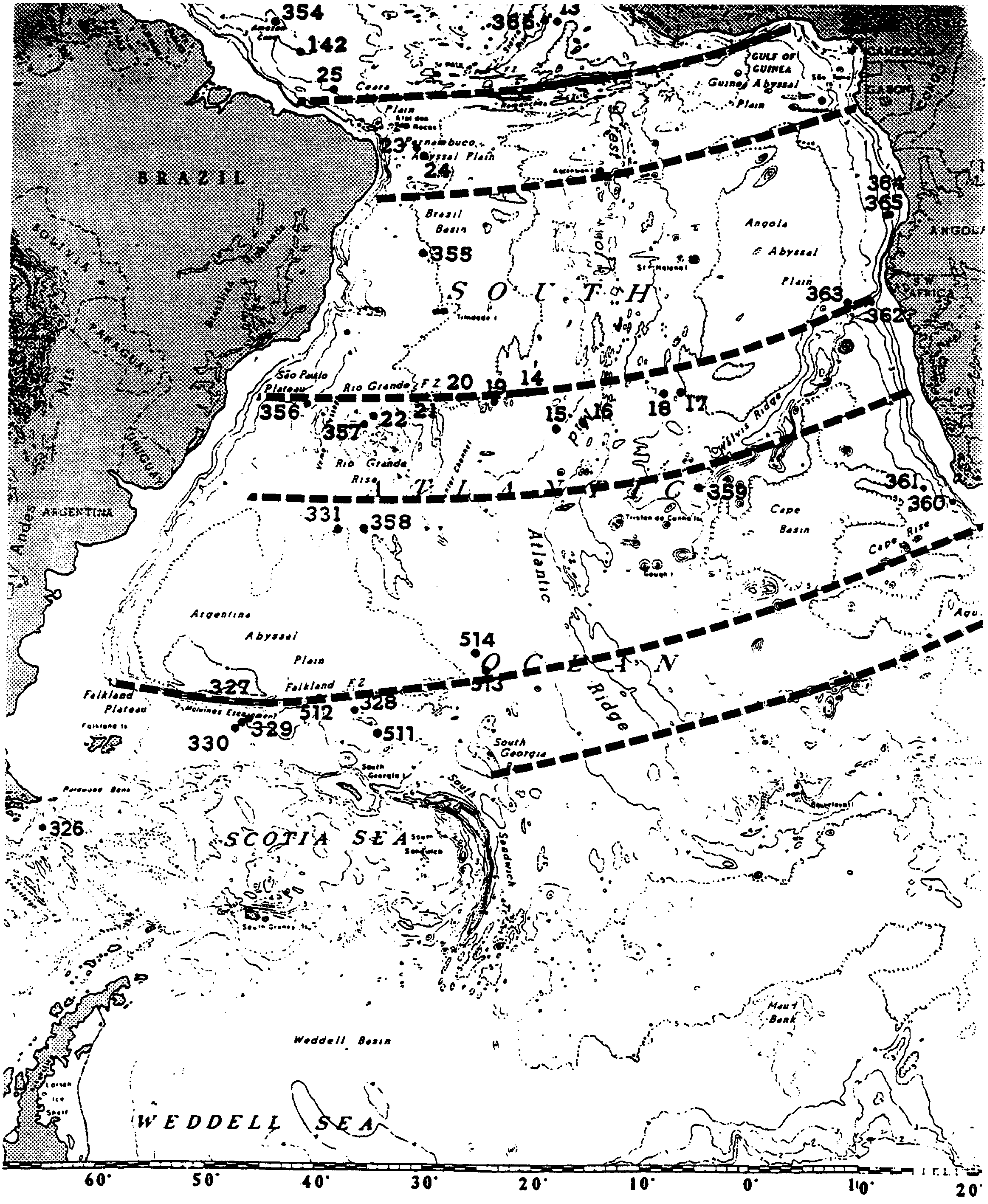

Figure I.1.1. Physiographic map of the South Atlantic displaying major bathymetric features and its segmented character (fro Hayes, in prep.).

attempts should be made to identify crustal changes which occur when large-scale segmentation first develops between adjacent corridors, as well as the crustal differences across the same corridor boundary in very young crust.

DRILLING STRATEGY

The existence of oceanic lithosphere segmentation at several scales is relevant to future ODP drilling targets from two important perspectives:

1. Segmentation gives rise to a somewhat "orderly heterogeneity" of which all planning for drilling should take cognizance. For example, segmentation affects inferences about paleodepths, geochemical partitioning of the oceanic lithosphere, conjugate margin studies, the locus and effect of hot spot trails, etc. Therefore, the segmentation needs to be carefully defined and its potential effects on expected drilling products evaluated before suites of sites are chosen. The definition of the segmentation can probably best be done by a combination of satellite, airborne and marine geophysics coupled with the synthesis of existing geologic data. These data would be complimented by additional focused surface ship and near-bottom surveys where needed. It is clear that drilling is not the tool of choice to define the patterns of segmentation.

2. Once the segmentation has been adequately defined, however, drilling will be required to determine what unique geochemical/petrologic signals (if any) and sedimentation patterns are associated with its various scales. Because the segmentation is apparently manifest as both a space and time (i. e., evolution) phenomenon, it will not be possible to test for persistent geochemical imprints by dredge sampling of young, exposed oceanic crust alone. The drill should not be used to replace the dredge, but where "zero-age" geochemical segmentation can be demonstrated to coincide with known tectonic segmentation, then a series of crustal holes will be needed to establish whether or not individual tectonic corridors are associated with identifiable geochemical differences in the uppermost crust. Furthermore, drill holes will provide the only means of investigating the persistence of hypothetical geochemical signals over very long periods of time (on the order of 100 m.y.).

In order to establish causal relationships, it will be necessary to drill pairs of sites located on older isochrons and on opposite sides of a well-defined tectonic-corridor boundary. Ideally, more than one pair of sites should be drilled in order to investigate the geochemical signatures at more than one "old" isochron. Furthermore, it will be necessary to view each "site" as a cluster of holes, each cluster designed to determine the "average" petrologic characteristics within the corridor at a specific time.

One possible strategy could be to drill the first pair of "sites" on crust about 30-40 m.y. old, and later a second pair of sites on crust 60-70 m.y. old. Each pair of sites would require 40-50 days of on-site drilling operations. The Ascension F.Z., the Bode Verde F.Z. and the St. Helena F.Z. all appear to be potential boundaries to consider investigating adjacent but contrasting tectonic corridor properties. The existing geophysical data define differences that represent the integrated effects through the entire lithosphere, and it remains unknown whether or not such a signal is present or preserved in the "differentiated" uppermost part of the oceanic crust that is most likely to be sampled through drilling.

I.2. EVOLUTION OF CONJUGATE RIFTED MARGINS

BACKGROUND

The rifting of continents and subsequent formation of deep ocean basins by sea floor spreading creates rifted or "Atlantic-type" continental margins. These are active plate margins while rifting deforms continental crust and establishes the crustal modification processes which eventually lead to the formation of oceanic crust. This active margin phase ends as rifting is replaced by sea floor spreading, and resultant rapid separation of the continents carries the now passive continental margins away from the spreading center. Rifting produces a diverse suite of basement and deeper, intracrustal structures. Pre-rift, synrift and postrift sediments deposited over these structures record the structural evolution of the margin and its influences on sediment distribution patterns. However, observed variations in crustal structure and sediment depositional patterns along the strike of many passive margins suggest that individual margin segments must be compared and contrasted to understand their geologic histories in detail. Furthermore, **a need exists to study conjugate margin pairs**, particularly in light of the recent development of rifting models which predict asymmetric structural development of conjugate margins controlled by low-angle crustal detachment surfaces (Wernicke, 1985; Lister et al., 1986; LePichon and Barbier, 1987)

In this latter process, conjugate margins develop as either upper plate or lower plate margins (Lister et al., 1986), each exhibiting different responses to sediment loading, thermal subsidence and earliest oceanic crust formation. The large-scale segmentation patterns discussed above, which are evident on both sides of the South Atlantic (Fig. I.2.1), may be related to this asymmetric development of conjugate margins. Some of the segmentation may also be related to differing ages of transition from rifting to sea floor spreading and the distribution of preexisting structures in the continental crust.

Characteristic sedimentary, basement and deeper crustal structures associated with rifted margins have been studied in the northern and central Atlantic and are also found in the South Atlantic. One important difference, however, is that the drift sediments of the South Atlantic are intermediate in thickness between the very thick (>8 km) sections found along the Atlantic margin of North America and the sediment-starved (<2 km) margins of parts of the eastern North Atlantic. Basement structures include a basement hinge zone found along the seaward edge of continental platforms (Austin and Uchupi, 1982), graben and tilted block structures within and just seaward of the hinge zone, a zone of seaward-dipping seismic reflectors within basement under the oldest sea-floor-spreading magnetic lineations (Mutter, 1985), and, finally, typical oceanic basement. Sedimentary units, which include pre-rift material on tilted (continental crust) blocks, deformed synrift deposits along and just seaward of the hinge zone and late synrift/earliest postrift deposits mildly faulted by postrift thermal subsidence, drape basement and fill topographic lows created by the rifting process. Excellent examples of these structures are displayed on University of Texas at Austin MCS line AM-01 (Fig. I.2.2; Austin and Uchupi, 1982), which crosses the Southwest African margin near Walvis Bay. On this line, the sedimentary surface A-II (mid-Albian) forms the upper bound of early postrift units. Although sediments older than A-II were penetrated at DSDP sites 361 and 530(?) (Bolli, Ryan et al., 1978; Hay, Sibuet et al., 1984), only the uppermost 350 m of this margin section has as yet been sampled. Consequently, the nature of the oldest postrift and synrift deposits is unknown on either side of the South Atlantic. However, the abrupt termination of salt (Aptian?) deposition on the north side of the Walvis Ridge-Sao Paulo Ridge system (Fig. I.2.1) is one of the most distinctive examples of the segmented nature of late synrift/early postrift (?) depositional patterns found anywhere in the Atlantic, and needs to be explored further.

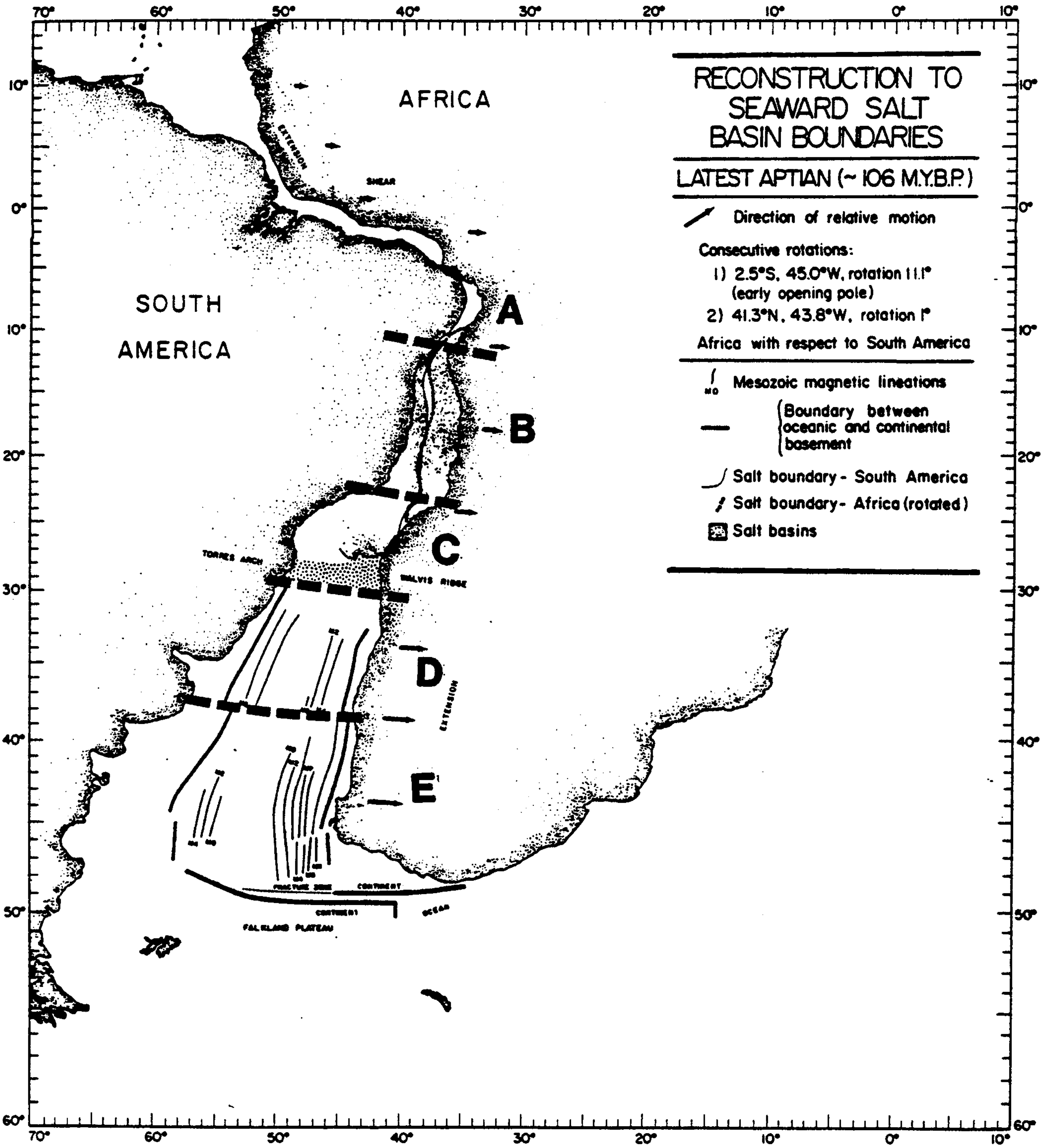

Figure I.2.1. Reconstruction of the continental configuration around the South Atlantic in mid-Cretaceous time (Rabinowitz and LaBrecque, 1979). Segmentation of passive margin structure is indicated.

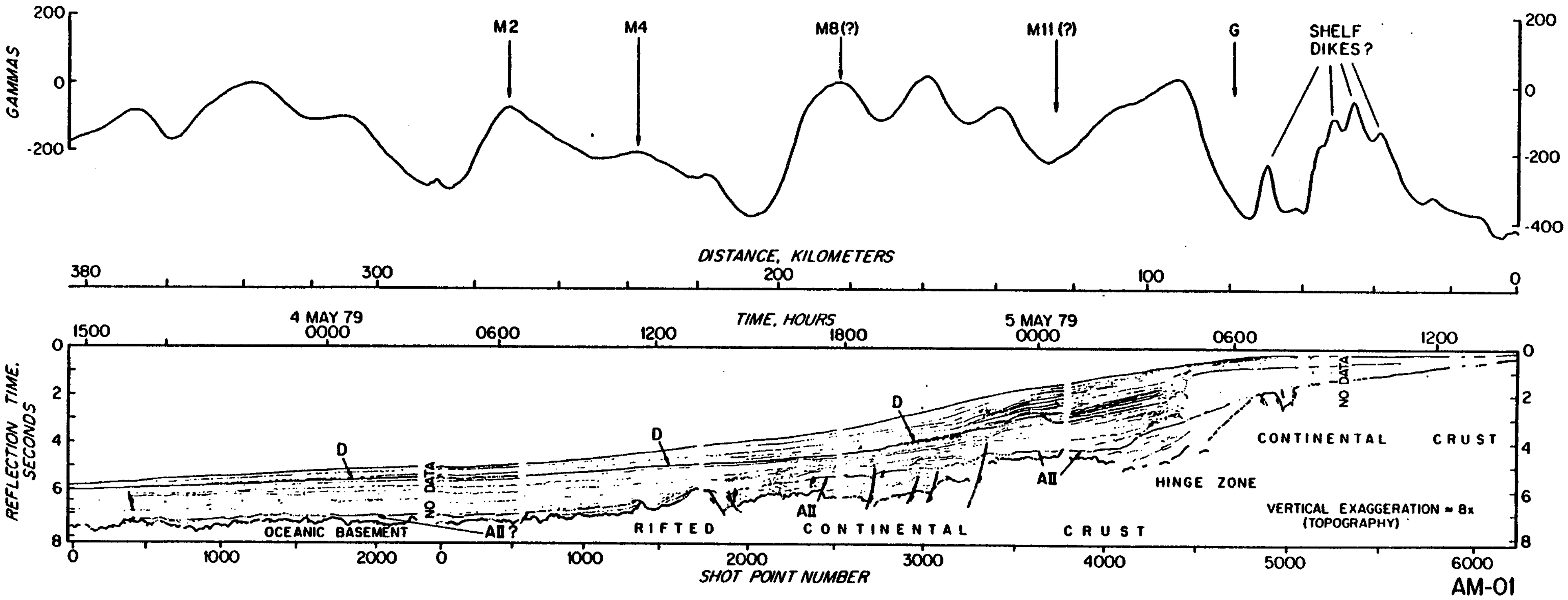

Figure I.2.2. Seismic reflection profile AM-01 acquired by the University of Texas across the Southwest African margin near Walvis Bay (Austin and Uchupi, 1982, Fig. 8).

DRILLING OBJECTIVES AND STRATEGY

The study of conjugate rifted margins in the South Atlantic requires a suite of deep-penetration (>3 km) holes in water depths of 3 to 4 km. Primary goals of these sites will be the sampling of the early postrift, synrift and perhaps pre-rift deposits on at least two conjugate margin pairs (i. e., at least 4 sites). The general geologic objectives are to determine early sedimentation history and the nature of the underlying crystalline basement. An essential tectonic objective will be to ascertain the duration of faulting observed on MCS profiles (Fig. I.2.2). Does it continue into the postrift section and, if so, how much can be attributed to differential subsidence across the margin?

It will also be important to identify the nature of sedimentation and crustal formation near the landward limit of oceanic crust. As on the U.S. Atlantic margin, the landward limit of well-defined oceanic crust can be mapped using seismic reflection data, and Gerrard and Smith (1982) have identified this landward limit as the continent-ocean boundary off Southwest Africa. However, sedimentary (and volcanic?) units partially mask basement farther landward, where clear sea floor spreading lineations indicate that oceanic crust should still exist (Figs. I.2.1 and I.2.2; Rabinowitz and LaBrecque, 1979; Austin and Uchupi, 1982). The nature of basement in this masked zone should be examined in at least one location.

Marginal basins have developed along the South Atlantic margins seaward of the basement hinge zone and landward of a marginal outer basement high (Gerrard and Smith, 1982; Austin and Uchupi, 1982; Fig. I.2.2.). Similar outer basement highs have been proposed to exist along other passive margins, but these highs are clearly imaged on existing seismic reflection data off Southwest Africa and therefore may be possible drilling targets. On the Southwest African margin, these outer basement highs are found near the landward edge of sea floor spreading magnetic lineations (Rabinowitz and LaBrecque, 1979; Austin and Uchupi, 1982), so sampling them may be critical to developing a clearer understanding of crustal evolution at/near ocean-continent boundaries.

I.3. EVOLUTION OF TRANSFORM-SHEAR MARGINS

BACKGROUND

Crustal evolution of shear zone margins has not been investigated with the same intensity as the evolution of rifted margins. Many DSDP/ODP legs have been devoted to studies of passive margins sedimentary records. By comparison, transform margins, which result from early transcurrent motion between continents, are almost unknown. Whereas a rifted margin is likely to evolve rather quickly from an active margin (along a rift zone) to a passive margin (adjacent to a spreading system), a shear margin can remain "active" for a much longer time. Moreover, transform margins contain, as do most areas involved in strike-slip motion, sedimentary basins characterized by: (1.) high rates of sedimentation and subsidence, (2.) high heat flows, and (3.) structural deformation (pull-aparts, shear folds, flower structures, rotated blocks) generated during sedimentation accompanied by continuing transform motion. These characteristics also increase the economic potential of such margins.

An active, sheared margin can exhibit a variety of crustal types. Different phases of crustal modification and sedimentation are associated with each type. For example, transform margins are often areas of very sharp contrast (less than a few km) between thick continental crust and oceanic crust and/or between shallow water sediments (deposited on continental platforms) and deep sea sediments (lying directly upon oceanic crust). A study of modern transform margins may be a key to understanding parts of orogenic belts now characterized by rapid sedimentological and crustal transitions and/or widespread nonconformities, which could indicate consequences of transform motion rather than early convergence or collision events.

The evolution of shear zone margins can be characterized by four main stages, each exhibiting a distinctive type of crustal modification and sedimentation (Fig. I.3.1; Mascle and Blarez, 1987):

1) Shearing between thick sections of continental crust (equivalent to an early rifting stage on passive margins);

2) Shearing between thick sections of continental crust and transitional (i. e., extended, rifted continental) crust (equivalent to a late rifting stage);

3) Shearing between oceanic and continental or transitional crust (equivalent to an early drift stage), and

4) Shearing between oceanic and oceanic crust - a typical transform fault within a spreading center system.

During the first stage, two continental plates are shearing past each other, with brittle deformation in the upper part of the plate and ductile deformation at depth. This is a phase of primarily mechanical deformation, as small, pull-apart basins and rotated blocks/crustal fragments develop in the brittle crust. If brittle failure occurs along low-angle detachment surfaces, then an asymmetric pattern of rift-shear structures develops on the conjugate margins.

During the second stage, the development of a well-defined rift system (with associated igneous activity) juxtaposes transitional crust and thick continental crust. This active rift zone may evolve into a spreading center. Within the shear zone, small pull-apart basins surrounded by land masses are characterized by high rates of terrigenous sedimentation and shear deformation along the basin transform boundaries. Deformation of sedimentary units and influence of the active rift on adjacent continental crust may migrate along the shear zone, thereby allowing calibration of its evolution. As tectonic activity alternates between extension and compression, marginal ridges can develop parallel to the shearing direction. These marginal ridges may be constructed of folded sedimentary units, volcanic buildups and/or deeper magmatic material added by underplating.

The third stage of shear-margin evolution occurs as the spreading center axes migrate past both thick continental crust and pull-apart basins underlain by transitional crust. Thermal and mechanical influences of these spreading centers should create different styles of sediment deformation than that created by simple shearing. Changes in sediment sources and distribution should also indicate a shift from phase two to phase three.

During the fourth stage, the shear-zone margin becomes a passive margin. The active plate boundary is now a typical spreading center-transform fault system seaward of the margin. The margin subsides under the influences of both thermal cooling and sediment loading, as on rifted margins.

A crucial aspect of shear-margin evolution is the variation in age of different styles of tectonic activity. Shear margins are not necessarily a single, long transform fault, but often include several smaller rifts offset by long transform zones. Each of the rift-transform-rift segments will go through the four stages described above, with a timing controlled partially by the length of transform offset. A short-offset segment will pass quickly through the four evolutionary stages, while a large-offset segment will spend a longer time in the second phase.

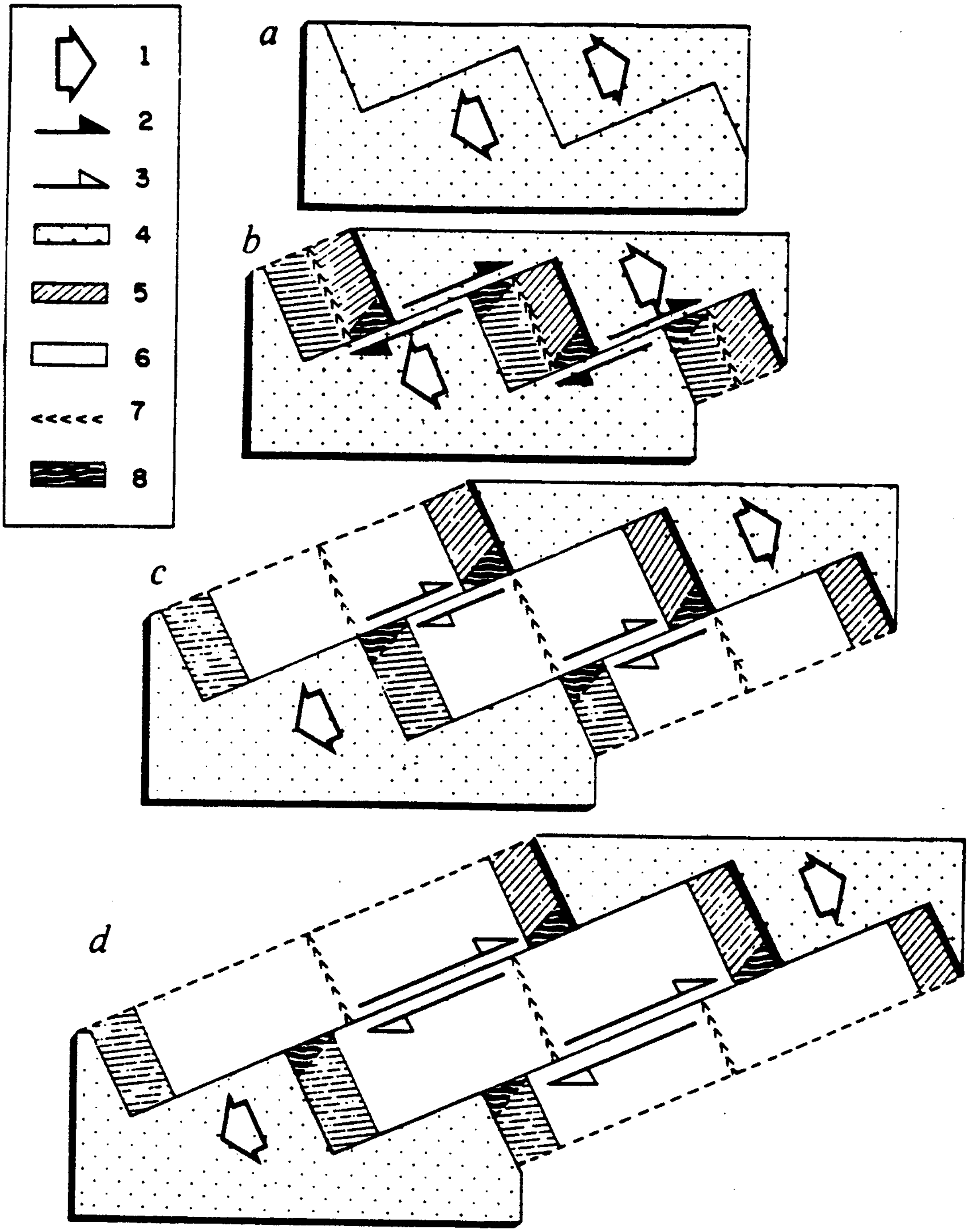

Figure I.3.1. Schematic model for evolution of transform margins (Mascle and Blarez, 1987, Fig. 3).

A simplified model for the evolution of transform margins based on the example of Ivory Coast and Ghana margins (see text for detailed explanation). *a*, Continent to continent active transform contact. *b*, Continent to continental margin (thinned crusts and sedimentary cover) active contact, creation of lateral marginal ridge and associated tectonics by shearing. *c*, Progressive drift of the margin along a hot accretionary centre. Thermal exchange between a continental lithosphere and an oceanic lithosphere leading to vertical readjustments. *d*, Mature stage. Thermal subsidence evolution. 1, Divergence, 2, transform motion between continental crusts; 3, transform motion between oceanic crusts (fracture zones); 4, thick continental crust; 5, thinned continental crust; 6, oceanic crust; 7, mid-oceanic ridge axis; 8, marginal ridge and related tectonics (thinned crustal blocks and deformed sedimentary wedge).

The net result, however, is a repeat in the pattern of deformation ages along the sheared margin, which should be recorded in the sedimentary units adjacent to the shear zone. A succession of sedimentary nonconformities should record perturbations of thermal subsidence by the passing rift-spreading center system.

The South Atlantic contains spectacular examples of transform-shear margins, formed along the northern and southern ends of the South Atlantic rift and spreading center system: the equatorial Atlantic transform margins and the Falkland-Agulhas plateaus (Fig. I.3.2). Conjugate shear margins are preserved off the southern part of West Africa and the northeastern shoulder of South America. However, the Falkland Plateau, which sheared away from the South African margin and the Agulhas Plateau, appears to be least deformed by subsequent tectonic activity. Both shear zones record the early separation of the African and South American plates, and the kinematic response of continental lithosphere to stretching, shearing and migrating thermal anomalies. These shear zones also form the gateways between the South Atlantic and adjacent ocean basins, an important fact examined further below (section I.4).

DRILLING OBJECTIVES

Investigations of the southern and northern sheared margins of the South Atlantic should be based on the study of conjugates. Primary targets for such studies are:

1) Guinea marginal plateau - Demerara Rise (Guinea F.Z.; Fig. I.3.3)
2) Ivory Coast/Ghana marginal ridge - north Brazilian ridge (St. Paul F.Z. to Romanche F.Z.; Fig. I.3.3)
3) Agulhas marginal ridge - Falkland Plateau and marginal ridge (Falkland-Agulhas F.Z. system)

The two pairs of equatorial Atlantic shear margins should provide the basis for comparing two different rift-transform-rift segments (Fig. I.3.4a) of the same shear zone, while the Falkland-Agulhas pair (Fig. I.3.4b) will provide complementary timing and kinematic information from the opposite end of the ocean basin system.

Objectives of drilling are to obtain a detailed chronology of deformation and to identify variations in sediment sources along these margins. Multiple sites would have to be chosen where pre-rift, synrift, and early postrift sedimentary units and underlying basement could be sampled both along and across each margin and on its conjugate. This strategy would help to explain the formation of submerged marginal ridges and plateaus and constrain working models for their development as structural features adjacent to both thick continental crust and oceanic fractures zones. Sediment compositions and ages of sedimentary structures caused by deformation would also provide important constraints on the origin of marginal ridges, their relationship to fracture zone development and tectonic controls on pull-apart basin depositional patterns.

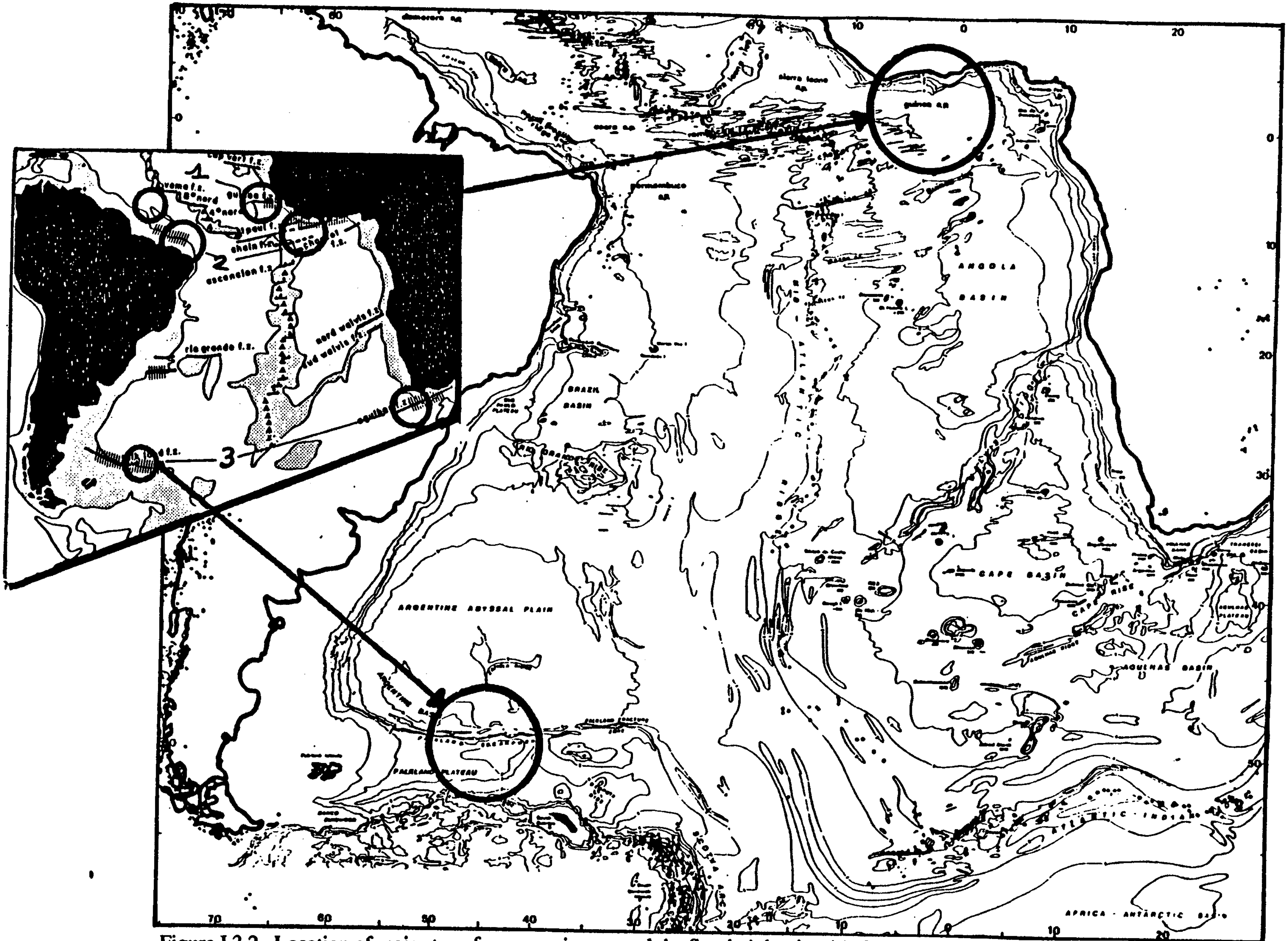

Figure I.3.2. Location of major transform margins around the South Atlantic: 1.) Southern Guinea-Demerara Plateau system: Jurassic rifted margin reactivated by oblique transform margin opening in Cretaceous (see also Fig., I.3.3); 2.) Gulf of Guinea-Northeast Brazil system. The Ivory Coast/Ghana margin

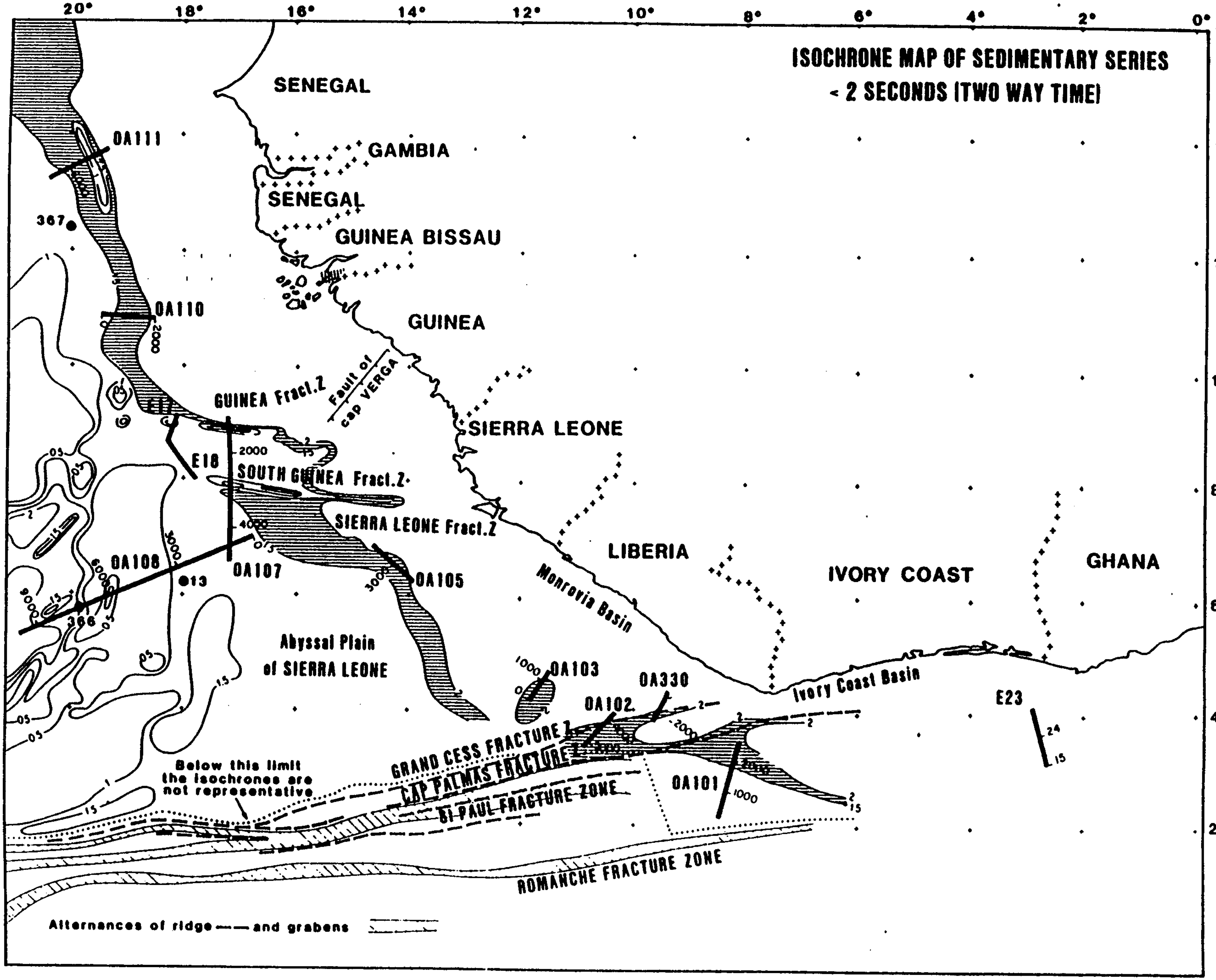

Fig. I.3.3. Isochron map of sediment thicknesses on the transform-shear margin off the southern part of West Africa (courtesy J.-P. Herbin and L. Montadert).

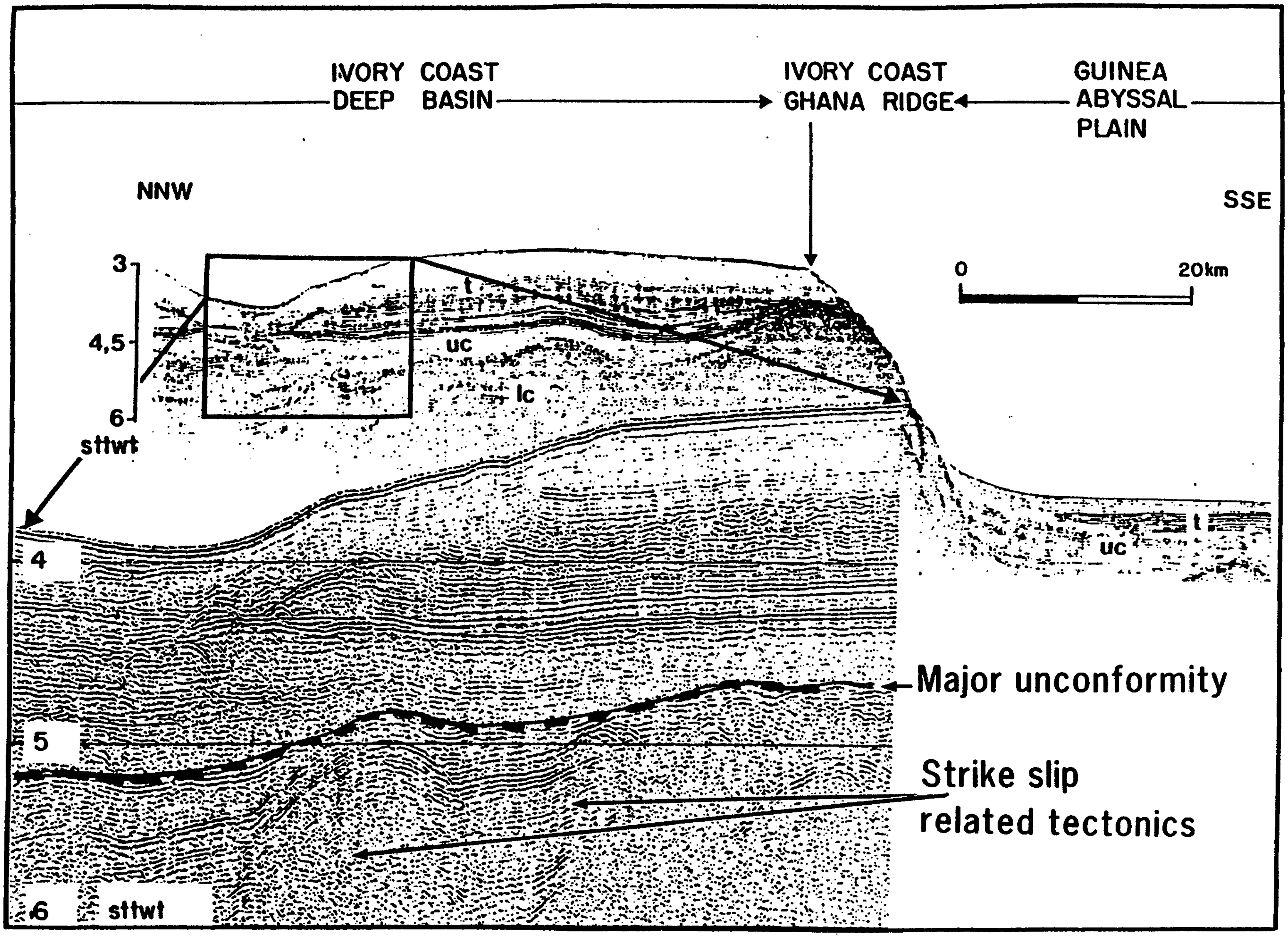

Figure I.3.4. Single channel seismic lines across South Atlantic shear zone margins: a. The Ivory Coast-Ghana continental margin, showing the deep margin basin bounded to the south by the Ivory Coast-Ghana Ridge; b. The Falkland marginal fracture ridge. Both lines show striking similarities, including an eroded marginal ridge damming a thick margin basin with sedimentary units characterized by strike-slip tectonic features (at the base of the sedimentary fill) and prominent acoustic unconformities.

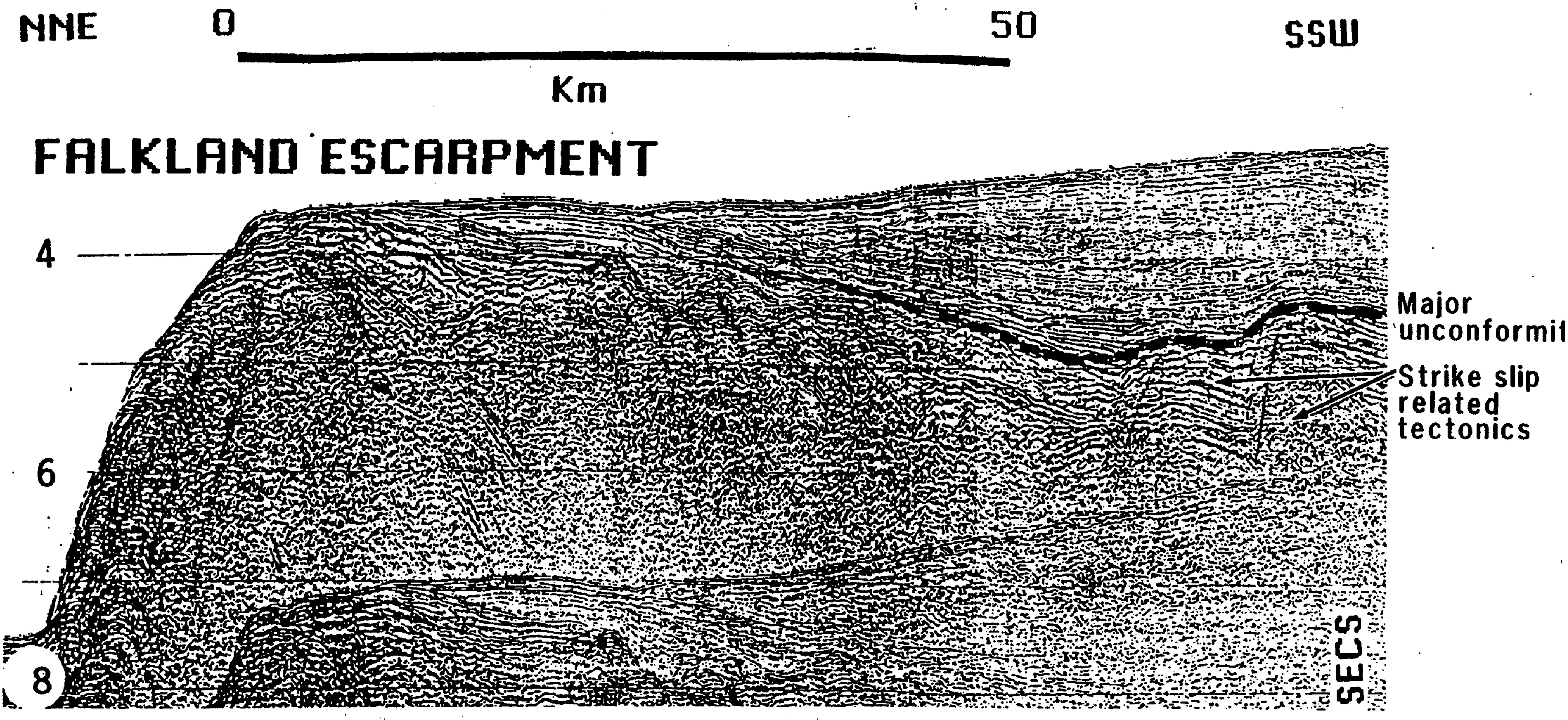

Figure I.3.4. Single channel seismic lines across South Atlantic shear zone margins: a. The Ivory Coast-Ghana continental margin, showing the deep margin basin bounded to the south by the Ivory Coast-Ghana Ridge; b. The Falkland marginal fracture ridge. Both lines show striking similarities, including an eroded marginal ridge damming a thick margin basin with sedimentary units characterized by strike-slip tectonic features (at the base of the sedimentary fill) and prominent acoustic unconformities.

I.4. TECTONIC CONTROLS ON PALEOCEANOGRAPHIC GATEWAYS

BACKGROUND

Changing sea floor morphology, as narrow rifts evolve into major ocean basins, provides a primary control on paleo-circulation, paleo-environment and paleo-deposition patterns. A significant aspect of this changing morphology is the creation, alteration or closure of major seaways (i. e., "gateways") between different ocean basins. Timing, distribution and character of sedimentation during rifting and early postrift phases of basin evolution are constrained not only by plate configurations and motions, but also by the nature of plate boundaries (i. e., "gateways") linking the new basin to other major ocean systems.

The South Atlantic provides one of the best ocean basin systems for examining the formation of gateways because its kinematic history appears comparatively simple and clear sea floor spreading magnetic lineation patterns exist which record that history. Major gateways at both ends of the South Atlantic are long shear-transform zones (section I.3) which opened during the Cretaceous, eventually connecting the young South Atlantic to the older central Atlantic and Indian Ocean basins (Fig. I.4.1). These narrow connections now contain depocenters which record the evolution of these gateways. A third gateway developed between South America and Antarctica during the Tertiary, thereby connecting the South Atlantic with the South Pacific. The evolution of this gateway is closely tied to the island arc systems around the Scotia Sea (section I.5).

DRILLING OBJECTIVES

There are two basic objectives of gateway studies in the South Atlantic. **First, we must understand the overall process of gateway development**, as a transform-shear margin evolves from a continent-continent shear zone to a system of large ocean crust transform faults (see also section I.3). To do this, careful documentation of sedimentation patterns is needed to trace the transition from rifting to sea floor spreading, with the aim of establishing a detailed chronology of paleoceanographic changes as plates slide past each other. **Second, we must attempt to link major changes in paleoceano-graphic conditions in and around these gateway to their causes, e. g. specific postrift tectonic events.** A significant component of the last objective revolves around understanding the evolution of central and South Atlantic triple junctions. Both ends of the South Atlantic spreading system were initially connected by long transform zones to ridge-ridge-ridge triple junctions, then evolved to ridge-transform-transform triple junctions, and presently are linked via one limb to island arc systems. However, as the northern and southern ends of the South Atlantic have broadened, the bathymetric features of these triple junctions have continued to serve as partial barriers to circulation. Consequently, selected drilling sites in the vicinity of gateways should be able to establish the timing and magnitude of variations in paleoceanographic conditions and relate them to changes in tectonic and sedimentation patterns.

I.5. EVOLUTION OF THE SCOTIA SEA: MICROPLATE EVOLUTION ALONG A TRANSPRESSION PLATE BOUNDARY SYSTEM

BACKGROUND

The Scotia Sea (Fig. I.5.1) has evolved over the past 30 to 40 m.y. as a back-arc extensional complication of the South American-Antarctic (SAM-ANT) plate boundary. It is

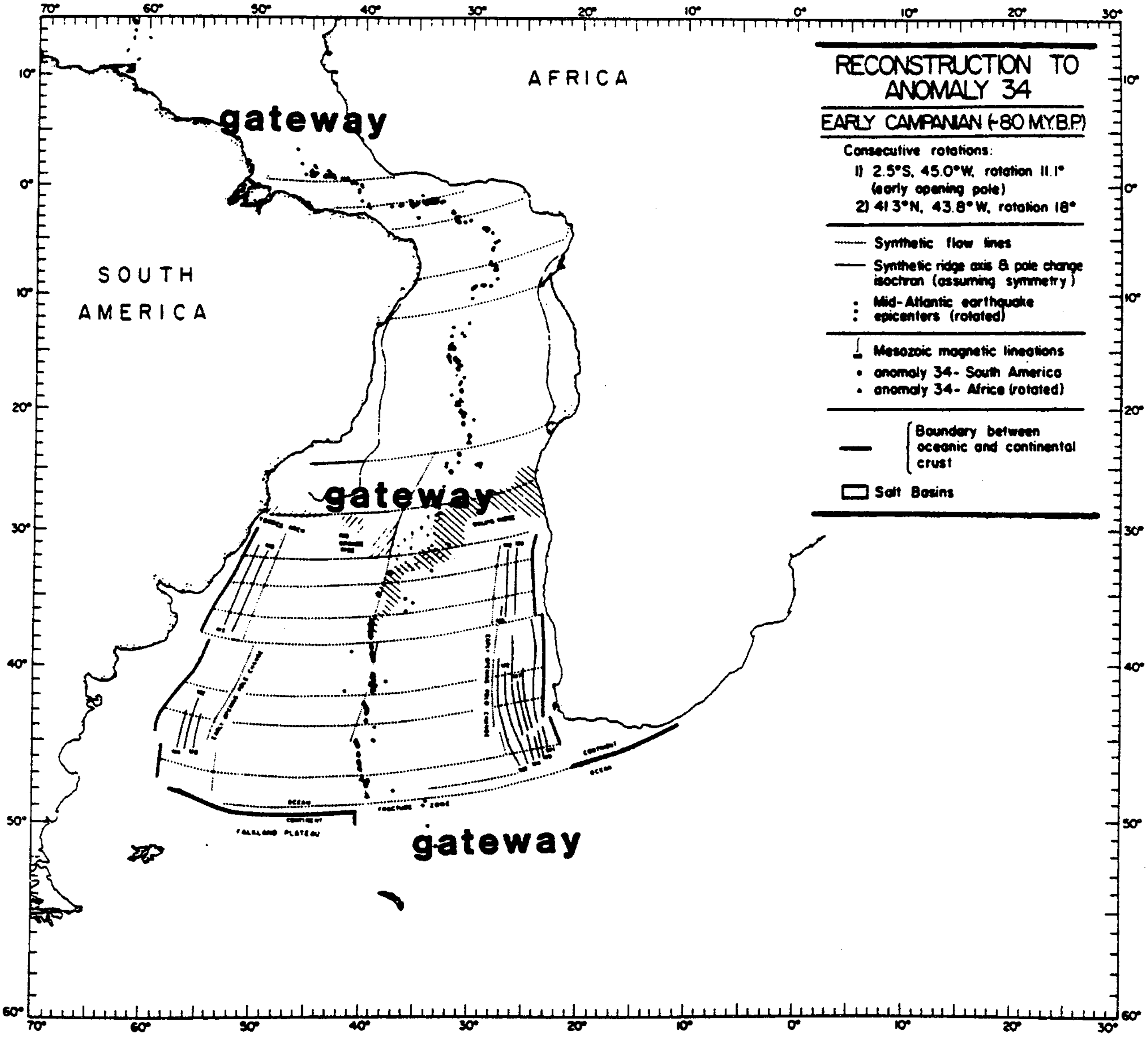

Figure I.4.1. Reconstruction of the continental configuration around the South Atlantic in Late Cretaceous time (Rabinowitz and LaBrecque, 1979). Major gateways into and through the South Atlantic are indicated.

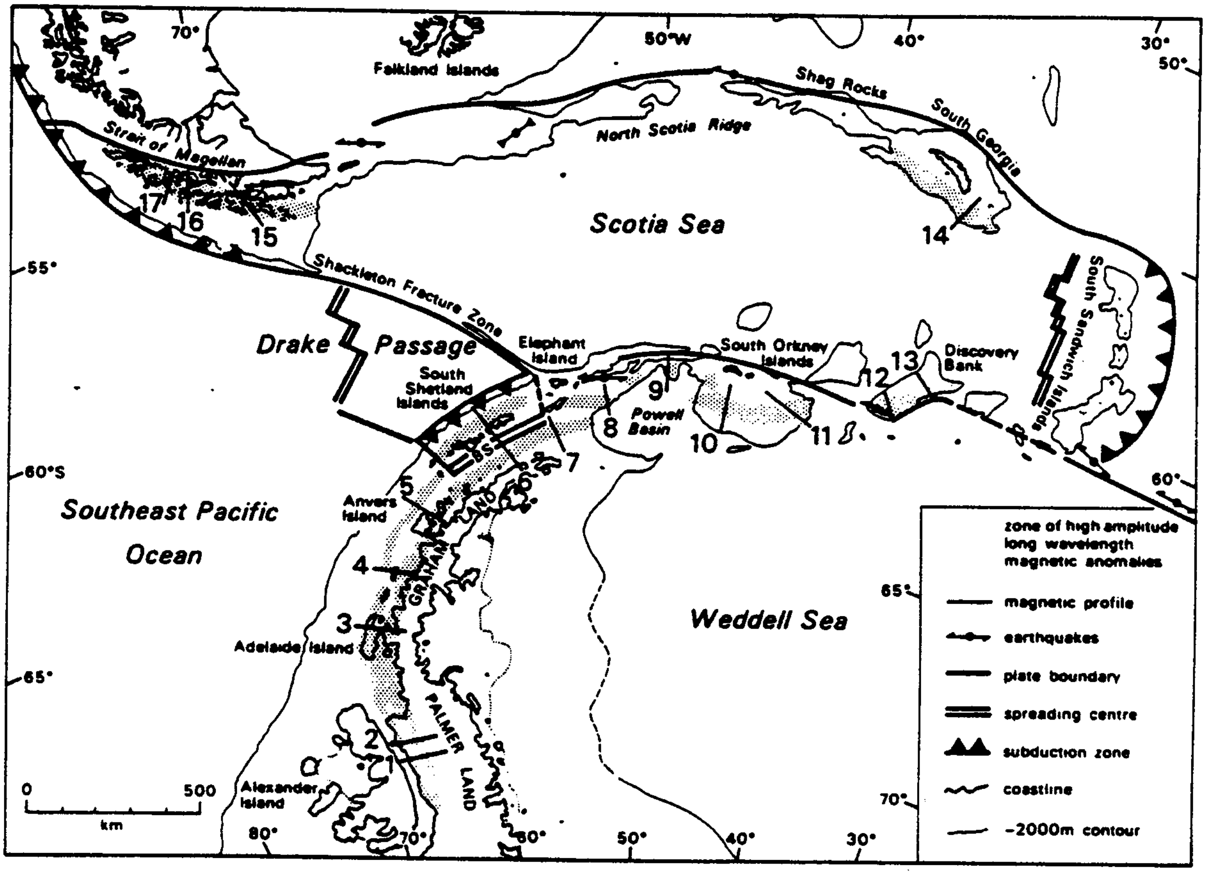

Figure I.5.1. Tectonic setting of the Scotia Sea region (Garrett et al., 1986-87).

bounded on the north and south by shear-zone ridges and on the east by the South Sandwich arc and trench. A detailed understanding of its tectonic evolution would be of great interest both in the investigation of plate boundary interactions and the influence of a broad compressional plate boundary on paleocirculation patterns.

DRILLING OBJECTIVES

1) Ridge Crest-Trench Collisions

Scotia Sea evolution has involved the opening of several short-lived back-arc basins in various directions, often with several basins opening at the same time (Barker et al., 1983). The back-arc opening has been essentially filling the space left by the rapid eastward migration of the South Sandwich arc and trench and other ancestral subduction zones. Subduction (and thus the back-arc extension) has been interrupted by a series of collisions between the trench and spreading ridge sections of the SAM-ANT plate boundary to the east. The trench subducts all available SAM oceanic lithosphere, but appears never to have been able to subduct ANT ocean floor across the ridge crest. Therefore, the South Scotia Ridge is the site of a series of ridge crest-trench collisions in which an abandoned fore-arc is juxtaposed against young oceanic crust created on the ANT plate.

These ridge crest-trench collisions are of considerable interest because they enable examination of the influence of varying thermal regimes on the subduction process. First, it is possible that either overthrusting or subduction has been involved in these collisions. The lower fore-arc typically has disappeared through tectonic erosion, although the closest ocean floor is anomalously shallow and apparently anomalously thick. There are also indications of anomalous, late-stage silicic volcanism. Because of this complexity, it is not easy to select precise drilling targets at present, but **it seems likely that drilling would contribute to understanding the tectonic processes of island arc subduction by documenting the timing and nature of sediment accretion and variations in this accretion as the ridge crest collides with the trench.**

2) Antarctic Circumpolar Current (ACC) Development

Perhaps the most important reason for seeking a detailed understanding of Scotia Sea evolution is concerned with the evolution of the ACC. At present, the ACC axis runs through Drake Passage and across the North Scotia Ridge into the South Atlantic (Fig. I.5.1). The gateway in this region was the last to open, completing the present deep-water circumpolar pattern. About 23 m.y. ago, the western Drake Passage opened (Barker and Burrell, 1977; Barker et al., 1982). At that time, however, there was probably still at least a partial barrier to the east, formed by a more compact arrangement than now exists of continental fragments, island arcs and remnant arcs which now make up the north and south Scotia Ridges (Fig. I.5.1). A complete assessment of the growth of a deep-water pathway requires a knowledge of: (1.) the age of the ocean floor within the Scotia Sea, (2.) the nature and subsidence history of elevated areas, and (c) major plate (SAM-ANT) motions during the Cenozoic. Most of these data are now available, but key uncertainties remain concerning the timing and variations in sediment types which can be resolved by drilling.

3) Bottom Water Flow

Antarctic Bottom Water (particularly the freshly generated Weddell Sea Bottom Water [WSBW]) flows out of the Weddell Sea through deep channels into the South Atlantic (beneath the ACC) and westward to the South Pacific. As is also true for the ACC, the pathways available to WSBW have changed considerably during the course of Scotia Sea evolution. **It will be impossible to extract a history of bottom water production and**

transport from the sedimentary record without some understanding of the tectonic control on gateways in the Scotia Sea region.

DRILLING STRATEGY

There is a range of ways in which drilling might help solve the problems posed above:

1) By sampling all the way to basement at small spreading centers, the paleoceanographic record of circulation and climatic change in the overlying sediments should also be recovered.

2) The vertical movements of basement through time, for example during the course of ridge crest-trench collisions, can be derived indirectly from the stratigraphy preserved along the flanks of erosionally truncated blocks.

3) Evidence for opening of specific gateways can be derived by sampling the sediments directly downstream.

I.6. ABSOLUTE PLATE MOTIONS: HOT SPOT EVOLUTION AND SHIFTING PLATE BOUNDARIES

BACKGROUND

With improvements in marine geophysical data bases and recent developments in satellite remote-sensing techniques, the relative motion history of the major plates around the South Atlantic and adjacent Southern Ocean is becoming well established. The Mesozoic-Cenozoic "absolute" motions of these plates are nevertheless still rather uncertain. Although there is substantial controversy about their number and exact location, numerous intraplate hot spots are found within the African plate. They provide unique opportunities for: (1.) refining global plate kinematic models by means of improved knowledge of African absolute motion, (2) studying the different expressions and effects of mantle plumes on oceanic and adjacent continental lithosphere, and (3) providing important constraints on the compositional heterogeneity and related(?) deep circulation patterns of the mantle.

Current quantitative models of African plate motion are determined mainly by modeling the relationship between a hot spot center at or near the island of Tristan da Cunha and the physiographically prominent Walvis Ridge. Additional constraints are provided by the trend of a seamount chain extending northeastward from the island of St. Helena, and by a correlation between Vema Seamount in the Cape Basin and a 38 m.y. old alkaline volcanic province in the coastal region of Namibia. Prior to about 40 m.y. ago, African absolute motion history depends on the Tristan track combined with information derived from hot spot traces on other plates (e. g. the New England Seamount track on the North American plate, converted into the African reference-frame using relative motion models).

Although heavy reliance is placed on the Tristan hot spot track, experience with kinematic modeling shows that it is not well-located to resolve even substantial changes between successive stages in the absolute motion history of the African plate. Better information could be obtained from the far South Atlantic, where the existence of the Bouvet, Discovery and Meteor hot spots has been postulated. In this region, however, the controversy about the present-day location of these hot spots is particularly acute. There are additional complicating factors involving hot-spot-plate boundary interactions (e. g. transform offset "crossing", ridge-jumps) and possibly changing stability conditions around the Bouvet (Africa-Antarctica-South America) triple junction.

From the perspective of mantle geochemistry and deep convective circulation patterns, this same region is situated across the boundary of the extensive "Dupal anomaly" in the Southern Hemisphere. Because geochemical signatures similar to those found in the Dupal oceanic islands group are seen in the Mesozoic kimberlite provinces of South Africa, a possible direct kinematic link exists between these continental volcanic phenomena and present-day mantle plume sources in the deep ocean basins, with fascinating implications for the origin, size and longevity of major mantle heterogeneities.

From a global geodynamic perspective, knowledge of the "absolute" motions of the African and (by relative motion chaining) the South American plate is also critical to eventual understanding of Andean orogenic processes. It is known that during the Early Cretaceous opening phase of the South Atlantic, the western subducting margin of the South American plate was in an extensional or "neutral" stress state, and a composite back-arc basin extended along 7,500 km of the Andean margin. This composite basin was inverted/collapsed during the first main Andean compression, which coincided with the mid-Cretaceous phase of faster spreading and northward lengthening of the South Atlantic ridge system. It is likely that other changes in the spreading regime in the South Atlantic, as well as changes on the absolute motion of the South American plate, have played a major role in the development of the Andean cordillera. Therefore, refinement of the hot spot reference frame in the South Atlantic offers an opportunity for an improved understanding of cordilleran orogenic processes.

DRILLING OBJECTIVES AND STRATEGY

A series of holes, probably a minimum of 5, is needed east of the southernmost MAR in the Cape and Agulhas basins. Specific targets would include the following:

1) The central part of the newly-proposed "Shona" hot spot, located in an off-axis seamount area west and north of the Bouvet triple junction.
2) The central portion of Shona Ridge on the African plate.
3) The "cusp" region between Meteor Rise and the northeastern seamount extensions of Shona Ridge.
4) The central part of Agulhas Ridge on the northern margin of the (western) Agulhas Basin.
5) The fossil spreading ridge in the Agulhas Basin.

With the exception of the "hotspot center" hole (1.), these holes should be sited such that each penetrates a relatively thin, but nevertheless well-preserved, continuous sedimentary sequence overlying volcanic basement. Ideally, the sedimentary section should provide lithological and paleontological information about the subsidence history of different segments of the aseismic ridge system, and possibly also paleoceanographic data on movements and evolution of the overlying water masses. The sediments immediately above basement should provide information on its maximum age. A substantial penetration of the underlying volcanic basement is also needed in order to sample fresh igneous materials for geochronological, geochemical and paleomagnetic analyses.

Hole 1 will characterize the postulated hot spot center. Holes 2, 3 and 4 will show whether the same geochemical signature(s) are present in the Shona Ridge-Meteor Rise - Agulhas Ridge system and whether there is a definite age progression in a northeasterly direction. Hole 5 will establish the age of extinction of the fossel ridge system in the Agulhas

Basin, and may show that there is a definite correlation with the age of the Meteor Rise - Shona Ridge cusp (determined by Hole 3).

Why is the South Atlantic the best location for this study?

1) The angular distance from the African absolute rotation pole is maximized in this region.
2) The Shona track extends to an economically important (diamondiferous), and hence very well-studied, continental lithospheric expression.
3) Where else?

What new data need to be acquired?

1) Deep-penetration seismic data are needed over segments of the aseismic ridge system.
2) A preliminary dredging program is required near Hole 1 to augment existing on-axis data.
3) Multibeam bathymetric data acquisition may be required around all proposed sites.

II. BIOSTRATIGRAPHY

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INTRODUCTION

Because of the symmetrical distribution of land and sea in the southern hemisphere around South America and South Africa, the South Atlantic is probably the most stable ocean basin with respect to atmospheric circulation. First, the equatorial-desert belt (i. e., tropical Hadley cell) is difficult to perturb. Second, the temperate high and low pressure systems are locked onto the continents and ocean more firmly than anywhere else in the world. In contrast, in the northern hemisphere, Rossley waves extend much further north and south than those of the south hemisphere. Furthermore, the southern oscillation, induced by the special Indian Ocean/Himalayas-Tibet relationship, causes major perturbations in the Indian Ocean-Australia-South Pacific system (El Niño events). Therefore, the South Atlantic is probably the best place to study long-term climate stability.

The biostratigraphy working group summarized its deliberations on the importance of scientific ocean drilling to biostratigraphic problems in the South Atlantic by identifying the following themes:

II.1 Water mass distribution in space and time.

II.2 Climatic history.

II.3 Sea level history and effects.

II.4 Mesozoic black shale paleoceanography.

II.5 Biochronology.

II.6 Stratigraphy in carbonate-poor sediments, and

II.7 Nature of biogeographic change in surface to deep waters.

II.1. WATER MASS DISTRIBUTION IN SPACE AND TIME

INTRODUCTION

The South Atlantic Ocean provides unique topographic constraints on the flow of deep water. Today's deep water in the eastern basins of the South Atlantic originates in the western basins, flows across low latitude fracture zones and resides within the eastern basins for long periods. Therefore, the chemistry of the deep water in the eastern South Atlantic can differ from that of the western South Atlantic because of greater degradation of organic material and mixing from different source regions. These processes cause large chemical gradients between the basins, which are predictable if the end-member deep water compositions are known and the topographic barriers to flow are understood.

The processes of deep-water mixing and changing topographic barriers have affected the chemistry and circulation of the deep water in the South Atlantic throughout it history. Since changes in deep water circulation and chemistry affect global climate, reconstructing the Mesozoic and Cenozoic history of the deep water circulation of the South Atlantic is critical for evaluating the history of earth's climate.

Several general questions important to an understanding of the history of deep water circulation can be answered in well-chosen South Atlantic drilling sites:

1) What are the latitudinal, bathymetric gradients in mixing between northern and southern component deep-water in the western South Atlantic?

2) What changes in deep-water chemistry can be observed between the eastern and the western basins of the South Atlantic? Are the differences a result of mixing between different end-member water masses, or do they result from in situ degradation of organic and inorganic settling particles?

3) When did the ocean's deep water change from warm and saline to colder and less saline? How does that event relate to changes in the earth's climate?

4) Do changes in deep-water circulation and chemistry precede, coincide with or postdate major climatic transitions? Do changes in deep-water chemistry provide a mechanism to cause or amplify earth's climatic changes?

DRILLING OBJECTIVES AND STRATEGY

Synoptic profiles of sediment lithology and benthic faunal chemistry vs. water depth record critical gradients in deep-water chemistry and physical properties. Since these gradients reflect deep-water mixing and circulation processes, the geological profiles provide a means to reconstruct the past history of deep-water flow. **The southern and equatorial portions of the Atlantic Ocean contain five well-sedimented, aseismic rises (Rio Grande Rise, Walvis Ridge, Sierra Leone Rise, Ceara Rise and Maud Rise) which are suitable target areas for sampling transects across a number of water depths. These targets should allow isolation of end-member compositions of the northern and southern deep water masses, identify the mixing gradients between the water masses (both horizontally and vertically) and determine the chemical and physical gradients between the eastern and western basins.** Each target area should be APC/XCB-cored in depth transects that range from at least 2000 m down to 4500-5000 m. Because the chemical and lithologic gradients are not always linear, 6 sites should be cored on each rise, and the maximum bathymetric separation between sites should be 500 m. These sites should be chosen to complement existing sites on the Walvis Ridge, Rio Grande Rise and Sierra Leone Rise.

II.2. CLIMATIC HISTORY

LATITUDINAL THERMAL-GRADIENT CHANGES THROUGH THE CRETACEOUS AND CENOZOIC

The earth's climate underwent marked changes during the mid- and Late Cenozoic as a response to the redistribution of land masses and the buildup of ice sheets at high latitudes. The Atlantic formed a corridor between the northern and southern centers of ice growth, and its entire history is preserved in basin sediments. These sediments provide a sensitive record of the response of surface-ocean circulation to the progressive refrigeration of high latitudes. **In order to reconstruct the detailed history of changes in the South Atlantic's heat budget, it is necessary to generate surface-ocean temperature records for all the climatic bands (tropical, warm subtropical, cool subtropical, temperate, subantarctic and antarctic).**

Important questions to be answered are the following:

1) How did the equator-to-pole thermal gradient change with the isolation of Antarctica, with the buildup of Antarctic ice and with the initiation of northern-hemisphere glaciation?

2) Has the buildup of ice on the globe intensified climatic (e. g. orbitally-forced) cycles?

3) How can we relate the thermal regime of the South Atlantic to changes in atmospheric circulation?

CRETACEOUS PALEOTEMPERATURE

Most of the Cretaceous oxygen isotope paleotemperature analyses have been done using mixed benthic assemblages and diagenetically altered planktonic foraminiferal tests. Except for estimated surface and bottom water temperatures from the Antarctic Peninsula, virtually no Cretaceous data exist for the South Atlantic. **Drilling in continental margin sediments deposited above the CCD in low- to mid-latitude environments offers the greatest potential for recovery of diagenetically unaltered foraminiferal calcite.**

OCEAN CHEMISTRY AND CLIMATE

Changes in Pleistocene climate are accompanied by large changes in atmospheric and ocean chemistry. In particular, ice core analyses of trapped air bubbles show that a large increase in pCO_2 concentration of the atmosphere accompanied the last deglaciation. This change in atmosphere pCO_2 amplified the changes in climate caused by variations in the earth's orbit. In fact, it has been shown that the changes in pCO_2 preceded the changes in climate and may have contributed to the deglaciation. While the effects of changes in the carbon cycle have clearly played a role in Late Quaternary climate, knowledge of its role in pre-Pleistocene climate is severely limited. The relationship of carbon cycle changes and ocean chemistry must be understood in order to decipher the major changes in climate observed during the last 100 m.y.

The pCO_2 concentration of the atmospheric is controlled by the distribution of CO_2 in the ocean because the ocean is the largest reservoir of CO_2, and because exchange of CO_2

between the atmosphere and the ocean is geologically rapid. Temperature determines how much CO_2 can be dissolved in sea water. Within the ocean itself, the distribution of CO_2 is controlled by: 1.) the rate of exchange between the deep ocean and the surface ocean; 2.) the rate of carbonate and organic carbon particulate removal from the euphotic zone at both high and low latitudes; 3.) the rate of carbonate and organic carbon particle degradation in deep water; and 4.) the rate of deep water formation and flow. Therefore, past climates may be linked to past changes in ocean circulation and productivity, and each of these processes is recorded by (or can be reconstructed from) some measurement of deep-sea sediment lithology or chemistry.

Important questions related to ocean chemistry and climate include the following:

1) What is the Mesozoic and Cenozoic history of atmospheric pCO_2?

2) How have global changes in sediment lithology and deposition rate affected the chemistry of the oceans and atmosphere?

3) How did changes in the global carbon cycle affect atmospheric and ocean chemistry? What is the relationship between changes in the carbon cycle and Mesozoic-Cenozoic climate? What variations occurred in the partitioning of carbon between terrestrial and oceanic sources?

DRILLING OBJECTIVES AND STRATEGY

Because the processes which control ocean and atmospheric chemistry are global in nature, a global approach to their study must be followed. South Atlantic sites will be important because sediment budgets for the South Atlantic contribute a significant proportion of the global sediment budget. Furthermore, deep-water circulation plays a significant role in determining ocean chemistry, and the history of deep-water formation is well-recorded in the South Atlantic. **A drilling strategy identifying both depth and latitudinal transects for coring in order to quantify the effects of carbon cycle changes on South Atlantic sediments and deep water chemistry is essential.**

CORRELATION OF CLIMATIC CHANGES BETWEEN LAND AND OCEAN

In order to improve our understanding of the history and causes of climatic change, it is critical to combine climatic records from both the oceans and the continents. Unfortunately, it is notoriously difficult to recover continuous sections from land areas that are amenable to paleoclimatic analysis. The use of marine proxy records of terrigenous input is thus a major tool in understanding climatic change on land. Recent results demonstrate that marine-based records yield valuable information on both cyclical (e. g. Milankovitch) and secular (e. g. Pliocene aridification of northwest Africa) events on land. Furthermore, these results can be directly correlated to events in the oceans by taking samples from the same levels and applying the same stratigraphic frameworks. ODP Leg 108 began this task (Leg 108 Scientific Party, 1986). The following areas should be targeted:

1) Walvis Ridge and northern Cape Basin: Studies of the Walvis Ridge have shown promise in reconstructing climatic change in the Namib/Kalahari region by palynological techniques. Similar records should be obtainable in the northern Cape Basin, and they should also contain windblown, freshwater diatoms and opal phytoliths. Was increased aridity in southwestern Africa linked to the development

of the Benguela Current in the Miocene? Can orbital forcing of the onset of southwestern Africa aridity be detected?

2) Amazon Cone and Ceara Rise: Fluviatile input should provide detailed proxy data on climatic changes in the Amazon Basin, particularly using the lithogenic fraction. For instance, how does the moisture budget of the Amazon Basin respond to climatic cycles in the Plio-Pleistocene (see also section III.3)?

3) Eastern equatorial Atlantic: By coring on the continental margin of the Gulf of Guinea, increased knowledge of eolian input from arid regions of northwest Africa is possible. Drilling either the Niger or Zaire fans shouldyield valuable information on river input under various climatic conditions.

4) Southwestern South Atlantic: Drilling on the continental margin off Uruguay or Argentina will allow a reconstruction of the development of the semi-arid regions of southern South America in response to the uplift of the Andes.

II.3. SEA LEVEL HISTORY AND EFFECTS

INTRODUCTION

The primary goal is to recover a record of eustatic fluctuations by drilling on the South American, African and Antarctic continental margins, along depth transects from shelf, slope and rise settings. It is desirable to evaluate the validity and calibration of the EXXON onlap/offlap curves through acquisition of additional seismic and borehole data. Similar sea level events identified on all of the above continental margins probably represent global eustatic change. Non-similar events may represent overprints generated by tectonic or other continent-specific processes.

RELATIONSHIP TO ANTARCTIC GLACIATION

The mid- to Late Cenozoic eustatic record in Antarctica is complicated by the effects of isostatic ice-loading/unloading events and continental shelf scour. However, sea level changes and glaciation are intimately linked; so separating the eustatic from the isostatic record in Antarctica can be accomplished in part by comparing it with the eustatic history in Africa and South America. Understanding the record of Cenozoic eustatic changes is critical for estimating the magnitude and timing of glacial events, and vice versa. **Future South Atlantic drilling should emphasize the recovery of proxy data, such as the record of ice-rafted debris, climate-induced faunal and floral migrations, bottom water history and deep-sea sediment scour, all of which reflect glacial and climatic conditions in Antarctica and the Southern Ocean.**

Sea level changes can also induce positive feedback-linked advance and retreat of the grounding line/zone of ice sheets which result in the rapid accumulation and removal of ice on Antarctica. The degree to which northern hemisphere glacial fluctuations influence Antarctic ice volume, through the above mechanism, is also still poorly understood.

INFLUENCE OF SEDIMENT STORAGE, EROSION AND TRANSFER: SHELF VS. DEEP SEA

Eustatic conditions influence whether carbonate and siliciclastic sediments accumulate in the deep sea or are stored on the continental shelf, play a major role in the distribution of nutrients, etc. Eustatic fall may result in the rapid transfer of shelf material to the deep sea, submarine canyon and fan development, production of major disconformities (i. e., seismic reflectors), and the transport of shallow water fossil assemblages and sediments to the deep sea. Cross-shelf and slope migration of the oxygen minimum zone, also influenced by changes in sea level, determines where organic matter will accumulate. Therefore, **drilling should occur along depth transects from shelf to abyssal depths in order to sample the various sedimentologic processes acting on the various depositional environments through time.**

TIME SCALES OF EUSTATIC CHANGES

Numerous processes have been proposed to explain changes in relative sea level, including: ice volume, variation in seafloor spreading rates and changes in the shape of the geoid. Because these processes act on different time scales, **drilling strategies should be designed to accommodate studies requiring resolution capable of identifying events in both "Milankovitch-type" and "Vail-type" time scales.**

II.4. MESOZOIC BLACK SHALE PALEOCEANOGRAPHY

Deep-sea drilling has provided much information on the occurrence of "black shales" in the North Atlantic, but questions continue to proliferate on the genesis and paleoenvironments of deposition of these sediments. Information is more limited in the South Atlantic, and is tied primarily to DSDP sites on the Falkland Plateau and in the Cape and Angola basins. The potential exists to establish a detailed north-south transect with added sites in the Sergipe-Alagoas basin of Brazil, the Gulf of Guinea and on the Dronning Maud Land margin of East Antarctica.

Most of the previous work resulting from studies of black shale sequences has been summarized in the report of the JOI/USSAC Workshop on Cretaceous Black Shales (1985). This does not include the recent discovery of Aptian-Albian black shales on the Dronning Maud Land margin during ODP Leg 113 (Leg 113 Scientific Party, 1987). Based on this input, we define the following objectives for future drilling in the South Atlantic:

1) Timing and distribution of black shale deposition:

    a) Establish global and/or regional synchroneity (or lack thereof) among and between basins. To accomplish this, improved biostratigraphic resolution is badly needed, particularly in non-calcareous sequences. A major effort needs to be made to improve the palynomorph and radiolarian biostratigraphy of these deposits.

    b) Paleodepths determined by paleontology need to be established for these deposits in order to determine vertical water-mass stratification and circulation patterns.

2) Relationship between sea floor and water column:

a) Biogenic productivity: Do black shales represent high or low productivity? What is responsible for the productivity and the preservation of organic matter in the sedimentary record?
b) How is preservation affected by the sedimentation rate and geochemistry of the aqueous and sedimentary environments?
c) How does paleoenvironment and diagenesis affect the distribution of fossil organisms in the sediment? How do oxygen-deficient environments affect the distribution of benthic communities, the establishment of periferal isolates, provinciality, the origin of new taxa and the phenomenon of punctuated equilibrium in evolution? How do the expansion and contraction of the oxygen minimum layer through time affect the distribution and extinction of deeper-dwelling planktonic species?

3) Global implications:

a) How did global paleoclimate affect deposition of black shales and their contained biota?
b) What were the effects of temperature and latitudinal gradients?
c) What was the effect of the carbon cycle?
d) What was the effect of pCO_2?
e) What is the global distribution of specific events, such as the Oceanic Anoxic Event (OAE)?

Recommendations:

1) **An integrated team approach is needed,** by which paleontologists, sedimentologists, geochemists, geophysicists, etc. study the same black shale sequences.

2) **A north-south transect of sites from the equator to high southern latitudes should be established.** This transect should include new sites off the Sergipe-Alagoas basin of Brazil, in the Gulf of Guinea and on the Dronning Maud Land margin of East Antarctica.

3) **The sedimentary sequence to be drilled should range from the Upper Jurassic (where feasible e. g. the southern part of the Falkland Plateau) through the Turonian.** Every effort should be made to obtain an uppermost Jurassic through Barremain section for the South Atlantic. Such a section is not presently available.

4) **Comparisons should be made between marine black shale sections and those available on land.**

II.5. BIOCHRONOLOGY

THE PROBLEMS

The formulation of well-constrained models of paleoceanographic processes requires that the rates by which these processes occur can be accurately assessed. Despite the fact that much effort has been made to establish high-quality magnetostratigraphic records form deep-sea sediments, this critical information is still lacking for many parts of the stratigraphic column. Moreover, there is still room for improvement regarding the precise sequencing of (or relative distance between) biostratigraphic species events, both within and between microfossil groups. Provided that adequate magnetostratigraphy becomes established, we can transform the biostratigraphic information into an accurate biochronology. By obtaining good magnetostratigraphic control from a wide latitudinal range, we can address the ubiquitous problem of synchroneity vs. diachroneity of evolutionary events.

DRILLING OBJECTIVES AND STRATEGY

The key to solving the biochronology problem(s) is to obtain continuous magnetostratigraphic records from low, mid- and high latitude environments. The drilling strategy employed by DSDP Leg 73 in the southeastern Atlantic (Hsü, LaBrecque et al., 1984) probably represents the most promising means of achieving this objective. **This strategy is based on the drilling of east-west transects on the MAR, in order to acquire a series of holes on basement of increasing age.** Leg 73 results demonstrated that the best-preserved sediments are obtained at the ridge-crest and during the first ~10 m.y. of subsidence and sediment accumulation. Therefore, by spacing a series of sites ~7-8 m.y. apart, as viewed from the perspective of increasing basement age, a complete stratigraphic section should be obtained by compositing multiple sites along a single transect.

The success of Leg 73 illustrated that the South Atlantic is ideally suited to such an approach. High-resolution studies (e. g. the detection of precessional cycles) based upon future drilling efforts in these sediments are likely to yield excellent magnetostratigraphy. Furthermore, the suggested sampling strategy should result in refined sea floor spreading rates in the South Atlantic and thereby improve age estimates of geomagnetic reversal boundaries there.

II.6. STRATIGRAPHY IN CARBONATE-POOR SEDIMENTS

INTRODUCTION

Many of the past targets for drilling in the South Atlantic have been chosen so as to recover well-preserved carbonate sequences. Although this has made it easier to generate stratigraphic control, it has greatly restricted the areas where holes have been drilled. In order to expand geographic coverage, **it is important to develop stratigraphic and time control in carbonate-poor areas at high latitudes and below the CCD.** Improved bio- and chronostratigraphic control using other fossil groups, especially siliceous microfossils, agglutinated benthic foraminifera, and ichthyoliths is essential to this task.

SILICEOUS MICROFOSSILS

The stratigraphic utility of diatoms, radiolaria and silicoflagellates has been exploited to any real extent only in the Subantarctic and Antarctic regions. Much work remains to be done, primarily in three areas: (1.) filling in gaps in the existing record (e. g. early to middle Eocene, early Paleocene, Cretaceous), (2.) improving biochronological control, for which high-quality paleomagnetic data will be indispensable, and (3.) improving correlations with siliceous assemblages from other regions. This last goal is most critical for diatoms, which show a high degree of endemism in high southern latitudes.

At lower latitudes, siliceous preservation should be very good in certain deep basins of the eastern Atlantic, where carbonate preservation is poor. In particular, the Gulf of Guinea and the northern Angola Basin are deep-water regions exhibiting high siliceous productivity (and hence good preservation of opal in the sediments). An additional priority is a reference site which combines good siliceous and carbonate preservation with a high-resolution paleomagnetic record, either in the Cape Basin or the northern Angola Basin.

AGGLUTINATED BENTHIC FORAMINIFERA

Although a potentially valuable stratigraphic tool, little is known of the temporal and geographic distribution of agglutinated benthic foraminifera in the South Atlantic and adjacent Southern Ocean. The stratigraphic record of these microfossils is best known from high northern latitudes. Results from the North Atlantic show diachroneity in species ranges of agglutinated benthic foraminifera, in terms of both latitude and water depth. Recovery of complete sections by APC/XCB coring in the Antarctic sector of the South Atlantic, and from abyssal plains at lower latitudes, should permit the development of a detailed stratigraphic framework for agglutinated benthic foraminifera for the Late Mesozoic through the present. In addition, it would allow the record of diachronous species ranges to be extended from Arctic to Antarctic waters through the South Atlantic.

ICHTHYOLITHS

Little attention has been paid to the stratigraphic potential of these microfossils. The South Atlantic is a good place to develop ichthyolith stratigraphy further. Because its deep basins receive terrigenous input, sediment disturbances do not appear to be extensive and older oceanic crust is not subducted. Therefore, South Atlantic basins promise longer records and higher sedimentation rates than deep Pacific basins, factors which should allow improvement of the temporal resolution of ichthyolith datums.

II.7. NATURE OF BIOGEOGRAPHIC CHANGE IN SURFACE TO DEEP WATERS

THE PROBLEM

The South Atlantic's spreading history and complex ocean bottom physiography have directed a unique pattern of biotic migration and speciation since its initial opening. East-west trending sills acted as biogeographic barriers to faunal distribution until sufficient spreading and subsidence permitted surface and deep water communication among neighboring basins. Also peculiar to South Atlantic evolution has been the juxtaposition of a salt basin and an anoxic basin. These have preserved separate records of biotic adaptations to restricted environments and the gradual change to normal marine, open-water sedimentation. Basin isolation resulted in northwardly restricted marine faunas and provincialism until marine communication routes were established. Biotic "injection events" (Berggren and Hollister, 1977) followed the progressive opening of new basins to the north. Communication between the North and South Atlantic occurred as early as the late Albian, but gateways for bottom water circulation in the southern South Atlantic were probably not available at least until the Santonian.

A test for the high latitude origin of deep sea faunas can be made in the South Atlantic by using continuous core recovery techniques combined with high resolution biostratigraphy. A number of benthic species of foraminifera, asteroids, bivalves, gastropods, crinoids and decapods are thought to have migrated from Late Mesozoic/Early Cenozoic temperate shelf seas of the polar regions to deep ocean environments as high latitude cooling progressed. However, spatial and temporal gaps have hitherto prevented an accurate assessment of this high latitude heterochroneity theory.

The biogeographic record of South Atlantic plankton from the Late Mesozoic through the Cenozoic is characterized by increasing provincialism. This is the result of:

1) Segregation of silled basins until at least the Cenomanian.

2) Development of at least two surface gyres as the South Atlantic widened.

3) Intensification of latitudinal thermal gradients as a result of climatic cooling, and

4) Establishment of new routes for oceanic circulation (e. g. circum-Antarctic currents).

Among the planktonic biota, a northward increase in provincialism occurred as early as the Aptian. Latitudinally-controlled endemism progressed with high latitude cooling through the remainder of the Cretaceous and was particularly prevalent after the Eocene. However, the positions of biogeographic boundaries and their temporal variation remain poorly constrained. **Stratigraphic recovery of provincial boundaries will aid in tying high-and low-latitude zonal schemes and may provide greater insight to mechanisms controlling South Atlantic surface circulation.**

From a global perspective, the need for biogeographic and paleoclimatic information from the high latitudes of the South Atlantic is becoming more acute as complimentary studies progress in the boreal provinces of the northern hemisphere (primarily in the British, Scandinavian, north German and Russian regions). Current work there is focusing on biogeographic studies of microfossils, floras and invertebrates of the Upper Jurassic-Lower Cretaceous. However, comparable paleoenvironments from the South Atlantic, particularly south of the Falkland Plateau, are poorly known.

Critical to gaining a perspective on the biogeographic and paleoceanographic problems is drilling between 30 and 40°S, a continuous marine proxy record for Antarctica, and the filling of major gaps in the stratigraphic record. These gaps include the following:

1) Biostratigraphic:

   a) Uppermost Jurassic through Hauterivian: There is no known marine record of this age from the deep ocean basins as a result of a major hiatus associated with the opening of the South Atlantic. The most likely place to recover this section is from the Dronning Maud Land margin of Antarctica, provided that this area was sufficiently far removed from the South Atlantic proper during this time. Another target might be the basinal province of the Falkland Plateau.

   b) Upper Cenomanian to lower Turonian: This section is either missing or non-fossiliferous on the Falkland Plateau and at other existing South Atlantic sites.

2) Geographic:

   a) The upwelling system off southwestern Africa, dominated by the Benguela Current, is one of the most productive in the world. This regime is thought to have originated in the Miocene, possibly associated with increasing aridity in the Namib/Kalahari region of Africa. No oceanic cores from this region span that entire interval of time. **A north-south transect from Walvis Ridge into the northern Cape Basin will allow us to monitor the intensity and latitudinal variability of flow in the Benguela Current.** Coring in this region will also permit a search for Milankovitch or other periodicities in eastern-boundary current flow (see also III.4).

b) **There are virtually nor DSDP/ODP drillholes on the continental margins of the South Atlantic.**

c) **No DSDP/ODP sites exist between 30 and 40°S latitude.** Ridge-flank drilling is required to fill this gap for the Neogene record, but continental margin drilling is needed to recover the older Cenozoic and Mesozoic record.

3) Paleoclimatic: the timing and initiation of ice rafting during the mid- Cenozoic has not been established from Antarctic drilling. Sites (some of which have already been proposed) off the East Antarctic margin might fill this gap.

DRILLING STRATEGY

1) Continuous core recovery from closely-spaced latitudinal and depth transects on high- and mid-latitude plateaus, and the MAR.

2) Continental margin drilling in latitudinal belts and in stratigraphic intervals which have not been drilled (see above for specific examples).

3) High-resolution chronostratigraphy of closely-spaced core samples from double-HPC/APC-cored sequences.

III. PHYSICAL STRATIGRAPHY/DEVELOPMENT OF THE SEDIMENTARY RECORD

RAPPORTEUR: James A. Austin, Jr. (also acted as workshop convenor)

MEMBERS:
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INTRODUCTION

The physical stratigraphy working group summarized its discussions concerning the evolution of the sedimentary record in the South Atlantic by identifying five major themes:

III.1 Gateways.

III.2 History of deep circulation.

III.3 Fan growth and evolution as keys to equatorial climate and continental denudation.

III.4 Coastal upwelling and the history of shallow circulation.

III.5 Definition of eustatic sea level changes.

Once these themes had been developed, the group went on to consider where they could be addressed optimally by drilling and what drilling strategies were necessary for each target area or areas.

III.1. GATEWAYS (summary by F. McCoy, with H. Buser, A. Castro, J. P. Herbin, R. Kowsmann and C. Urien)

INTRODUCTION

The South Atlantic is an ideal place to study the role of gateways in controlling oceanic circulation and sedimentation for the following reasons:

1) **It has always been a north-south oriented ocean with a pole-to-equator, thermally-driven circulation and minimal Tethyan interaction** except for limited shallow-water and bioplanktonic exchanges via the Benue Trough in the late Cenomanian, Turonian and Maastrichtian-early Paleocene.

2) **It has the simplest paleophysiography to reconstruct in a plate tectonic setting**: conjugate passive margins that appear to have changed little since initial rifting and are uncomplicated by subduction (except in the far south), a well-defined medial ridge without drastic ridge jumps and overlapping spreading centers (except in the vicinity of the Rio Grande Rise-Walvis Ridge system) and four distinct basins, each with a unique geophysical and geological history.

3) **Modern analogs exist for almost every step of its paleophysiographic evolution,** from early rifting and pull-apart of salt margins (e. g. modern Red Sea) to episodic anoxia and drastic circulation changes (e. g. late Quaternary-Pleistocene eastern Mediterranean). Therefore, the South Atlantic becomes a model for interpretations of both past conditions in other ocean basins and modern conditions in existing basins.

4) **The stratigraphy contained in its deep basins (particularly north of the São Paulo Plateau/Rio Grande Rise-Walvis Ridge barrier) is a well-preserved record of the ocean's early, shallow-water sedimentation history.** Using this record, direct stratigraphic ties (using nonconformities, distinctive lithologies such as salts and sapropels, and major fossil groups such as ammonites) can be made to adjoining ocean basins.

Examples of major gateways in the South Atlantic can be arranged chronologically according to their time of opening and/or operation, as follows:

1) Early Cretaceous: Southernmost opening and ventilation of the Cape Basin to deep-water circulation from the Southern Ocean. This is best approached as a circulation problem and probably best recorded by sediments deposited along the southern Africa margin.

2) Early/mid-Cretaceous: São Paulo Plateau/Rio Grande Rise-Walvis Ridge barrier and its influence on surface circulation into the Brazil-Angola basins, deposition of salts and sapropels, etc. This is best approached as a circulation and geochemistry problem.

3) Mid-Cretaceous: Northerly connections to other oceans, first to the North Atlantic, with shallow-water exchange via a sheared margin passage in the late Albian; second to the Tethys, with shallow-water exchange via the Benue Trough in the late Cenomanian, Turonian and Maastrichtian-early Paleocene; and finally to the North Atlantic, with deep-water exchange via the sheared margin passage upon the complete separation of Africa and South America.

4) Mid-/Late Tertiary: Deep-water circulation into and through the South Atlantic basins, and then up into the North Atlantic as a result of physiographic changes (e. g. development of the Hunter Channel, Vema Channel, breaches in the Walvis Ridge) in response to sea floor spreading, and as a result of polar cooling and climatic change producing a thermohaline circulation system with distinct bottom water. This is best approached as a circulation problem.

THE NORTHERN GATEWAY: DRILLING IN THE EQUATORIAL ATLANTIC

INTRODUCTION

A major focus for the study of gateways must be on the North-South Atlantic connection in the mid-Cretaceous. While the other major gateways (see below) are certainly important, and studying any of them will contribute to aspects of South Atlantic history, they are better approached/discussed/emphasized as problems in deep circulation, geochemistry and/or the study of sea level changes. The general aim of the study of the "northern gateway" is to explore the largely unknown area of transition between the North and South Atlantic oceans in order to determine the way in which the modern Atlantic Ocean evolved from more restricted northern and southern seas during the Mesozoic. Little is known about the nature of the relationship between these two seas and the birth of the Atlantic Ocean. Nearly 24° of latitude separate Site 367 (abyssal plain off Gambia; Lancelot, Seibold et al., 1977) from Site 364 (Angola Basin; Bolli, Ryan et al., 1978). Furthermore, only Site 144 on the Demerara Rise yielded any Cretaceous paleoenvironmental data, and there core recovery was very poor (less than 8%; Hayes, Pimm et al., 1972).

SCIENTIFIC OBJECTIVES

In the Mesozoic section, the main scientific targets are:

1) to discover the nature and age of the first sediments deposited on oceanic crust as well as the age of the crust itself, and to reconstruct the initial position of the continents;

2) to study the formation of sedimentary facies during the opening phase, particularly the so-called "black shales", which were deposited in the North and South Atlantic up to the Turonian-early Coniacian (Sites 364-367); and

3) to understand the relationship between volcanism, sedimentation and tectonic events during the evolution of the equatorial fracture zones.

The recovery of Cenozoic sediments would permit study of the the following important problems:

1) the evolution of Eocene and Oligocene hiatuses, particularly in regard to eustatic sea level fluctuations;

2) the history of deep-water circulation, e. g. the beginning of Antarctic Bottom Water (AABW) flow near the Eocene-Oligocene boundary; and

3) climatic evolution. Cenozoic glaciation began during mid-late Eocene times and is strongly recorded in the high latitudes, but seems less extensive in the tropical zones. Drilling in the equatorial zone would clarify whether polar glaciation led to sympathetic changes in continental humidity and runoff rates.

The problem of the formation and extent of deep-sea nonconformities is also addressable as part of a comprehensive study of the "northern gateway". Both deep-sea and marginal basin sections in this region have numerous, presumably correlative, nonconformities during the mid-Cretaceous, the time of North and South Atlantic connection. Presuming a causal relationship, the opening of the northern gateway presents a constrained situation for: 1) creating such an nonconformity (i. e., vigorous bottom-current flow); 2) tracking its areal extent (only in the north?, or south?, are pull-apart basins affected?, are marginal basins also influenced?); and 3) finding and sampling the materials eroded and transported as the connection between the two major basins evolved.

DRILLING OBJECTIVES AND STRATEGY

An optimum drilling strategy for the equatorial Atlantic would be, **ideally, a transect of (at least) 3 holes, one just north and one just south of the large-offset equatorial fracture zone region, and a third somewhere in the zone of translation.** At least two sites are necessary along the African margin in order to study the north-south evolution of the margins off Sierra Leore and Liberia (Fig. I.3.3; see below). A third one, on the Demerara Rise off the South American margin, would allow a complementary study of east-west evolution. **Minimum: 2 holes, one just south of the Guinea F.Z. (Fig. I.3.3) and another just south of the Chain F.Z.,** thereby providing:

1) North- and south-gateway stratigraphic sections in pelagic settings for comparative stratigraphic studies.

2) Minimal complexities related to tectonic factors at the sheared margins, such as slumps, faults, exotic blocks, etc.

As a result of technological limitations of the *JOIDES Resolution*, the proposed sites must be restricted at present to sedimentary sequences of less than 1,500 m depth (i. e., about 1 sec reflection time on available seismic profiles; see Fig. I.3.4a).

The site located south of the Guinea F.Z. in the eastern equatorial Atlantic sits on a distinct boundary between an area to the north comprising a Jurassic salt and carbonate succession (belonging to the North Atlantic) and an area to the south where coeval and younger sediments are mainly detrital. Available reconstructions show that: 1.) initial opening in this area is late Neocomian in age, 2.) the oceanic basin becomes "wide" (i. e., unrestricted) after the Coniacian, which corresponds to the upward disappearance of "black shales" rich in marine organic matter at Site 367 (Lancelot, Seibold et al., 1977). These black shales, characteristic deposits of anoxic environments, persist at least to the early Coniacian in both the North and South Atlantic (Sites 367 vs. 364/530).

Further support for additional drill sites in the eastern equatorial Atlantic comes from the need to correlate ongoing land studies in West Africa with the coeval marine record. From Angola to Senegal, and inland to the Benue-Chad-Niger region, two paleostructural elements, the Northern Nigerian Anticlinorium and the Enugu-Air paleoculmination, have influenced both sedimentation and faunal development during four successive transgression-regression cycles (Aptian-Albian; Cenomanian-Turonian; Senonian/Maastrichtian-Danian; Tertiary) (Buser, 1966). Four faunal provinces can be distinguished and direct control of sedimentation by paleostructures is documented. A shift of marine influence from east to west along the Enugu-Air Paleoculmination is also recorded:

1) Aptian-Albian transgressions occur only on the east side of the Enugu-Air Paleoculmination, from the north (Mediterranean province) into Chad and from the south (Atlantic province) into the Benue area. At this time, no transgression and interchange occurs across the Northern Nigerian Anticlinorium.

2) During the Cenomanian-Turonian, marine influences still predominate in the two provinces east of the Enugu-Air Paleoculmination, but small transgressions are also beginning to occur farther west.

3) Senonian/Maastrichtian-Danian regressions occur in the two eastern provinces, while transgressions occur in the west.

4) During the rest of the Tertiary, transgressions occur only along the west side of the Enugu-Air Culmination. There is no discernible evidence for marine exchange across the Northern Nigerian Anticlinorium.

In order to have equivalent data on the South American margin, particularly as regards black shale deposition, a site on the Demerara Rise is a logical complement to the conjugate margin sites off Sierra Leone-Liberia. Another possibility is a site in the Pernambuco Basin off Brazil, and another along its conjugate off Nigeria. The continent/ocean boundary off Pernambuco is abrupt and lies at the foot of a steep continental slope at water depths of approximately 3 km. This boundary is covered by sediments approximately 1,700 m thick, consisting of slump deposits near the base of the slope but becoming acoustically well-stratified a few km farther offshore. Unlike other shelf areas along the South Atlantic, the adjacent continental shelf provides no clue as to when drift onset occurred. This shelf has apparently undergone little crustal extension, and has received only a thin veneer of sediment since the Santonian. Faunal evidence from adjacent Brazilian basins and long-distance correlations using the available DSDP results suggest, however, that an oceanographic link between the North and South Atlantic was already well-established by mid-Albian time. In the Pernambuco area, Albian sediments have been recovered only by dredging the Pernambuco Plateau adjacent to the shelf. The Albian Sea may have been very shallow, since only platform carbonates of this age have been sampled to date.

SITE SURVEYS

Although single-channel seismic lines fanning out from Recife, Brazil are available from LDGO, and other seismic information has been collected by both France (e. g. Mascle and Blarez, 1987), Brazil (i.e., PETROBRAS®) and the United States (e. g. Emery et al., 1975), all of the sites proposed will require additional regional and site-specific geophysical investigations.

THE SOUTHERN GATEWAY: DRILLING BETWEEN THE SãO PAULO PLATEAU AND THE WALVIS RIDGE

INTRODUCTION

The gateway between the São Paulo Plateau and the Walvis Ridge is also important to the evolution of the South Atlantic. During the Aptian, this gateway effectively separated a restricted-circulation salt province to the north from an open ocean basin to the south, and continued to influence South Atlantic sedimentation throughout the Cretaceous and well into the Cenozoic. However, despite drilling operations in the vicinity of Walvis Ridge during DSDP Legs 73 and 74 (Hsü, LaBrecque et al., 1984; Rabinowitz, Moore et al., et al., 1984), little information exists concerning the progression of the early South Atlantic seaway between this barrier and the equatorial barrier further north. Sites located between these latitudes have been invariably located seaward of anomaly 34, and thus have missed the early sedimentation history along the circulation pathway.

DRILLING OBJECTIVES AND STRATEGY

New geophysical and drilling investigations should be concentrated as near as possible to the oldest oceanic crust just seaward of the salt scarps mapped in the Brazil and Angola basins (Fig. I. 2.1). At present, the best-surveyed area adjacent to the salt edge lies along the Brasilian margin between 21° and 22°30'S, where abundant multichannel seismic coverage from PETROBRAS® is available. Unfortunately, the total sediment thickness (~4 km) makes this well-documented area presently inaccessible to deep drilling operations by ODP.

SITE SURVEYS

In order to identify suitable drilling targets characterized by thinner sediment cover over old (oldest) oceanic crust, other areas along the strike of the salt scarp(s), and perhaps slightly seaward, should be investigated seismically.

III.2. HISTORY OF DEEP CIRCULATION (summary by B. Tucholke, with M. Ledbetter and A. Shor)

NONCONFORMITIES: THE PROBLEM

What is the timing/nature of Tertiary "regional" nonconformities? How are they related to climatic/sea level fluctuations? The Atlantic Ocean sedimentary record has been strongly affected by vigorous bottom-water circulation at least since the beginning of Oligocene time. However, after nearly 18 years of deep-sea drilling, the timing, magnitude and source of the deep circulation are not as yet well-constrained. This situation primarily results from the fact that almost no drilling to date has been designed to look specifically at the age of deep, current-eroded nonconformities which are the only direct evidence of strong, deep-circulation events (unlike inferences based on geochemical techniques and grain size).

The appropriate locations to study these "regional" nonconformities are along the seaward edges of continental margins, where these nonconformities become conformable. Continuously cored drill holes at these points should recover complete sedimentary sections. Attempts to date such nonconformities on more proximal, higher-gradient, or flow-constricted areas of continental margins will be frustrated by the occurrence of long-duration hiatuses (Figs. III.2.1 and 2).

What is the balance and timing of Antarctic versus Arctic events on South Atlantic paleoceanography? A first-order question in deep paleocirculation studies is the nature of the timing and source area(s) of the first strong abyssal circulation in the Atlantic Ocean. This question appears to be closely linked to the question of how the global psycrosphere was developed in the early Oligocene. Only after the psycrosphere developed did the basin-to-basin fractionation of bottom-water begin and evolve in response to an increasingly glaciated world. North Atlantic studies suggest a northern source of bottom water that entered the basin and caused extensive erosion of western-basin margins in the latest Eocene to earliest Oligocene. Perhaps a teleconnection was created by the introduction of this water mass, such that deep North Atlantic waters upwelled and cooled around Antarctica to form an early analog of modern Antarctic Bottom Water. It is also possible that dense bottom waters were formed around Antarctica about the same time, but independently, of events in the North Atlantic.

White areas = no sedimentary record.

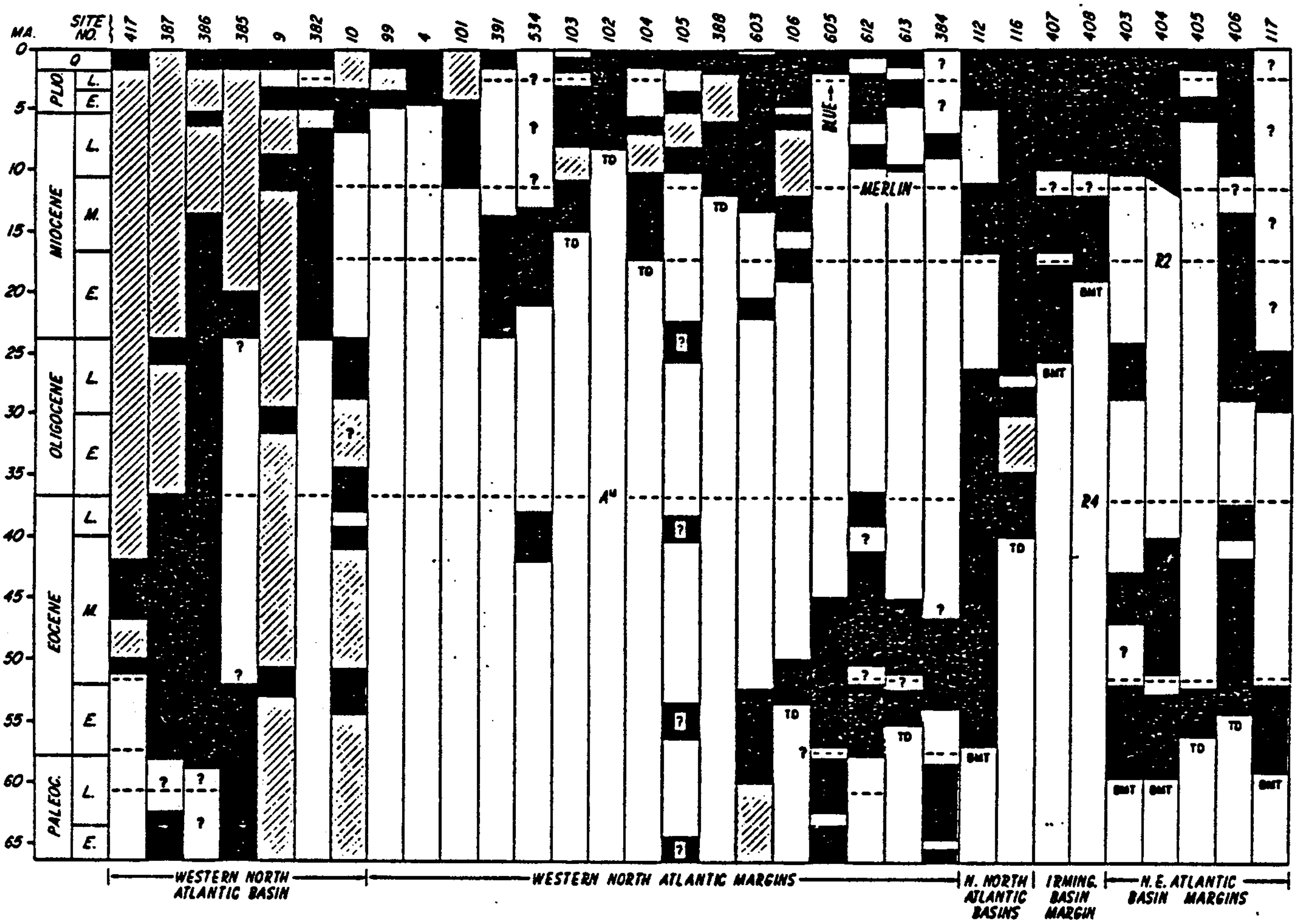


Fig. III.2.1. Cenozoic sedimentary record in selected DSDP drillsites in the western and northern North Atlantic. Solid red - recovered section; hachured - uncored or undated, but inferred continuous sedimentation; blank - hiatus, except below total depth (TD) of hole or where hole bottomed in basement (BMT). Significant unconformities of regional extent are indicated by dashed lines; color code shows known correlation to labelled seismic reflection boundaries. Core record based on Tucholke (1979), Kaneps and others (1981), Miller and Tucholke (1983), Sheridan and Gradstein (1983), Poag (1985), van Hinte and Wise (1986), and Poag and Watts (1986).

Shaded areas = no sedimentary record.

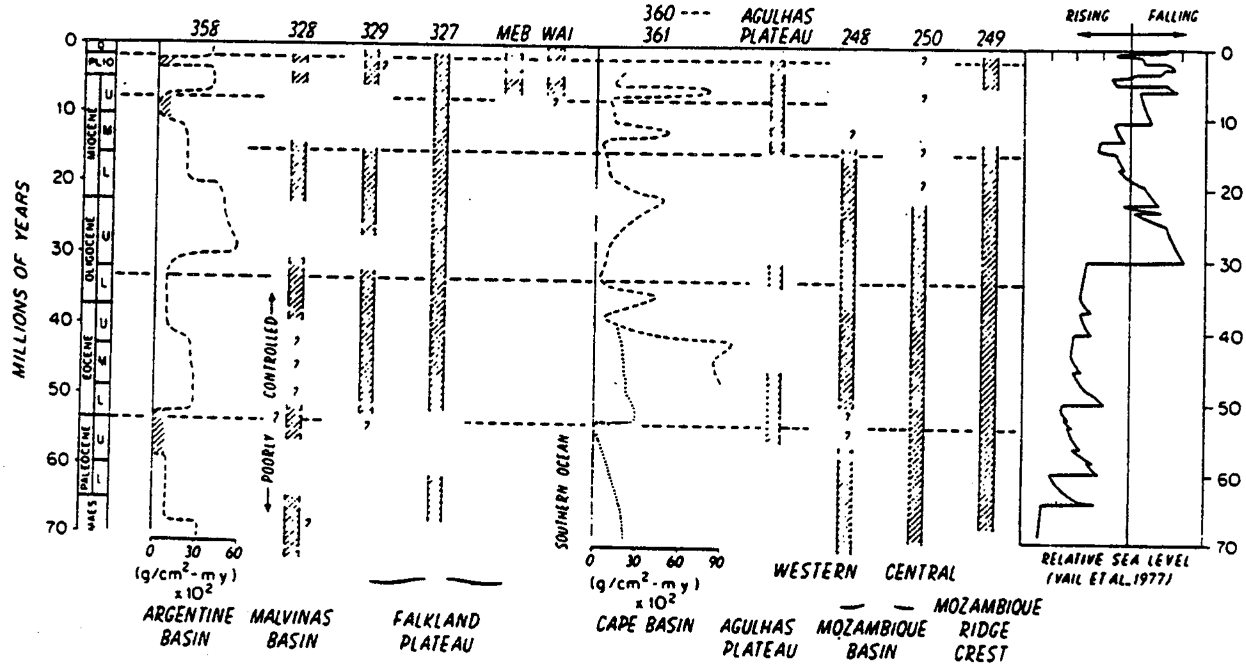


Fig. III.2.2. Summary of hiatuses (shaded, and correlated with dashed lines) and/or sediment accumulation rates at DSDP drillsites and from piston-core studies: MEB - Maurice Ewing Bank (Falkland Plateau; Ciesielski, Ledbetter, and Ellwood, 1982); WAI - Weddell Basin/ Atlantic-Indian Ridge (Ledbetter and Ciesielski, 1982); Agulhas Plateau (Tucholke and Carpenter, 1977). Drillsite information derived from Bolli and Ryan (1978), Barker and Dalziel (1976), Davies and Luyendyk (1974), Simpson and Schlich (1974), and Supko and Perch-Nielson (1977).

SAMPLING STRATEGY

The best way to address this question is to date the exact times at which the first major current-controlled nonconformities were formed in both the South and North Atlantic oceans and to study the faunal, geochemical and lithologic changes associated with those boundaries. One or more carefully selected drill sites, perhaps along transects, should be targeted for each of the mid- to high-latitude basins in the western South Atlantic (Argentine, Brazil). A similar strategy needs to be developed for the Cape Basin, which has been open to flow of circum-Antarctic bottom waters since the Late Cretaceous. The relative timing of strong paleocirculation in each basin will reveal the progression (synchroneity?) between basins of strong, deep circulation and, with North Atlantic drilling, results will reveal the relative timing of northern and southern bottom water generation.

Younger events in the deep-circulation history represent a second-order problem which can be studied in the same way, recognizing that the best definition of the events will come from coring correlative conformities. These younger unconformities represent major responses to (causes of ?) the climatic evolution which resulted in both Antarctic and Arctic glaciation. No other data set gives unequivocal evidence of the major changes in deep circulation. In all instances it is essential to have a well-defined regional to sub-regional seismic stratigraphic framework to test with the drillstring. It is also desirable for this framework to be as simple as possible; thus, nonconformities and their interrelations should be well-defined, sediment mass movements and diagenetically generated reflectors should be absent, and siting should be well away from the shallower portions of margins where sedimentation patterns are strongly influenced by sea level events. However, in some instances, shallow rises must be drilled in order to date intermediate and surface (especially Antarctic Circumpolar Current) paleocirculation events so that the coupling of surface, intermediate and deep circulation may be examined.

One location which does not meet all the above criteria, but which deserves mention in the context of studying deep-circulation history, is the Agulhas Plateau. Several well-defined nonconformities are present in the sedimentary sequence capping and flanking the upper margins of the plateau, and they appear to represent major deep-circulation events (Fig. III.2.2). The greatest single advantage of this location is that the sediments are calcareous oozes, so that biostratigraphic resolution should be optimized in comparison to other sites with a stronger terrigenous input. Detailed (i.e., three-dimensional), high-resolution (e.g. water-gun) site surveys would be required in this area to document sites where the durations of the hiatuses would be minimized.

DUMPING GROUNDS: THE PROBLEM

Another, less direct method for examining the history of deep circulation is to study the stratigraphic record in the "dumping ground" where eroded sediments have been deposited. These drift deposits contain not only a record of upstream erosion, but also document smaller-magnitude, deep-circulation events which may be correlated to paleoclimate, sea level and paleoceanography. Those events will be recorded by reworked microfossils, grain size and lithologic changes.

SAMPLING STRATEGY

The best way to address this question is to date depositional events in drift deposits within the deepest basins with long, continuously cored holes.

These deposits have formed in response to sediment supply (itself a composite product of tectonics, sea level, climate, bottom-current erosion and transport) and to fluctuations in intensity of bottom-currents at the depositional site. The drift deposits in the Argentine and Cape basins are "dumping grounds" suitable for such drilling, perhaps using transects of holes along the defined paths of bottom water masses.

III.3. FAN GROWTH AND EVOLUTION AS KEYS TO EQUATORIAL CLIMATE AND CONTINENTAL DENUDATION (summary by J. Damuth, R. Flood, R. Kowsmann, P. Manley, C. Pirmez and A. Shor)

BACKGROUND

Very large, mud-rich, deep-sea fans, like the Amazon, Mississippi, Indus and Bengal, are developed along the continental margins of the modern oceans. Such fans are formed by the localized input of riverine sediments derived from extremely large drainage basins. Sediment sequences of many fans are known to be controlled by glacio-eustatic sea level fluctuations and concomitant climatic changes over the continental source areas (for example, see Damuth and Fairbridge, 1970; Damuth and Kumar, 1975). Tectonics also plays an important role in fan sedimentation. Therefore, fan sediments contain an important, but as yet poorly understood, record of these variables. However, the details of such relationships back through the Pleistocene and Neogene are not yet well documented, primarily because of the lack of deep penetration and sampling of submarine fans.

The Amazon Fan (Fig. III.3.1) off equatorial South America is an ideal location to study the development of a typical large, mud-rich fan and the relationship of its development to glacio-eustatic sea level fluctuations and climatic change. Studies of land fauna and Pleistocene geology within the Amazon drainage basin indicate that climate there during glacial cycles was vastly different from that of today; during glacials, the vast tropical rain forests shrank and all but disappeared, and semi-arid savannahs prevailed (Damuth and Fairbridge, 1970). However, the land record of these changes is incomplete and poorly dated. In contrast, the sediments of the Amazon Fan should contain a virtually continuous record of climate change in the interior of South America. To date, only the last 50,000 yrs or so of fan history have been documented, because piston cores allow recovery of only the youngest fan sediments. However, core material studied to date shows the influence of both sea level fluctuations and climate change on fan sedimentation. For example, the high sea level stand of the Holocene interglacial has temporarily shut off terrigenous sediment deposition on the fan. In contrast, during sea level lowering (150-200 m) in the late Wisconsin glacial, terrigenous sediments rapidly accumulated on the fan (Damuth and Kumar, 1975; Damuth and Flood, 1985).

The Amazon Fan contains sedimentary/acoustic sequences which are quite characteristic of large and small modern, mud-rich fans. Detailed studies using high-resolution seismics, long-range side-scan sonar (GLORIA), and bathymetric swath-mapping (Sea Beam) have shown that the middle fan is built of numerous lense-shaped sediment sequences, each of which represents an individual distributary channel-levee system (Figs. III. 3.1-6). The channel associated with each levee system often meanders (Figs. III.3.1-3; see also Damuth et al., 1983a; Flood and Damuth, 1987; Damuth et al., submitted). High-amplitude reflections beneath the channel floors (e. g. Figs. III.3.4-6) may represent coarse sediments trapped in the channel floor as the channel-levee system aggrades upward (e. g. the coarse gravels drilled on Mississippi Fan during DSDP Leg 96), or side echoes from the present channel floor (Flood, in press).

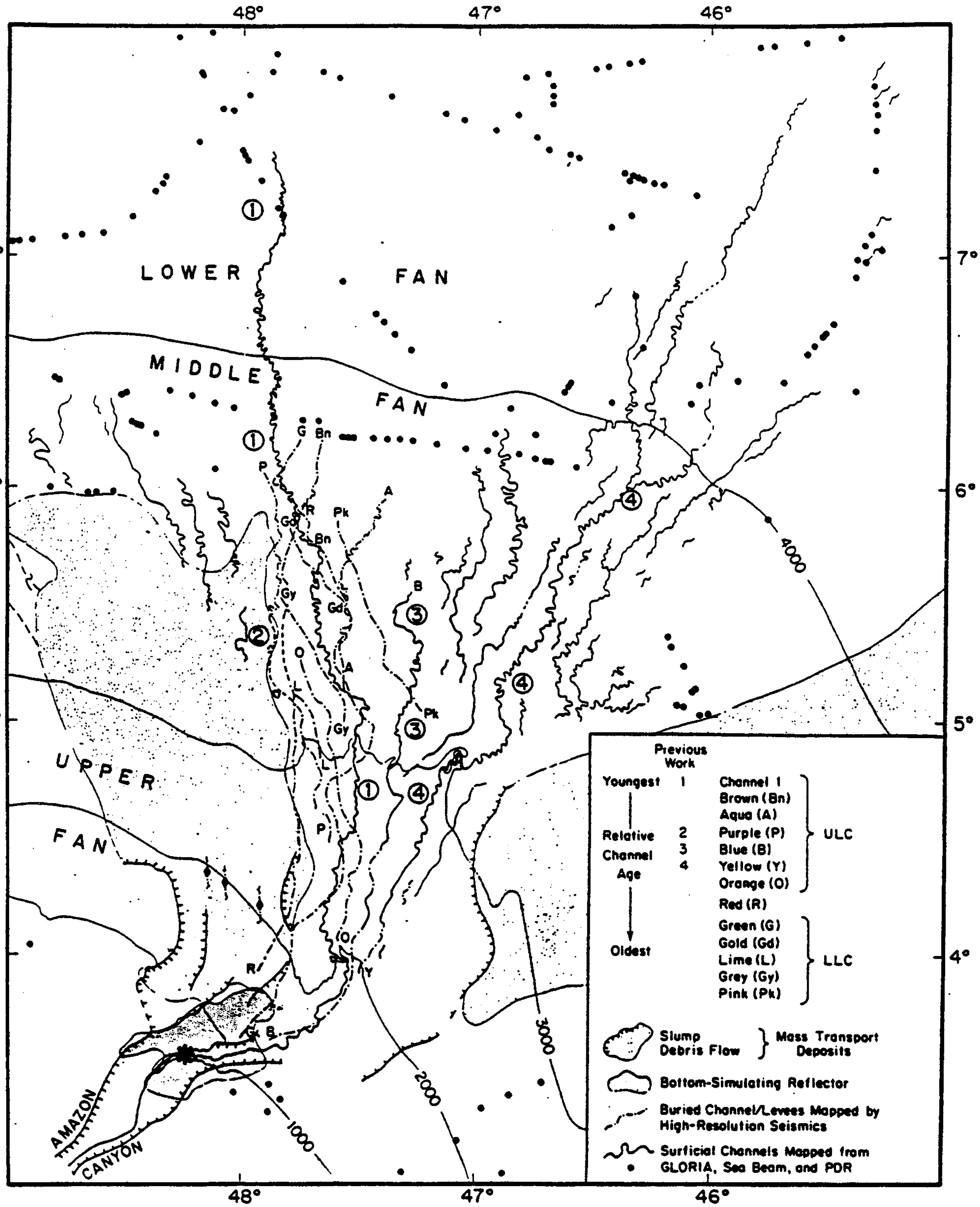
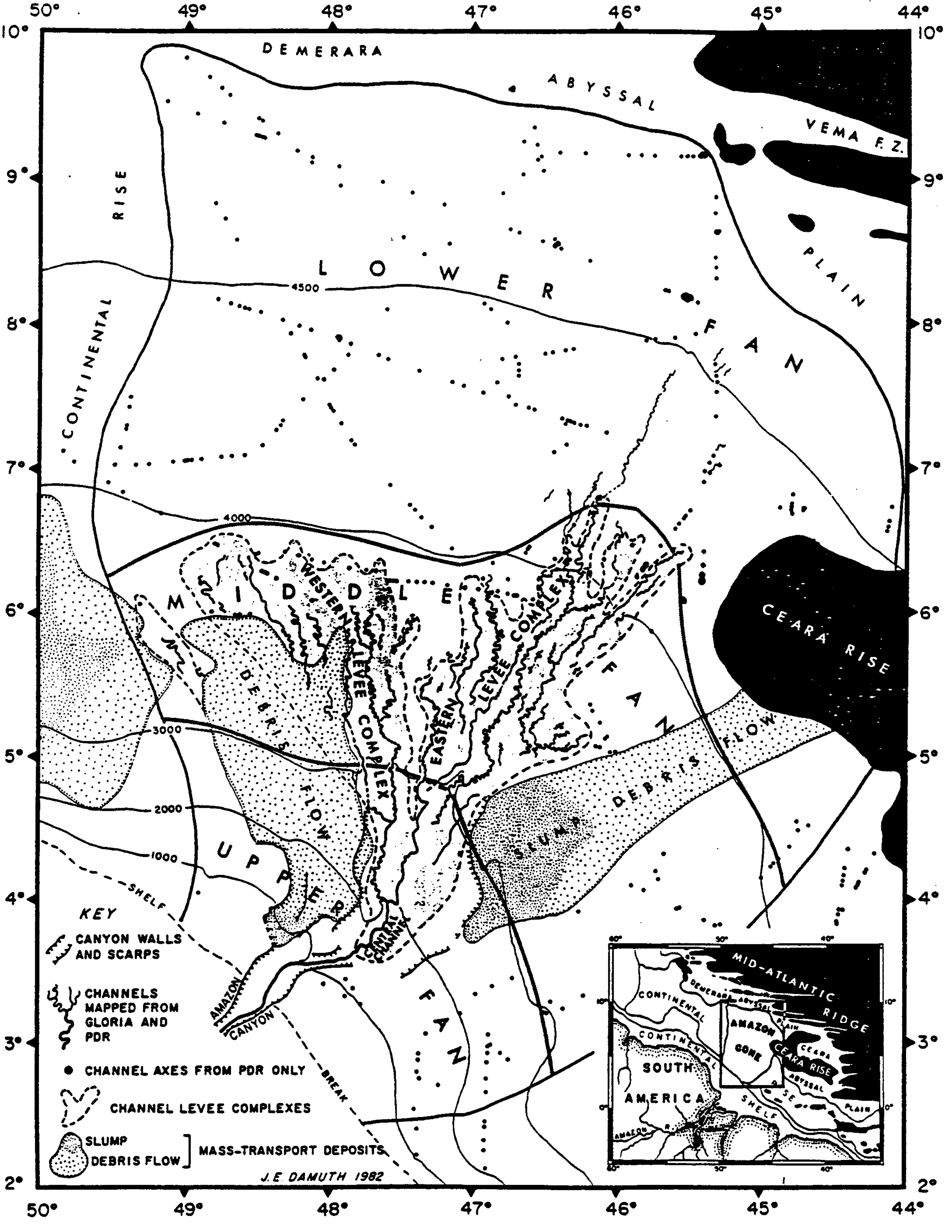


Fig. III.3.2. Locations and age relationships for surficial (solid lines) and buried (dot-dash lines) distributary channel-levee systems of the Amazon Fan (Manley and Flood, submitted). Surficial channel-levee systems were mapped using GLORIA, SeaBeam and 3.5-10 kHz seismic data. Buried channel-levee systems were mapped using high-resolution watergun seismic profiles.

Fig. III.3.1. Morphology of Amazon Fan showing present distributary channel pattern on the upper and middle fan as mapped with GLORIA side-scan sonar and high-resolution (3.5-10 kHz) seismic profiles (Damuth et al., 1983b). Bathymetry in corrected m. Black dots on lower fan show channels mapped with 3.5 kHz profiles only. Inset (lower right) shows regional location of fan.



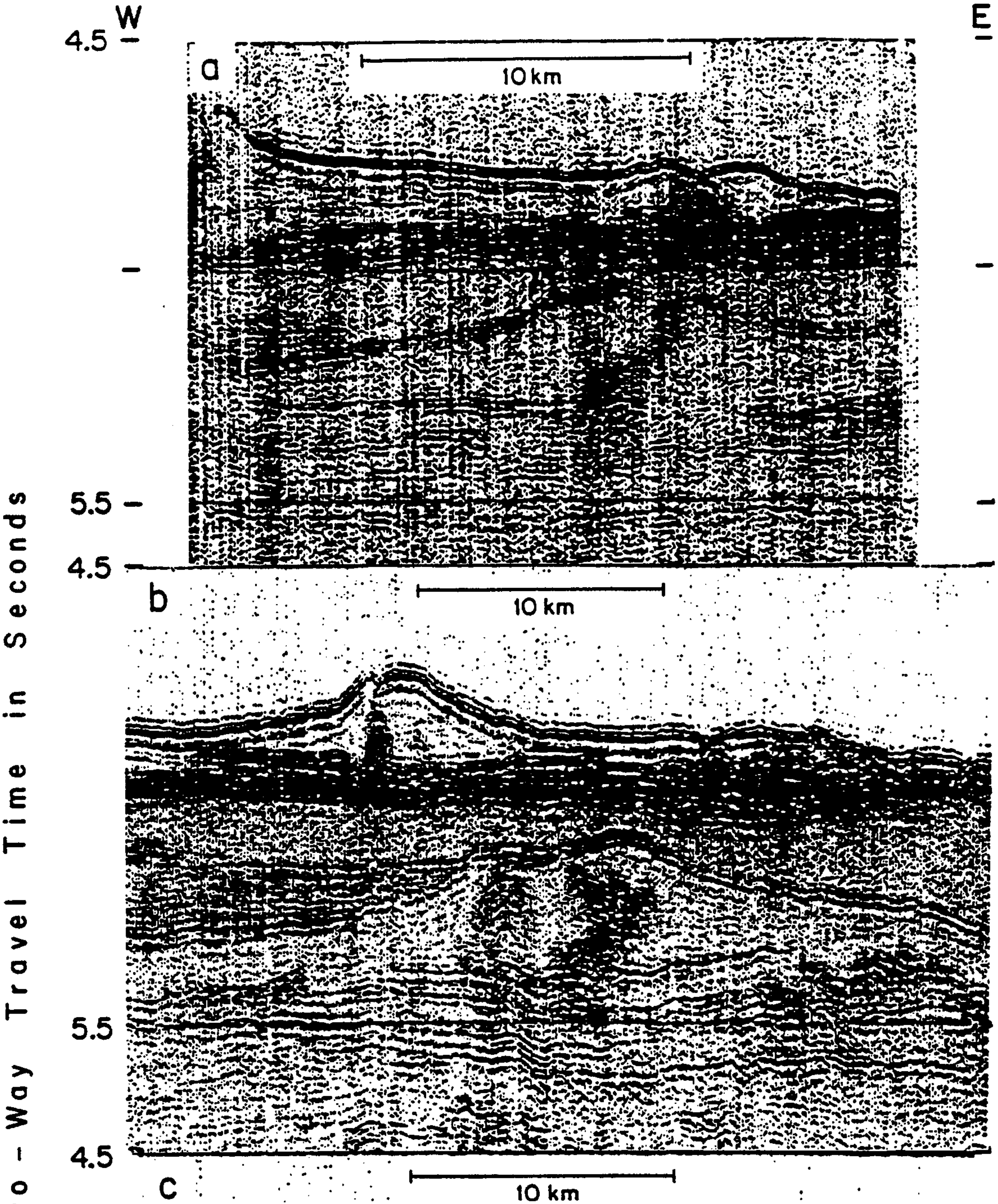
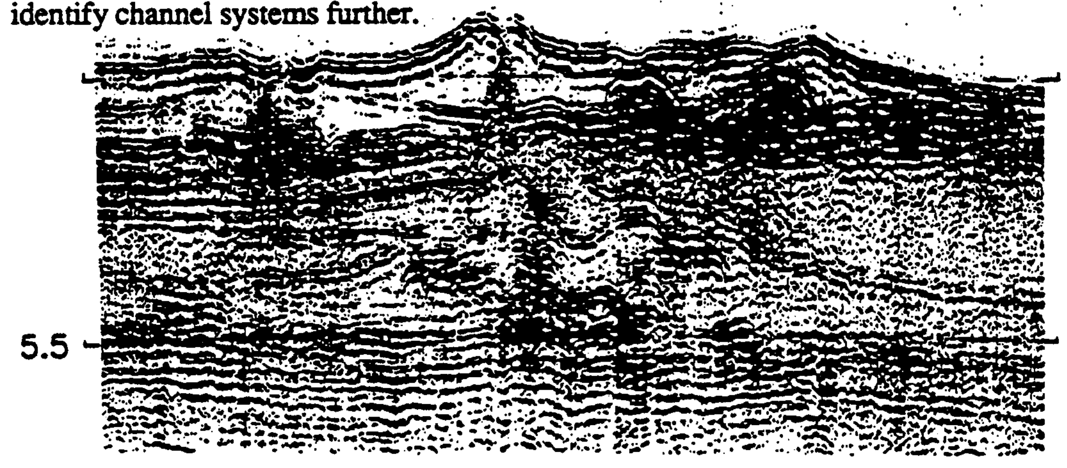


Fig. III.3.4. Three watergun profiles showing examples of typical surficial (modern) and buried channel-levee systems on several down fan crossings of the Amazon Fan (Manley and Flood, submitted). Note the occurrence of high-amplitude reflectors beneath channel axes, and the semi-transparent lense-shaped nature of the levee deposits. Line drawings in Fig. III.3.5. identify channel systems further.



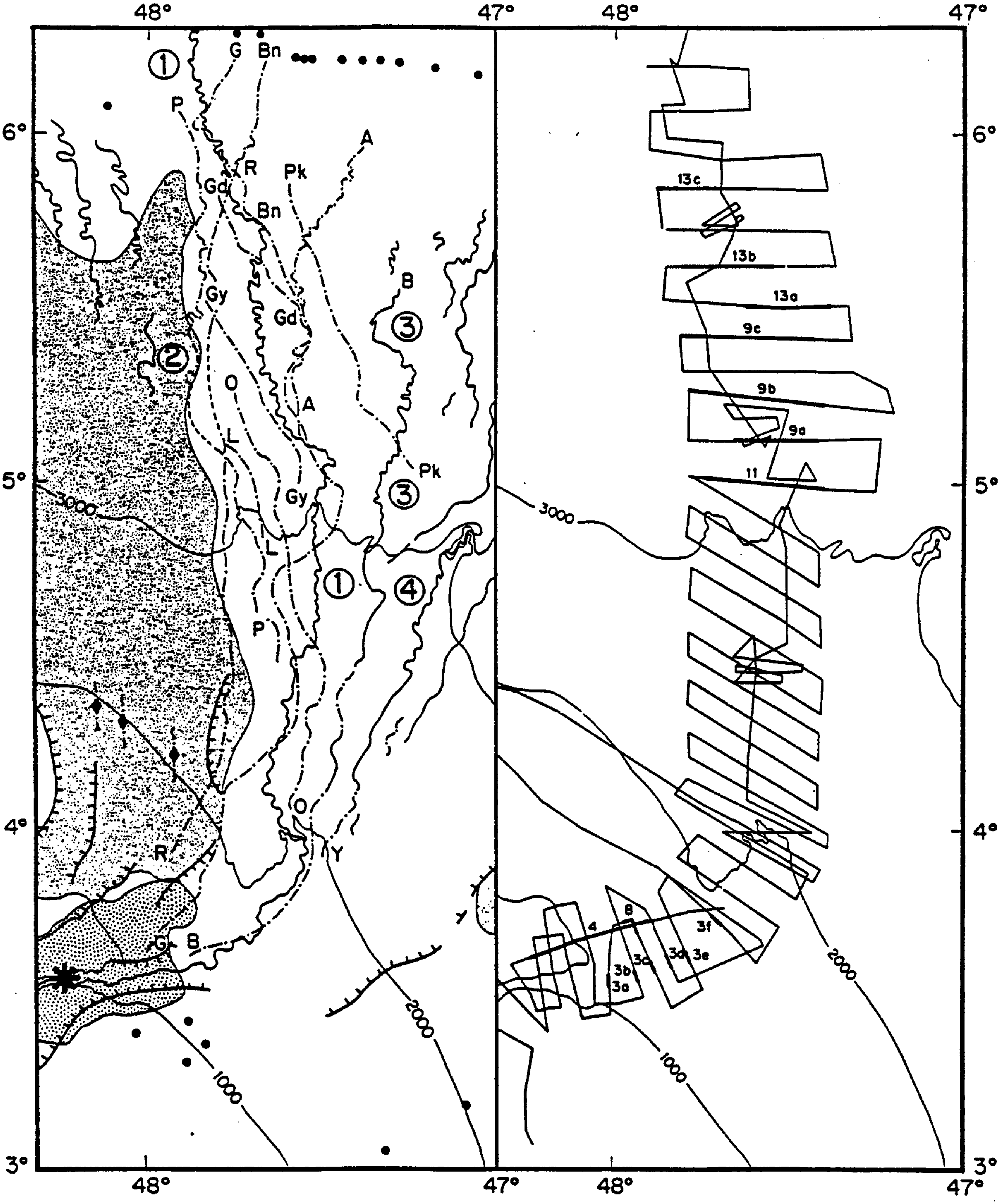


Fig. III.3.3. Enlargement from Fig. III.3..2 showing detailed relationships of buried channel-levee systems mapped on the western side of the fan (Manley and Flood, submitted). Track chart at right shows locations of high-resolution watergun seismic profiles.

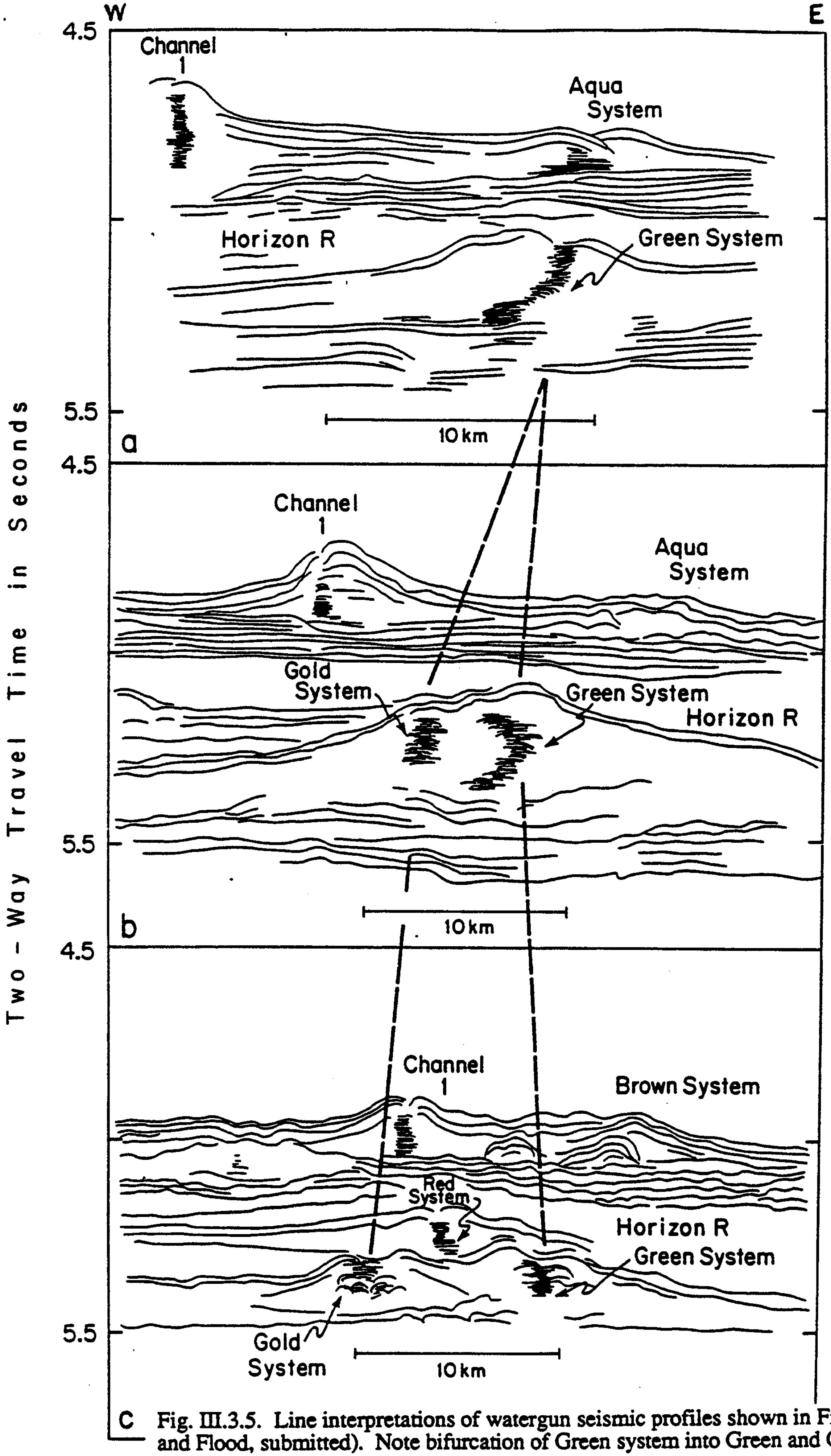


Fig. III.3.5. Line interpretations of watergun seismic profiles shown in Fig. III.3.4. (Manley and Flood, submitted). Note bifurcation of Green system into Green and Gold systems down fan.

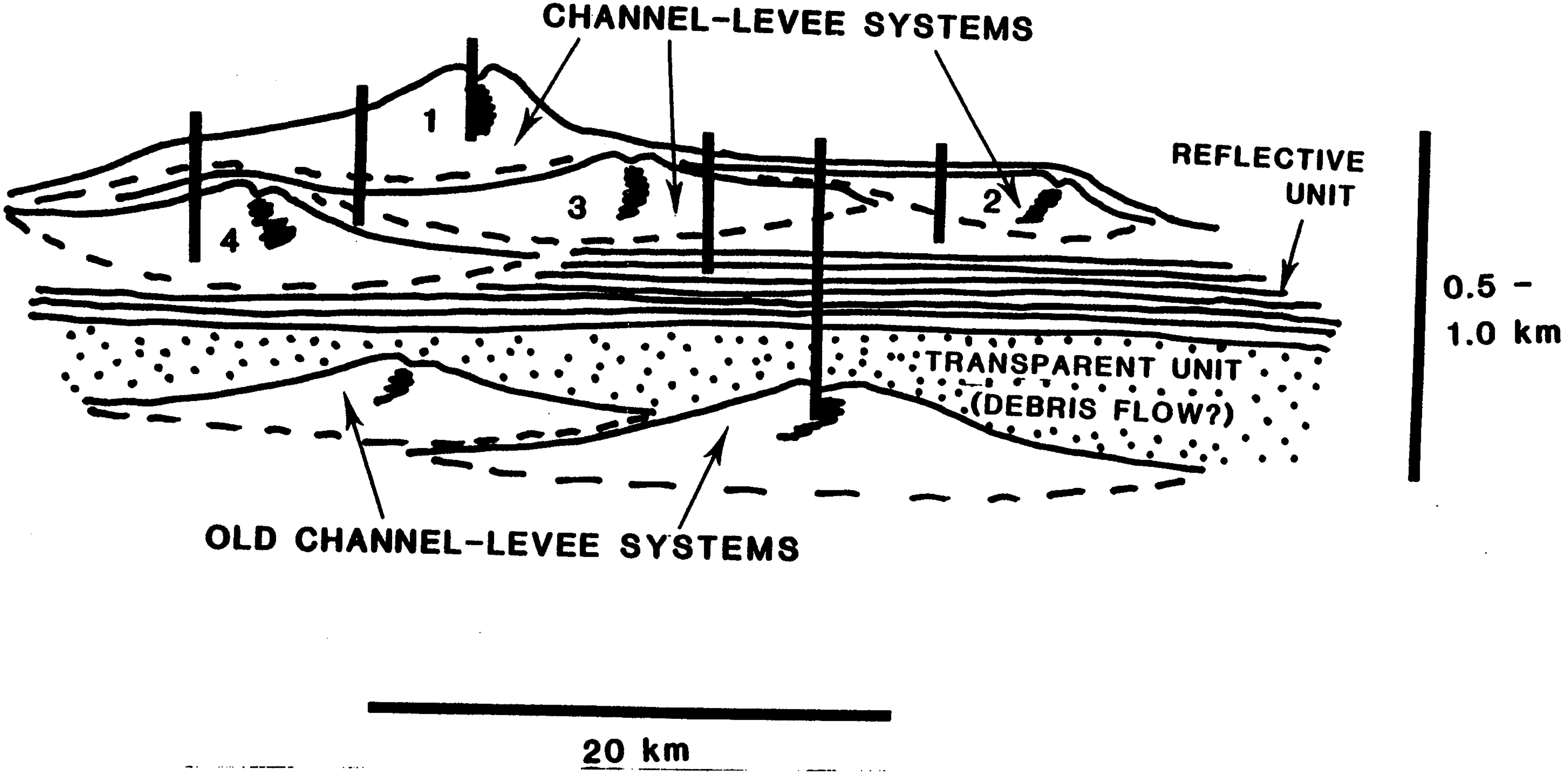


Fig. III.3.6. Schematic diagram showing stratigraphic relationships of middle-fan channel-levee systems and acoustic facies observed on the Amazon Fan. Black vertical lines show hypothetical HPC coring strategy (see text). HPC sites penetrating channel-levee systems of the upper (modern) levee complex will provide a continuous stratigraphy and depositional history for the fan. Deeper penetration HPC sites will sample older, now buried channel-levee systems, as well as acoustic facies (transparent and reflective) between levee complexes.*

Individual channel-levee systems, which are typically 20 km wide and up to 250 m thick (Figs. III.3.4-6), overlap one another and coalesce to form broad levee complexes composed of up to 15 or more individual systems (Figs. III.3.1 and 2). Seismic and morphological evidence suggests that only one major channel-levee system on the fan is active at any given time, and new channel-levee systems form periodically through avulsion (Damuth et al., 1983b). The two levee complexes at the fan surface today (Fig. III.3.1) are underlain by a widespread, flat-lying, highly reflective sequence which varies in acoustic character down-fan, and which, in turn, is underlain by an acoustically transparent unit thought to be extensive debris-flow deposits (?) (Figs. III.3.4-6). An older levee complex indicating a previous cycle of fan development is buried beneath this transparent unit (Manley and Flood, submitted).

The Amazon Fan is the best choice for HPC drilling because only the Amazon Fan possesses all three of the following characteristics:

1) **The Amazon Fan is one of the most extensively surveyed and thus best imaged of any of the large deep-sea fans.** Recent studies of this fan have used long-range side-scan sonar (GLORIA), bathymetric swath-mapping (Sea Beam), high-resolution (80 cu. in.) watergun and 3.5 kHz seismic reflection profiling. When combined, these data provide an excellent picture of the anatomy of the distributary channel system and the sequential growth pattern of the fan. Therefore, the necessary data base already exists for defining specific drilling objectives and specific sites.

2) **Studies of the Amazon Fan show that the fan contains a large number of spatially dispersed, discrete channel-levee sequences at or just beneath the present fan surface (Figs. III.3.1-6).** These sequences are now known to have developed sequentially (Damuth et al, 1983b), and they should provide a relatively continuous history of fan sedimentation during the Pleistocene. The fact that most of these channel-levee sequences are areally dispersed at, or just below, the fan surface makes them readily accessible with shallow drilling techniques (Fig. 6). Therefore, it should be possible to obtain a continuous record of sediment deposition without deep holes (see "Drilling Strategy").

3) In addition, **the Amazon Fan is the only major fan that provides an opportunity to investigate equatorial climatic changes.** Drilling this fan should provide an expanded record of climatic shifts (humid to semi-arid) in equatorial South America in response to glacial/interglacial fluctuations.

These factors make the Amazon Fan unique among all the major mud-rich fan systems. Other fans (i. e., Rhone and Mississippi) have excellent data bases, but they lack the large number of discrete, sequentially deposited channel-levee sequences at shallow depths characteristic of the Amazon Fan. Furthermore, the relative ages of existing channel-levee systems are less certain on these other fans, so drilling would have to be relatively deep to derive a continuous fan history. Large fans like the Indus and Bengal, which appear to be similar to the Amazon Fan (i. e., numerous channel-levee sequences aerially dispersed across the fan surface), are not yet well-imaged, especially with side-scan sonar or Sea Beam.

DRILLING OBJECTIVES

1) **Establishment of an absolute chronostratigraphic framework that will define the relationship, if any, between the development of fan depositional sequences (e. g. channel-levee systems) and sea level fluctuations.** This will establish whether sea level fluctuations control channel-levee development and associated sediment facies distributions, thereby determining the growth pattern of the fan.

Because of the popularity of the Exxon sea level curve (Haq et al., 1987) and the development of conceptual models for continental margin sedimentation based on seismic stratigraphy, many investigators of both modern and ancient fans attribute various acoustic facies of fans, as well as the development of channel-levee systems, sand lobes and fan divisions (i. e., upper, middle and lower), to specific sea level positions. Glacio-eustatic sea level fluctuations do influence fan sedimentation during at least the latest Quaternary (Damuth and Kumar, 1975). However, data do not yet exist for modern fans which clearly demonstrate that various fan facies, divisions, etc. have any specific relationship to sea levels or their fluctuation. **Continuous cores which span several sea level fluctuations need to be obtained and subjected to high-resolution stratigraphic studies (e. g. oxygen isotope analyses, biostratigraphy) in order to confirm the relationship, if any, between sea level and fan-growth patterns and facies distributions.**

2) **Determination of accumulation rates, both for discrete fan facies such as channel-levee systems, and for the fan as a whole.** True rates of deposition on the Amazon Fan are as yet unknown. How fast do individual channel-levee systems form? Drilling of the youngest levee system on the Mississippi Fan during DSDP Leg 96 revealed very high rates (up to 110 cm/1000 yr), but failed to provide conclusive data on the rates and timing for the formation of individual channel-levee systems. For example, how many levee systems develop during a 100,000 yr glacial/interglacial cycle (Damuth et al, 1983b; Manley and Flood, in press)? The stratigraphy of the Amazon Fan offers a chance to answer these questions (Fig. III.3.6). Such studies are also designed to determine rates of continental denudation and the volume of sediment transported to the deep sea.

3) **Determination of the nature of depositional processes which create highly meandering distributary channel systems.** GLORIA studies of the Amazon Fan (Damuth et al, 1983a; Damuth et al, submitted) reveal that distributary channels often meander (Figs. III.3.1-3). Highly meandering channels have also been discovered on other modern fans. However, the characteristics of the turbidity-flow processes which form, maintain and modify these channels remain uncertain (Damuth et al, 1983a; Flood and Damuth, 1987; Damuth et al, submitted). Classic, episodic turbidity currents seem to be too infrequent to account for channel formation and modification. A more continuous type of turbidity flow seems to be required. HPC coring of critical levee and channel environments on the Amazon Fan should help to reveal the nature of this process.

4) **Correlation of humid/arid climatic cycles within the Amazon drainage basin with glacial/interglacial fluctuations.** Although evidence (from pollen analysis) for alternation of extensive humid tropical rain forests with semi-arid to arid savannahs throughout the Amazon Basin has clearly occurred during the Pleistocene (Damuth and Fairbridge, 1970), correlation of these climatic fluctuations with glacial/interglacial episodes has not yet been confirmed. A continuous sediment record from the Amazon Fan spanning several glacial/interglacial cycles could confirm this correlation.

5) **Development of a chronostratigraphy for the various acoustic facies observed within the Amazon Fan.** What are the sedimentological causes of the distinctive acoustic facies observed in Amazon and other deep-sea fans? What is the relationship, if any, of various acoustic facies to sea level fluctuations? Previous fan studies have speculated that various acoustic facies are characteristic of specific fan sub-environments (e. g. lobes, channels, etc.) or deposits (e. g. debris flows, slumps, sand beds) and have also related the formation of acoustic facies to sea level curves (see 1 above). Sampling of acoustic facies should be designed both to determine their associated lithology (ies) and to correlate their formation to sea level fluctuations and/or other causative agents.

6) **Characterization of the sediment facies distributions within a large, mud-rich fan system in order to compare them to turbidite facies associations derived from ancient fans** (e. g. Mutti facies). A major gap in submarine fan knowledge is how facies distributions in modern fans compare with those defined for ancient fans from outcrops and cores. Drilling and coring on the Mississippi Fan has aimed at resolving this problem, but results have been inconclusive. Additional sampling of various sub-environments of large fans is needed to help resolve this problem.

DRILLING STRATEGY

As has already been discussed, channel-levee sequences (Figs. III.3.4-6) are the basic sedimentary units of large, muddy fans such as the Amazon. In particular, the middle fan is built of a large number of these sequences. **Multiple HPC sites (15 to 20) which penetrate a number of these middle-fan levee sequences (water depth about 3.5 km) should provide a complete stratigraphic sequence for the last major cycle of fan deposition (Fig. III.3.6).** These HPC sites should be on the levees of well-imaged channel-levee systems whose relative ages can be deduced from seismic profiles (Damuth et al, 1983b; Manley and Flood, in press). The record will be considerably expanded where the thickest (proximal) portions of the levees are cored, and somewhat compressed where the thinner, distal portions are sampled (Fig. III.3.6). However, to obtain a complete stratigraphy from a single environment (i. e., a levee), sections from more than one channel-levee system will have to be combined. Sampling of the fan will also have to include channel deposits and lobes in order to identify turbidite facies deposits and their relationships to finer-grained levee systems and the acoustic sequences (e. g. highly reflective and transparent, Fig. III.3.6) that underlie them. Sites should also be positioned along levee systems in order to determine if there are variations in timing of deposition down-fan. At least one site should be deep enough (400 to >600 m subbottom) to reach the previous cycle of fan deposition (older channel-levee systems, Fig. III.3.6) in order to determine the upper age limit of this cycle of channel-levee deposition, as well as the sedimentological nature of the transparent and highly reflective acoustic zones between channel-levee cycles (Fig. III.3.6).

One of the most critical problems will be sediment dating. High-resolution stratigraphy must be obtained from oxygen isotope determinations and foraminiferal zonations because short time intervals (i. e., on the order of several thousand years) are consistent with current estimates of channel-levee formation based on modern Amazon River sediment loads (Damuth et al, 1983b; Manley and Flood, in press). Furthermore, the stratigraphy of the uppermost depositional sequence (only 200 to 500 m thick [Figs. III.3.4-6]) is complex, and will require detailed control. This sequence is composed of 10 to 15 discrete channel-levee systems which, on the middle fan, represent an interval of time that could range from less than one glacial/interglacial cycle (~100,000 yrs) to the entire Pleistocene (> 2 m.y.).

III.4. COASTAL UPWELLING AND THE HISTORY OF SHALLOW CIRCULATION

(summary by L. Diester-Haass and W. Hay)

BACKGROUND

Today, upwelling off Southwest Africa is centered on the inner shelf and at the shelf break. The Benguela Current (BC) flows in a southwest-northeast direction parallel to and within ~180 km of the coast north to 23°-20°S, where it turns to the west (Fig. III.4.1). At ~20°S, warm, tropical water masses coming from the north unite with the cold BC water to form eddies. These eddies of cold, upwelled water contain radiolarian and diatom skeletons,

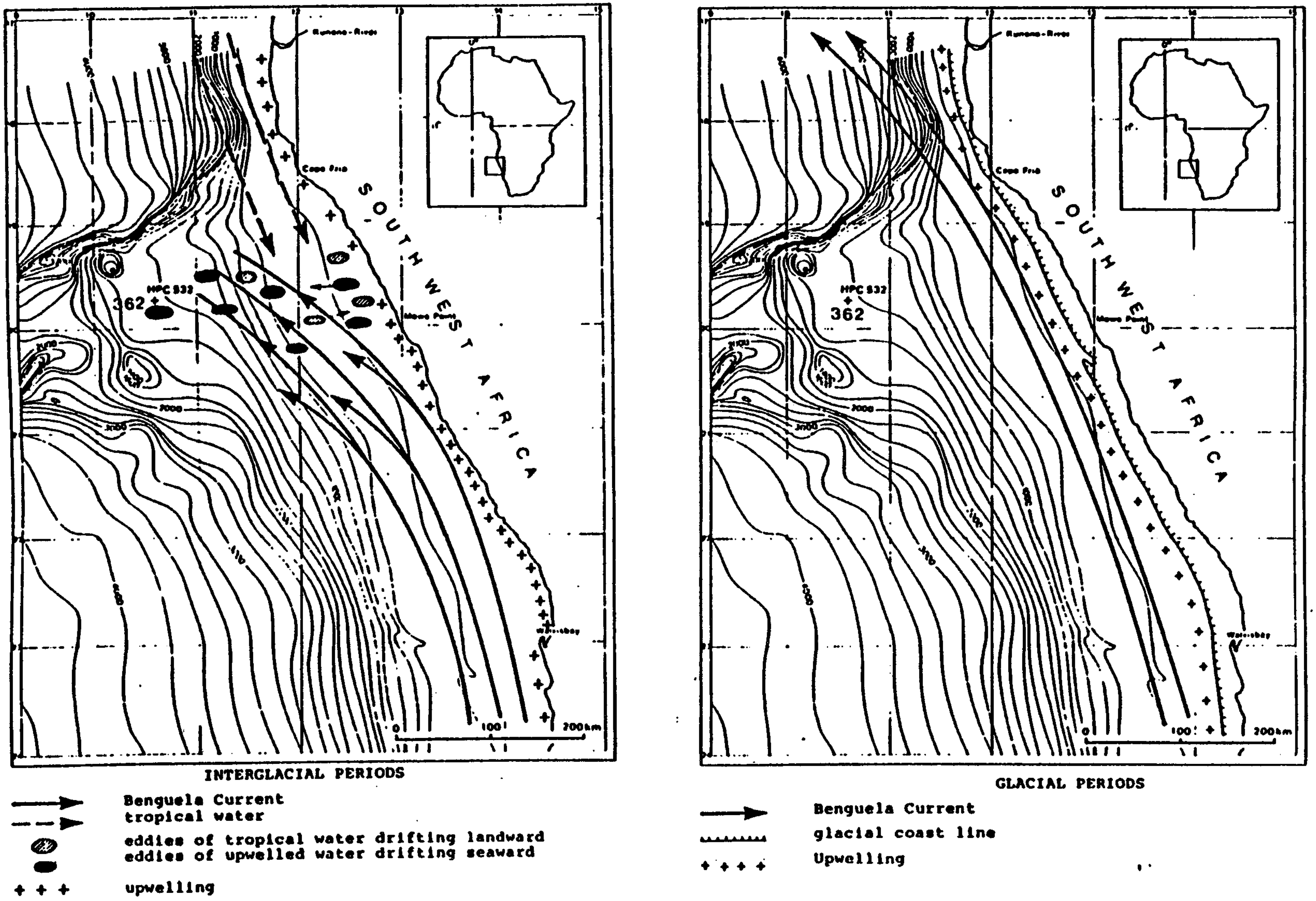


Fig. III.4.1. Response of the Benguela Current system to glacial-interglacial fluctuations.

which are transported from the upwelling area to the northern part of the Walvis Ridge, where they have been sampled at DSDP Site 532 (Hay, Sibuet et al., 1984).

During the last glacial maximum, the BC flowed parallel to the coast and over the eastern Walvis Ridge into the Angola Basin, finally bearing to the west at about 17°S. This has been confirmed by results from Site 532: sediments deposited there during the last glacial period contain very few or no opal skeletons (Hay, Sibuet et al., 1984). Upwelling may have continued to occur on the African shelf, but the BC did not transport that upwelling signal to the Walvis Ridge.

The influence of the BC as a transport agent of opal from the coastal upwelling area appears for the first time on the Walvis Ridge ~10 m.y. ago (Site 362; Bolli, Ryan et al., 1978). Contrary to the Quaternary, maximum opal contents occur during glacial periods and minima coincide with interglacials from 10 to ~6 m.y. At 5.2 m.y., the signal characteristic of the Quaternary is established: high interglacial opal contents, and lows during glacials. These results can be used to develop a tentative reconstruction of the evolution of the BC during the past 10 m.y. (Fig. III.4.2). The 5.2 m.y. boundary between the two upwelling regimes marks an important event. At this time, the late Quaternary-Recent circulation/upwelling pattern becomes established, perhaps in response to the migration of the polar front to its modern position at the same time.

The upwelling signal (i. e., opal content) in the Plio-Pleistocene section of Site 362 is by no means constant: large-scale changes are superimposed on smaller amplitude, glacial-interglacial cycles (Fig. III.4.3, upper part; Bolli, Ryan et al., 1978). These large-scale changes can be explained either by east-west migrations of the axis of the BC or by changes in its velocity. A strong increase in upwelling signal at 2.4 m.y. is synchronous with both a northward shift of the polar front in the South Atlantic and a lowering of sea level (Fig. III.4.3, lower part and Fig. III.4.4).

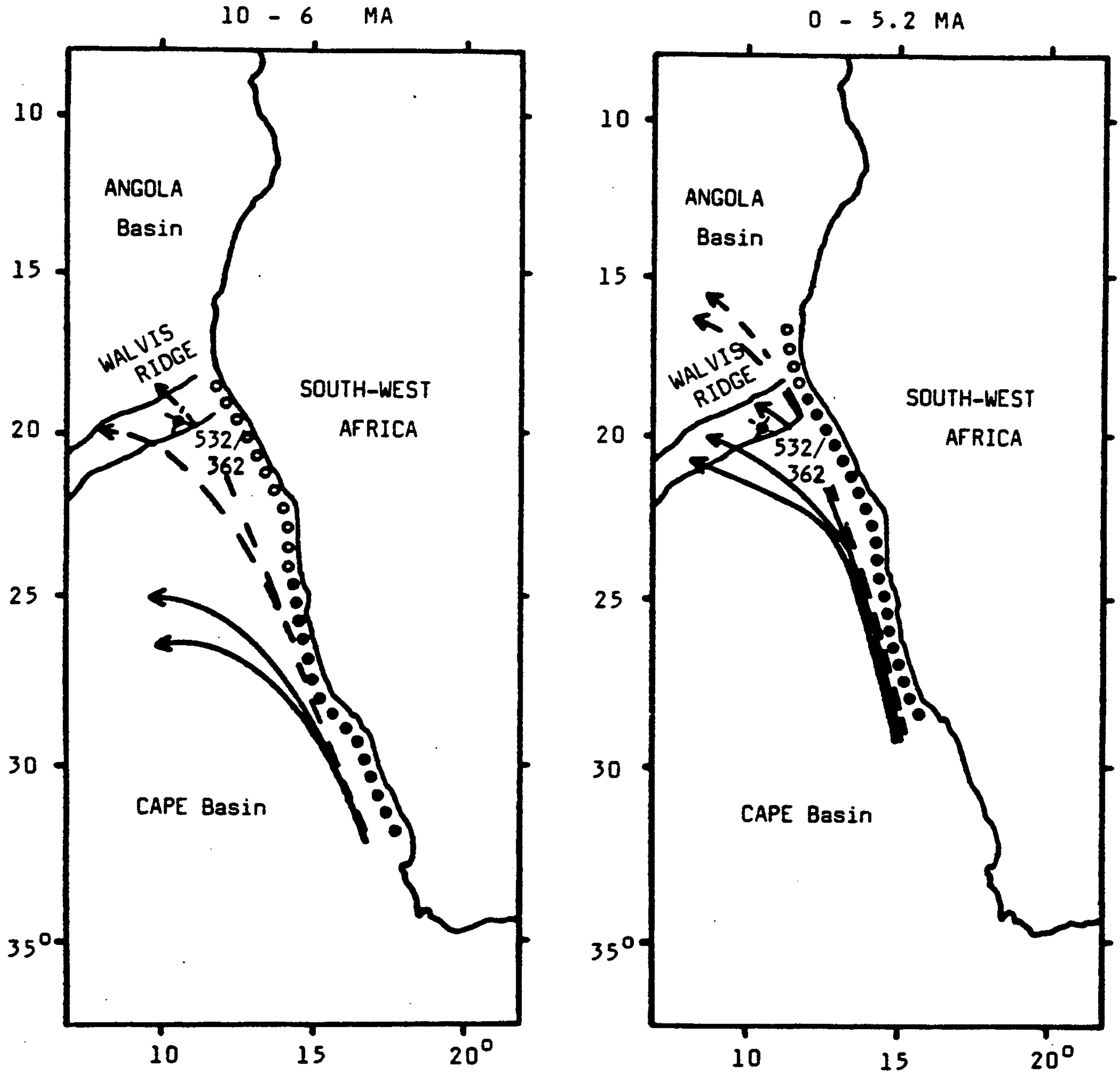
DRILLING OBJECTIVES

The results presented above suggest that there has been a general south to north migration of the BC upwelling system during the last 10 m.y. (Fig. III.4.2). Because the geometry of the South Atlantic has not changed appreciably during this time, the changes in the upwelling system must reflect global changes in ocean circulation. They may be an index of the global rate of return of nutrients from intermediate waters to the surface ocean through discrete upwelling systems (as opposed to general ocean-wide upwelling). Important questions that can be answered with additional drill sites in this region include:

1) Are the assumptions regarding changes in the BC system through time correct? Can the assumed equatorial migration of the BC be traced in a south-north drilling transect off Southwest Africa?

2) When did the BC (and related upwelling phenomena) appear for the first time in the southern Cape Basin? Is this first appearance related to any important tectonic event (e. g. opening of the Drake Passage) or climatic event (i. e., ice-growth phase in Antarctica)?

3) Did the northward migration of the BC occur gradually or in discrete steps, related to major oceanographic, climatic and/or tectonic changes?



position of the Benguela Current in the interval 10 - 6 MA and 5.2 to the present, during glacial (- - →) and interglacial (——→) periods. Near-coastal upwelling in glacial (o o o o) and interglacial (● ● ●) periods.

Fig. III.4.2. History of the Benguela Current system over the past 10 m.y. as deduced from Deep Sea Drilling Sites 362 and 532.

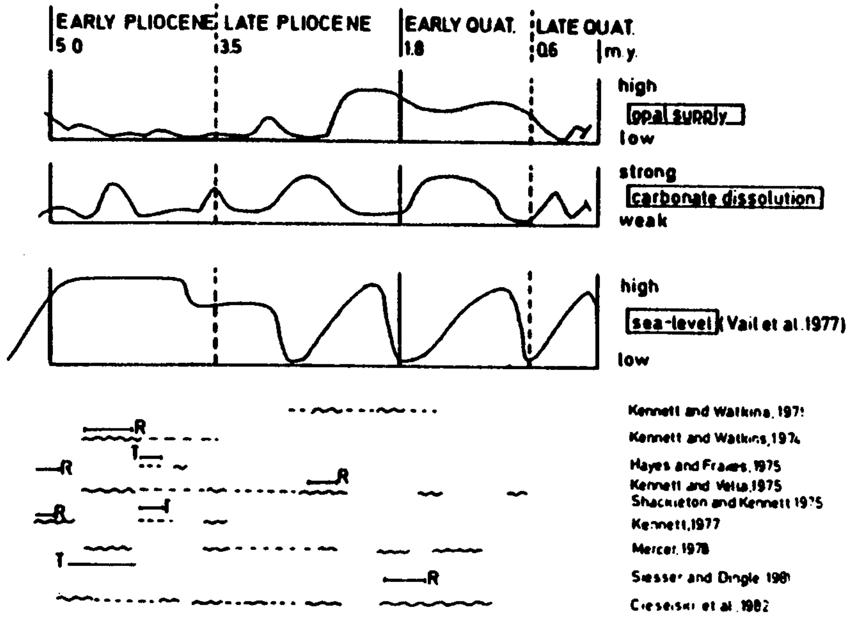


Fig. III.4.3. Schematic diagram showing the large-scale trends in opal supply/preservation, carbonate dissolution and postulated eustatic sea-level variations. The lower part of the diagram shows reported obervations (from either the continents or marine oxygen-isotope studies) on southern hemisphere cold/warm periods: solid line-cold; dashed line-warm period; R-regression; T-transgression.

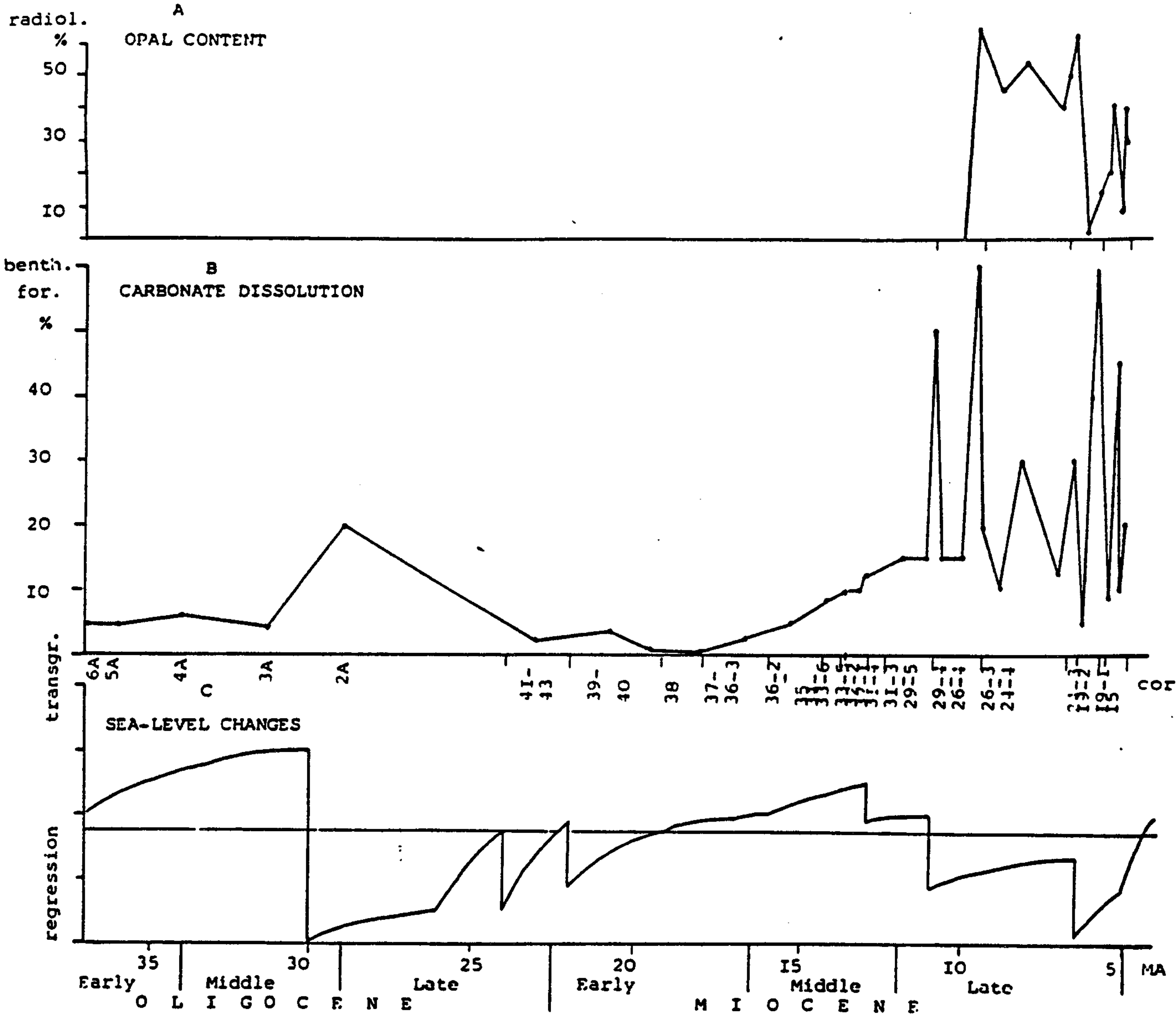


Fig. III.4.4. Semi-quantitative graph showing the variations in A. opal content (i.e., radiolaria, plotted as the ratio [radiolaria/radiolaria + benthic forამininfera] x 100 vs. B. carbonate dissolution (plotted as [benthonic foraminifera/benthonic + planktonic foraminifera] x 100 related to C. sea level changes (after Vail and his colleagues).

4) Are changes in continental climates related to changes in the surface current upwelling pattern? For example, is desertification of the Namib related to the initiation of upwelling off Southwest Africa?

Additional problems that drilling might help to solve are the following:

1) History of Southwest African climate. Changes in the position of the BC must be related to changes in the curl of the wind sheets at these latitudes. These changes are probably associated with the stability and size of the high and low pressure systems developed over the South Atlantic, southern Africa and the Indian Ocean. The upwelling system is driven by northward-flowing winds parallel to the coast, and the strength and stability of these winds depend on the strength and stability of the pressure systems. The climate on land will dramatically respond to these changes, and this proposed work offers an opportunity to investigate this significant part of the global climate system. Research on land has revealed important climatic changes in the Neogene, but the incompleteness of records and the complete lack of timing control has not yet permitted detailed interpretation of Southwest Africa's climatic history.

Sites close to the continent probably contain enough information (clay minerals, pollen, phytoliths) to allow a reconstruction of continental climatic changes and to determine whether these changes are synchronous with oceanographic changes (i. e., the establishment of upwelling off South Africa).

2) The problem of sea level changes (see also section III.5). Published eustatic sea level curves (Haq et al., 1987) can be tested off Southwest Africa not only seismically, but also by means of sedimentological investigations:

   a) During regressions, grain-by-grain transport off the shelf/shelf edge should be enhanced. These episodes can be detected in cores from the upper continental slope in the forms of shallow-water biogenic debris and glauconite.

   b) During regressions, supplies of organic matter to the upper slope are also increased, and should result in increased carbonate dissolution there (see Fig. III.4.4).

DRILLING STRATEGY

At least two east-west profiles are required in the Cape Basin and one in the southern Angola Basin. Undisturbed sediments must first be found by additional site surveying. The drill sites at the landward (i. e., the eastern) end of these transects must be situated as close as possible to the continent, in order to detect BC influence (which today is concentrated within about 180 km of the coast in the area of Walvis Ridge). **The best water depth is about 1000-1500 m.** Water depths shallower than 1 km should be excluded, because drilling results off northwestern Africa have shown that above this depth, a supply of sand-sized particles from the shelf/shelf edge confuses the interpretation of the sedimentary record, especially during glacial regressions, when these off-shelf transport processes are intensified. **A second site on the east-west profiles should be chosen in water depths of about 1600-2000 m, and a third one in about 2500 m, in order to detect possible east-west migrations of the BC axis and to obtain information on different water masses. All of these sites should be cored using HPC techniques until Oligocene sediments are encountered.**

Suggestions for the positions of the three east-west profiles are:

1) 32-34°S, south of Orange River canyon.
2) 26°S, off Lüderitz.
3) 16-17°S, off the Cunene River in the southern Angola Basin.

III.5. DEFINITION OF EUSTATIC SEA LEVEL CHANGES (summary by J. Austin, W. Hay, A. Lowrie, B. Tucholke, C. Urien and J. Watkins*)

*representing a larger proponent group

INTRODUCTION AND BACKGROUND

The confirmation of globally synchronous eustatic sea level changes has been one of the most exciting scientific events of the past decade. This phenomenon and its associated production of global nonconformities have revolutionized the interpretation of marine seismic data from sedimentary environments. Links appear to exist between between eustatic sea level fluctuations and climate, ocean chemistry, ocean circulation, CCD levels, faunal boundaries, depositional processes and lithologies, ice budget and the emplacement of hydrocarbon source rocks. However, it is not yet clear whether changes in sea level actuate these other processes or are controlled by them.

Paleo-oscillations of sea level are determined by examination of sediment interrelationships, both laterally along specific strata and vertically through the sedimentary column. Given a unique sea level position, the application of modern depositional patterns and general sedimentation principles can define sediment relationships along a stratal surface. However, inadequate age determination and imperfect vertical definition of individual stratigraphic units limit the resolution of individual sea level oscillations. Existing sea level curves (e. g., Haq et al., 1987) represent a hierarchical ordering of measurable units. The first order cycles represent durations of 10^8 years; second order cycles, 10^7 years; and third order cycles, 10^6 years. The spectrum of paleo-sea level oscillations recognizable in seismic reflection data ranges from 10^3-10^4 years up to 10^8 years, depending upon the acoustic wavelength used. Seismic sequences spanning only 10^5 to 10^4 years have also been recognized.

A third order cycle is composed of two roughly equal stratigraphic units. One unit comprises so-called "highstand deposits" (i. e., those strata deposited on the shelf), generally correlative to interglacial episodes. The other stratigraphic unit is the "lowstand wedge" (i. e.,those strata deposited at the shelf-break and along the slopes), believed to be produced during glacial phases. A suite of interrelated geologic processes define the conditions associated with either a glacial or an interglacial epoch: sea level, climate, oceanography, paleontology, productivity, energy of deposition,.erosion and seismic stratigraphy. When knowledge of any of these single processes is available, then activity of the other processes may be predicted in greater detail.

For the Neogene, highstand deposits are divided further into fourth order cycles of 10^4 years, while lowstand wedges are used to define cycles of 10^5 years. These 10^4-10^5 year events may be caused by fluctuations in solar insolation (i. e., Milankovitch cycles). These insolation changes modify long-term climatic patterns, including the existence of "ice ages".

There should be a correlation between deep sea hiatuses and those periods when lowstand wedges are deposited. However, there are known discrepancies between the two chronologies. The cause may be two-fold: conceptual misunderstanding of the cause(s) of deep sea hiatuses and/or incorrect dating of both hiatuses and lowstand wedges.

One method of examining the eustatic sea level curve which is wholly independent of seismic stratigraphy on the continental margins is detailed examination of depth fluctuations of the carbonate compensation depth (CCD). The most general changes in the CCD with time (i. e., generally high in the Cretaceous and descending to greater depths in the Cenozoic) correspond to the first order sea level cycles. However, these changes are probably not a direct response to sea level, but correspond to higher atmospheric CO_2 as a result of higher rates of seafloor spreading, as suggested by the BLAG (Berner, Lasaga, and Garrels) model. Superimposed on this very broad trend are significant changes of 1-2 km in the CCD in the Cenozoic; these correspond to large-scale changes in bottom water production in the world oceans.

Superimposed on the general CCD curve are short-term, rapid fluctuations of the CCD which appear to correspond to third order sea level cycles. At Site 530 (water depth: 4,629 m) in the Angola Basin, the Late Cretaceous and Cenozoic section had a carbonate content which exceeded 10% at only a number of discrete, short intervals. These intervals corresponded (except as noted below) within 1 m.y. to the drops in sea level associated with postulated third order cycle boundaries (Vail et al., 1977). The cycle boundaries which could be recognized are: top Q2, Q2/Q1, TP3/Q1, TP2/TP3, TM3.1/TM3.2, TM2.3/TM3.1, TO1/TO2.1 (which differs by 4 m.y. from Vail et al.'s timing, but biostratigraphic control at Site 530 was very poor), TE2.2/TE3, TE1.2/TE2.1, TE1.1/TE1.2, TP2.2/TP2.3 and TP1/TP2.1 (Hay, Sibuet et al., 1984). Cretaceous sea level falls could not be correlated because details of that part of the sea level curve had not then been published.

That the CCD should record eustatic sea level fluctuations is not surprising. When sea level rises, carbonate reef and bank areas are flooded and a significant amount of carbonate is withdrawn into shallow-water limestones, thereby reducing the supply of calcium carbonate to the deep sea and causing the CCD to rise in response. This withdrawal may, on the short term, exceeding the supply of calcium carbonate to the sea, amplifying the signal of sea level change. Despite progress of this kind, four major problems require resolution:

1) **Timing and amplitude of sea level cycles.** Poor definition of amplitudes and timing creates serious difficulties in the application of sea level curves to other problems and in the comparison of models with observed data. This problem is particularly serious for cycles with periods of less than 10 m.y.

2) **The mechanisms responsible for second-order (periods of a few m.y. to ten m.y. and more) and third-order (periods of less than a m.y. to a few m.y.) cycles.** These are completely unknown, except for glacial effects.

3) **The degree of global synchroneity of third-order cycles.** At present, correlation of third-order cycles approaches the limit of biostratigraphic resolution.

4) **Separation of global and regional sea level cycles.**

DRILLING OBJECTIVES

Perhaps unfortunately, no single avenue of investigation will solve all major problems associated with eustatic sea level cycles. A broad range of disciplines applied to several different geographic areas and geologic environments will be necessary.

Passive Margins

To determine the timing of sea level fluctuations and their effect on the development of sedimentary sequences along continental margins, it is necessary to understand sequence stratigraphy in carefully selected and well-documented locations. Passive margins and atolls appear the most promising. A good Upper Cretaceous-Tertiary section is necessary. The section should be as complete as possible, with good Neogene-Paleogene biostratigraphic resolution. Studies should initially concentrate (but not exclusively) on the Late Cretaceous-Recent interval, because these rocks are generally shallower (i. e., more accessible to the drill) and easier to date. (Strontium isotope dating is ineffective in pre-Tertiary rocks, and the lack of polarity reversals limits the effectiveness of magnetostratigraphy in much of the Mesozoic.)

Complexities exist, even on "passive" margins. For example, these margins are known from their historical tide-gauge records to experience differential uplift and subsidence along their lengths (D.G. Aubrey, pers. comm.). Therefore, it will be imperative to sample a number of diverse passive margin locations and then compare their relative sea level records in order to be successful in extracting a eustatic signal.

Passive margin drilling locations should have the following characteristics:

1) **A range of ages.** Specified time intervals at the various locations should have experienced different subsidence histories. Slower subsidence of older margins (drift onset > 100 m.y.) enhances the width of the onlap zone, whereas faster subsidence of younger margins (drift onset < 70 m.y.) enhances sedimentary sequence thicknesses.

2) **Undisturbed sediment sections that are also accumulating rapidly and continuously.** The stratigraphic and tectonic history of the area must be well-known. A well-developed, shallow water-to-abyssal plain sequence is necessary to obtain a complete record of cycles. However, there should be no major deltas in the drillingarea, as deltaic lobe boundaries could be mistaken for eustatic sequence boundaries.

3) **Sections thick enough that seismic correlations can be made both landward and seaward to improve control on sequence stratigraphy.** Well log and seismic data must be available.

4) **Location in mid-latitudes for optimum biostratigraphic resolution.** Passive margin drilling should include holes along the shelf, shelf-break, slope and on deep-sea fans/lower continental rises in order to provide multiple data points along a specific horizon/seismic reflector.

Carbonate Sections

One or more carbonate sites is also desirable. Strontium isotopes techniques, which provide the most precise dates currently available for Tertiary sea level change, work only in carbonates. Carbonate margins and atolls provide a precise quantitative estimate of the magnitude of sea level falls, because carbonates temporarily lifted above sea level tend to persist while unconsolidated sediments may seriously erode during uplift. As a "dead end" for bottom and intermediate waters from both the Arctic and Antarctic, **the Angola Basin is especially sensitive to the carbonate balance in the ocean** and has the greatest amplitude of CCD fluctuations in any of the known ocean basins, from 3-5 km over the past 90 m.y. Sensitive response to rapid eustatic sea level changes appears to be recorded there back to the Campanian, although the record is confused by carbonate turbidites in the Late Cretaceous and early Paleogene. The later Cenozoic (mid-Eocene to Recent) would therefore be the interval most suitable for exploration of the problem of eustatic sea level changes.

Eustatic sea level changes should affect Cape Basin CCD fluctuations as well as those in the Angola Basin, but the existing data from Sites 360 and 361 are wholly inadequate to show such detail. In the Cape Basin, the CCD is presently about 200 m shallower than in the Angola Basin. However, the gross histories of these two basins diverge in the past, and comparison of the Cape and Angola basin CCD's for ~ the last 10 m.y. indicates a difference of almost 2 km in the CCD on opposite sides of the Walvis Ridge. These large differences are a result of changing sources and strengths of bottom water formation in the world oceans, and the Cape Basin section should strongly reflect the nearby Weddell Sea bottom water source.

DRILLING STRATEGY

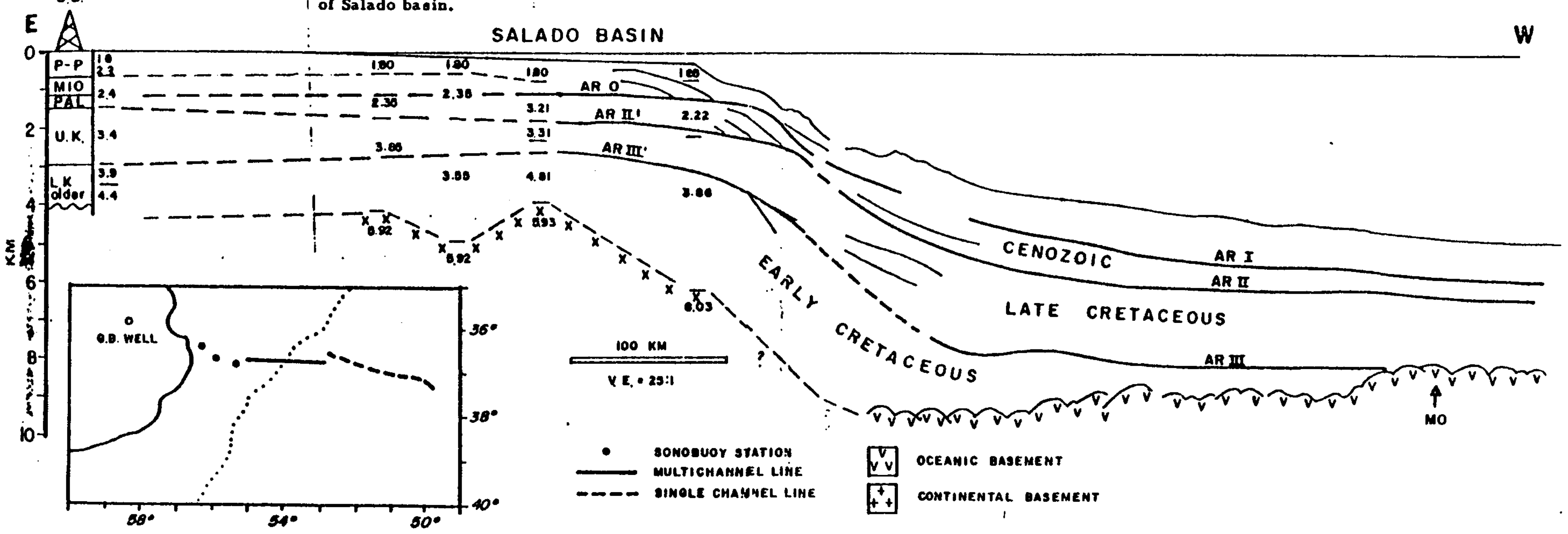
No single site or methodology can be expected to provide answers to questions involving eustatic sea level fluctuations. Rather, we see a need for careful coring with state-of-the-art logging, high-resolution seismic reflection (0.25-0.5 ms sampling rates), detailed biostratigraphy, cryogenic magnetostratigraphy, subsidence modeling and isotopic studies (especially Sr-87/Sr-86, and 0-18/0-16). High-resolution seismic reflection data are needed to improve core and log correlation with the seismic control. The resolution of core and well data is typically a few centimeters to a few meters, whereas most seismic data has a resolution of several tens of meters. Thinner sedimentary sequences associated with eustatic cycles are often poorly defined or not defined at all in conventional digital seismic reflection data sampled at 2-4 ms. Increasing the sampling rate will bring the resolution of seismic data closer to that of well control.

A minimum of three transects should be located in geographically separated areas of the world, one of which should be the South Atlantic. Geographic separation of sites is necessary to investigate the global nature of the cycles. Transects are required to obtain a complete record of individual cycles. For example, timing and magnitude of a rising sea level phase may be best-defined by the onlap of sediments on a sloping shelf, while a falling sea level phase may be best-defined by downlapping sediments on the outer shelf, upper slope or in the adjacent abyssal plain.

In the South Atlantic, perhaps the optimum location to test the Tertiary (late Paleogene-Neogene) part of the sea level record is the Argentine continental margin (Fig. III.5.1). This passive margin has well-defined seismic sequences deposited in response to sea level fluctuations, and the section is relatively thick and continuous. Numerous shelf wells have been drilled, and seismic ties from the wells to the outer shelf, slope and rise are clear. The age of the margin is approximately 125 m.y.

The Argentine margin contains a detailed record of South American evolution as well as sea level fluctuations. The Patagonian Cordillera to the west has formed since Late Cretaceous time, and the southern part of the South American continent has been affected by a gentle eastward tilt. During successive tectonic pulses, the warping

Seismic section across Argentine margin east of Salado basin.



Seismic cross section across Colorado basin.

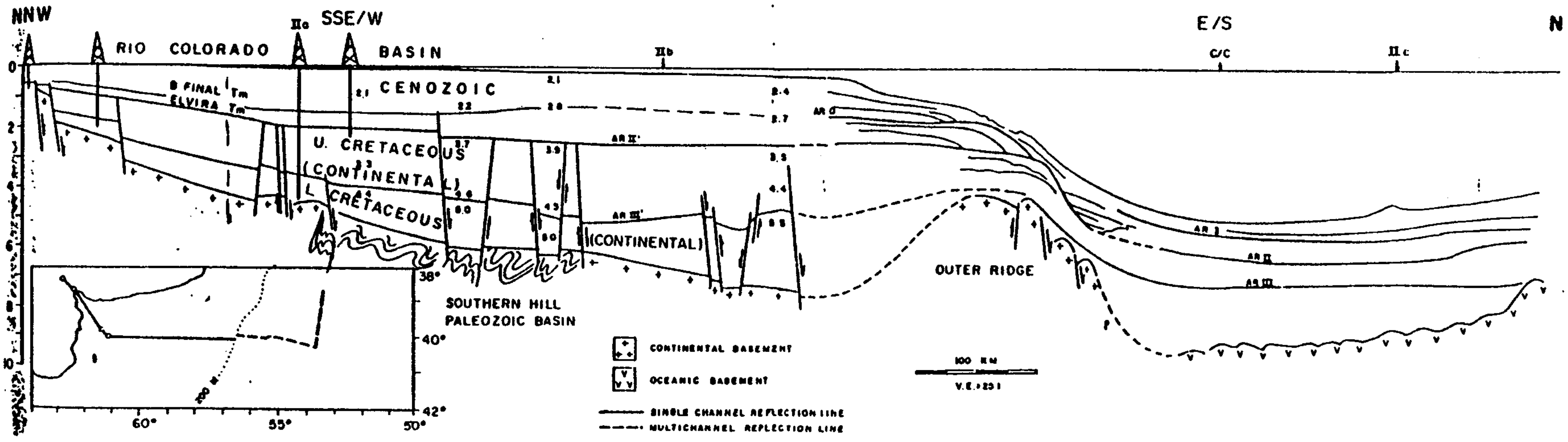


Fig. III.5.1. Two schematic cross-sections of seismic/geologic structure across the Argentine passive continental margin (courtesy C. Urien).

cordillera has provided a large volume of sediments to the Atlantic. Most of these sediments were not trapped in onshore basins, but bypassed to the continental shelf, slope and rise (Fig. III.5.1). Therefore, sedimentation has been controlled in part by cordilleran tectonic events, as well as by sea level fluctuations.

The available data for the South American continent and shallow marine basins include boreholes and multichannel seismic lines, and they allow correlations between the stratigraphic record and seismic nonconformities (Fig. III.5.1). Reflectors can be traced throughout the whole region. Therefore, sea level fluctuations, tectonic events and sedimentary accumulations can be correlated in most basins that are open to the ocean. Existing industry seismic and well data are restricted to the continental shelf and slope, but together with available single-channel academic data, they clearly define the regional geologic structure (Fig. III.5.1). However, **additional site-specific, high-resolution seismic surveys on the Argentine slope and rise will be needed.**

In summary, the Argentine margin is optimal for a study of eustatic sea level fluctuations because:

1) The southern part of South America is narrow enough to allow rapid bypassing of sediment from the cordillera to the continental shelf, slope, rise and the deep Argentine Basin.

2) Tectonic events during warping of the Patagonian Cordillera are recorded in the sedimentary record of the deep basin.

3) Climatic changes should be well-preserved in the stratigraphic record.

4) Coastal-basin data can easily be correlated through available seismic ties.

5) Basal sedimentary sequences at the foot of the continent cannot be reached because of the large sediment thickness near the lower slope. However, a high-resolution sea level and cordilleran tectonic record can be drilled in the Late Tertiary and Quaternary sedimentary section.

6) Sites should be located at the latitude of the Salado-Colorado basins and the central Patagonian basins, where sedimentary sequences are as complete as possible (Fig. III.5.1). However, these drill sites should be selected only after conducting additional high-resolution and multichannel seismic surveys and correlating these lines with existing information on the shelf and slope.

The Angola Basin is another South Atlantic location where a drilling transect could elucidate problems of eustatic sea level fluctuations. Two or three Angola Basin sites in water depths of 4400 to 4000 m would define the temporal duration and depth changes of the CCD there. **A similar transect in the Cape Basin would provide an important comparative check on Angola Basin results.**

IV. GEOCHEMISTRY

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INTRODUCTION

The geochemistry working group considered a variety of problems which could best be studied through geochemical approaches in the South Atlantic and adjacent Southern Ocean. These problems were grouped into two broad categories:

IV.1 Sediment geochemistry.

IV.2 Igneous petrology and geochemistry.

IV.1. SEDIMENT GEOCHEMISTRY

INTRODUCTION

Geochemical investigations of the long sedimentary records present in the four major basins of the South Atlantic Ocean and in the Weddell Basin can yield information about the development of surface/deep circulation patterns in these evolving basins and the accompanying changes in seawater chemistry, in the production and preservation of biogenic sediments, and in the diagenetic consequences of these factors. Interbasin comparisons provide opportunities not equaled elsewhere in the world's oceans. Problems of global significance relating to sediment geochemistry which can be addressed in the South Atlantic are described below, followed by an outline of drilling strategies which can be applied to address these questions.

CHEMICAL AND LITHOLOGIC FACIES OF THE EARLY SOUTH ATLANTIC-EVAPORITES AND "BLACK SHALES"

Two distinct chemical and lithologic facies are associated with the early opening of the South Atlantic. These are mid-Cretaceous evaporites and Lower to mid-Cretaceous organic-rich lithofacies (i. e., "black shales"). These facies are presumed to be characteristic of nascent passive continental margins in general, but are particularly well-developed on both sides of the South Atlantic. Thick (up to 3 km) evaporite deposits underlie the continental margins of Africa and South America (Fig. I.2.1). These evaporites are presumed to be of late Aptian to perhaps early Albian age based on stratigraphic studies of the salts themselves and of overlying and underlying deposits recovered from outcrops and from industry boreholes. These evaporites represent a period of constricted deep-water flow, possibly intense density stratification, and large-scale extraction of salts in a restricted basin that extended over 45° of latitude during the early opening of the South Atlantic (Fig. I.2.1). Their extent and thickness probably exceed those of the Miocene evaporites of the Mediterranean, so detailed knowledge of their age, volume and chemistry is critical to an understanding of the oceanographic and sedimentary conditions which prevailed during the mid-Cretaceous. Restricted circulation and associated evaporite deposition apparently was controlled by the Walvis Ridge-Rio Grande Rise to the south and the transform margin along the Romanche F.Z. (Fig. I.3.3) in the Gulf of Guinea to the north. Nonetheless, evidence for sympathetic changes in seawater chemistry should be manifested in the Aptian-Albian sedimentary record in the Cape-Argentine basin system to the south.

Questions that would be answered concerning these mid-Cretaceous evaporites by one or more latitudinal transects of deep boreholes in South Atlantic basins include:

1) What is the nature and timing of the transition from evaporite deposition to freely circulating, open-marine conditions that occurred in the Angola-Brazil basins during the Albian? Is there a symmetry in facies deposited at this time on both sides of the South Atlantic?

2) What are the time-equivalent facies in the Cape-Argentine basins and basins of the adjacent Southern Ocean?

3) Is there evidence of a coherent pattern of facies evolution in successively younger subbasins of the opening South Atlantic Ocean, first from restricted (evaporitic) environments, then to a phase of dominantly allochthonous input from shelf/upper slope basins ("black shale" facies), and finally to pelagic sedimentation?

The presence of evaporites may also have affected the accumulation of organic-rich sequences in the basins of the South Atlantic and adjacent Southern Ocean by promoting anoxia and helping to preserve organic matter. Organic-rich sequences of Early Cretaceous age are known from the four South Atlantic basins, as well as from basins of the Southern Ocean. The Lower Cretaceous (Neocomian) organic-rich strata occur within carbonate units. Most of the mid-Cretaceous (Aptian to Turonian) strata are carbonate-poor and clay-rich, resulting in cyclic interbedding of red, green and black claystone or shale. However, in general, organic-rich beds comprise only a minor part of the overall mid-Cretaceous sequence. Organic-rich sequences recovered from the Angola Basin (DSDP Sites 364 and 530; Bolli, Ryan et al., 1978; Hay, Sibuet et al., 1984) contain predominantly autochthonous marine organic matter that probably formed in highly productive marginal settings and was redeposited by turbidites and slumps at basinal sites.

Important questions related to the deposition of these "black shales" include:

1) Were anoxia and subsequent preservation of organic carbon in the Cape, Argentine and adjacent Southern Ocean basins coincident with, and ultimately related to, the spillover of evaporite brines from the Angola-Brazil basins?

2) Can the sources of organic matter be traced from basinal sites of accumulation to shallower sites of organic production?

3) Is the "black-shale" facies present in the Brazil Basin, as would be implied by the symmetrical evolution of Brazil-Angola passive margin basin systems (see Fig. I.2.1)? If so, is the organic matter of marine origin, or is there an east-west basin difference as there is in the North Atlantic, where the eastern basin off Africa contains predominantly marine organic matter, while the western basin off North America contains primarily terrestrial organic matter?

4) Were organic-rich sediments deposited in marginal settings such as the Falkland Plateau (DSDP Sites 327/330 and 511; Barker, Dalziel et al., 1976; Ludwig,

Krasheninikov et al., 1983) and Maud Rise (ODP Site 693; Leg 113 Scientific Party, 1987) sources of organic matter deposited in the Cape Basin (DSDP Site 361; Bolli, Ryan et al., 1978)? Does this allochthonous organic facies have an equivalent in the western Argentine Basin?

5) What are the nature, geochemical signature, paleoenvironment and age(s) of the organic-rich facies in the basins and margins of the Southern Ocean?

NEOGENE TO HOLOCENE UPWELLING OFF SOUTHWEST AFRICA

The history of the waxing and waning of the Benguela Current upwelling system is contained in the Miocene to Holocene sediment sequence off Namibia, Southwest Africa. This sequence consists of sediments rich in organic carbon, carbonate and biogenic silica deposited as cyclic interbeds with periodicities of tens of thousands of years. The sedimentary record of upwelling off Namibia is complete and has not been disrupted by tectonic events. If the history of the Benguela Current system is interpreted from the most complete drill site (DSDP Site 532; Hay, Sibuet et al., 1984), then upwelling began in late Miocene, reached a peak at the Plio-Pleistocene boundary and declined to a much lower level thereafter. And yet Benguela Current upwelling is active today, and the Namibian continental margin is one of the most productive areas of the modern oceans. Is the peak of productivity recorded at Site 532 indicative of changes in the Benguela Current upwelling system in general, or is it the result of shifting of the core of upwelling from offshore in late Pliocene-early Pleistocene to onshore during the Holocene?

DRILLING STRATEGIES

1) The age and chemistry of the evaporite sequences in the northern parts of the Angola and Brazil Basins, and the nature of the transition from restricted to freely circulating conditions in the Albian, can be documented by **slope-to-basin transects of deep holes** along the margins of Gabon and northern Brazil. It may not be necessary to penetrate the entire evaporite sequence, because it has already been sampled by wells onshore in Brazil.

2) Additional slope-to-basin transects should be drilled from the Falkland Plateau into the Argentine Basin in order to provide information on the transfer of organic matter from shallow sites of production to basinal sites of accumulation.

3) The age and nature of the mid-Cretaceous organic-rich facies of the Southern Oceans remains essentially unknown, except for a small amount of information derived from recent ODP drilling in the Weddell Sea (Leg 113 Scientific Party, 1987). This facies should be recovered from several sites along the Antarctic margin. These holes would also provide a detailed Jurassic and Lower Cretaceous sedimentary and biostratigraphic record of the remote and restricted marine environment in this southernmost part of Gondwanaland.

4) **Deep drilling** in the Angola and Brazil basins (evaporite sites), in the Cape and Argentine basins, and in the marginal basins of Antarctica would provide a **latitudinal transect of the Cretaceous "black-shale" facies** extending from a paleolatitude of about 15° to about 60°. These holes would also provide information on the symmetry or asymmetry of facies in the eastern and western basins of the South Atlantic.

5) **The development of the Benguela Current upwelling system could be traced by means of transects of hydraulic piston cores** collected along Walvis Ridge and the adjacent continental margin of Southwest Africa.

IV.2. IGNEOUS PETROLOGY AND GEOCHEMISTRY

INTRODUCTION

A major objective of marine petrology and geochemistry is understanding the processes that affect volcanism, mantle dynamics and crustal structure in ocean basins. The South Atlantic provides an opportunity to address a number of intraplate and plate boundary processes that are fundamental to that overall objective. Previous studies, primarily using isotopic and geochemical data from oceanic islands, have been instrumental in identifying a global mantle (i.e., the Dupal) anomaly located in the South Atlantic between 20°S and the Bouvet Triple Junction. Drilling must explore the spatial and temporal variations in the Dupal anomaly and its effect on ridge-crest processes.

Among the other distinctive features of the South Atlantic are the relative abundance of hotspots exhibiting unique geochemistries. A variety of hotspot-related problems can best be studied in the South Atlantic, where there are several off-ridge examples. Drilling should:

1) attempt to relate hotspot evolution to mantle (and mid-ocean ridge) geochemistry and the construction of associated topographic features (e. g. aseismic ridges and seamounts), and

2) assess the validity of using hotspots for calculating absolute plate motions and rates.

In addition, there are a number of other petrological problems related to magmatic and hydrothermal processes in specific tectonic settings (e. g. triple junctions, fracture zones and convergent/passive plate boundaries). These problems, all of which can be addressed by drilling programs in the South Atlantic, are outlined below.

MANTLE HETEROGENEITY

The abundance of off-ridge hotspots and the regional Dupal anomaly in the South Atlantic and Southern Ocean makes this region ideal for studying sub-oceanic mantle heterogeneities, hotspot evolution and their influence on newly formed oceanic crust and lithosphere. In particular, the South Atlantic lends itself to the study of two important aspects relating to mantle heterogeneities:

1) the relationship between hotspots and associated features such as aseismic ridges and seamount chains, and the use of such bathymetric features in constraining plate motion studies, and

2) the effects of off-ridge hotspots on the geochemistry of normal mid-ocean ridge basalts erupted along nearby spreading centers.

HOTSPOT TRACES

Two proposed hotspot traces are of particular interest in the South Atlantic/Southern Ocean. One is the major bathymetric anomaly comprised by the Agulhas Ridge-Meteor Rise-Shona Ridge, which has been proposed to reflect the paleo-trace of the Shona hotspot. The position of this proposed hotspot/"aseismic ridge" system (located at the southern end of the

Dupal anomaly) and the relationship of its paleo-position to the Agulhas F.Z. offers the opportunity to test important petrologic, mantle evolutionary and plate motion models that cannot be readily addressed in any other ocean basin.

Drilling sites at suitable locations along this hotspot trace will provide invaluable information relating to:

1) the nature and temporal variation of the geochemical signature of the Shona hotspot, and thereby the Dupal anomaly;

2) the interactions between a hotspot and an associated ridge-fracture zone system as it passes from one lithospheric plate to another;

3) the importance of pre-weakening of the lithosphere in controlling the position of ridge jumps; and

4) global and local plate motion models.

A second hotspot trace is defined by Trinidade Island and the Columbia seamount chain in the western South Atlantic at 20°S. Preliminary petrologic information from this region suggests that Trinidade reflects the modern surface expression of a mantle hotspot which bears a geochemical signature similar to that of Cretaceous-Tertiary Brazilian igneous rocks. This hotspot and associated bathymetric anomaly (which apparently extends across the continent-ocean boundary off this part of eastern Brazil) is one of the few located on the South American plate, and consequently provides an important constraint on plate motion studies in this region. Therefore, it is imperative to establish more clearly that this feature is indeed a hotspot trace. Furthermore, drilling along this bathymetric anomaly would also shed light on geochemical variability along strike, elucidating the changes in petrology and geochemistry of eruptives as a hotspot passes from beneath sub-continental to oceanic mantle.

RIDGE-HOTSPOT INTERACTIONS

Ridge-hotspot interactions are fundamental to our understanding of mantle dynamics and ridge processes, and the South Atlantic exhibits outstanding examples of those types of processes. The most distinctive compositional features of basalts erupting along the MAR in the South Atlantic are the large geochemical anomalies located along ridge segments in the vicinity of off-axis hotspots. The entire length of the MAR in the South Atlantic, except for a region between about 20 to 30°S, shows strong geochemical and isotopic anomalies believed to be hotspot-related. The geochemical signatures of these anomalies have been related to binary mixing between a "depleted" MORB ("mid-ocean ridge basalt") source and "enriched" hotspot sources. The mechanisms by which such mixing occurs are unknown, but models proposed range from preferential sub-crustal flow from the hotspot to the migrating ridge to "enriched" domains passively embedded in the mantle. Drilling into basement between the MAR and the influential off-ridge hotspots along well-defined flow lines (e. g. between the MAR and Tristan da Cunha Island, and within the Ascension Island-MAR-Circe system) would provide spatial and temporal constraints on these proposed models of hotspot-ridge interactions.

TECTONIC INFLUENCES ON MAGMA COMPOSITION

A number of petrologic and geochemical problems relating to the influence of tectonic setting on erupted magma composition can be addressed by drilling in the South Atlantic and Southern Ocean.

BOUVET TRIPLE JUNCTION

The Bouvet Triple Junction, located at the southern tip of the MAR, has been evolving in geometry and position as a consequence of plate reconstructions for ~60 m.y. The slow spreading ridges, ridge jumps and unusually evolved geochemistry of the basalts on at least one limb of the triple junction make this an important target area for understanding the influence of tectonic setting on the petrology and evolution of MORB's. **An on- and off-ridge drilling program in this area would provide fundamental information on the spatial and temporal variation in the geochemistry of basalts associated with an evolving triple junction located in the vicinity of two major hotspots (Bouvet and Shona).**

GEOCHEMICAL SIGNATURE OF TECTONIC SEGMENTATION

Studies of geoid anomalies along isochrons in the South Atlantic have shown major changes in residual height that appear to be coincidental with fracture zones. A fundamental aspect in interpreting these major breaks concerns the relation between these geoid anomalies and the geochemical/petrologic nature of the associated lithosphere. Consequently, **a drilling program along a non-zero age isochron crossing a major residual height change should be an important consideration in any South Atlantic drilling initiative.**

FRACTURE ZONES

The equatorial fracture zones in the South Atlantic have large offsets that document spreading history from initial continental breakup. Drilling along/across these fracture zones can provide samples of subcrustal material which will be crucial for understanding the origin and evolution of the oceanic lithosphere in a major zone of translational motion.

NORMAL RIDGE SEGMENTS

In view of the abundance of hotspot-influenced crust and lithosphere in the South Atlantic, **any drilling initiative in this region should consider the siting of a deep, on-axis hole on a "normal" ridge segment to provide a "type section" of crust unaffected by hotspot volcanism.**

CONVERGENT PLATE BOUNDARY

The Scotia Arc presents an opportunity to investigate the geochemistry of basaltic magmas generated in a back-arc tectonic environment associated with adjusting microplate boundaries. Drilling in this region could provide further constraints on tectonic influences over magmatic compositions in back-arc environments to be investigated by ODP elsewhere, e. g. in the western Pacific.

VOLCANISM AT CONTINENTAL-OCEANIC BOUNDARIES

Models of the geophysical and geochemical characteristics of continental-oceanic crustal boundaries, and an understanding of the geochemical and igneous processes that initially produce oceanic lithosphere, can only be accomplished by deep drilling into passive continental margins like those that bound much of the South Atlantic. Based on studies by PETROBRAS® of drill cores recovered from offshore southeastern Brazil, a systematic drilling program off Brazil and at the conjugate passive margin off Africa could sample crust that is transitional between continental and oceanic, thereby acquiring information about the geochemical characteristics of earliest oceanic lithosphere. Then, comparison of these rocks with the geochemical characteristics of both continental flood basalts in South America and Africa associated with continental rifting/plate separation and modern MAR basalts would help to establish the roles of continental and oceanic mantle in generating early basaltic magmas in the South Atlantic region.

HYDROTHERMAL SYSTEMS

Hydrothermal systems along spreading centers are well-known through direct observation from submersibles and study of fossil analogues exposed in ophiolite complexes. The heat that drives these circulation systems is provided by basaltic volcanism. However, as a result of the rapid cooling of basalts in the crust, the hydrothermal activity is short-lived and directly associated with periods of active volcanism. Although drilling at spreading centers to understand hydrothermal activity can be considered in any ocean, **the South Atlantic provides a unique opportunity for the investigation of hydrothermal systems association with islands and seamounts.** South Atlantic islands, and by analogy, South Atlantic seamounts, are unique in that they have differentiated to trachytic-rhyolitic composition. Plutonic equivalents of these rocks are capable of driving high-enthalpy hydrothermal systems over much longer periods of time than basaltic processes along "typical" spreading centers. A three-dimensional perspective of active hydrothermal processes, at spreading centers, islands and seamounts, is attainable only through drilling. The flanks of Ascension Island or Tristan da Cunha are recommended sites.

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