CARIBBEAN GEOLOGICAL EVOLUTION

REPORT OF A WORKSHOP TO DEFINE CARIBBEAN GEOLOGICAL PROBLEMS, NEEDED INVESTIGATIONS, AND INITIATIVES FOR OCEAN DRILLING

November 17-21, 1987

Oracabessa, Jamaica

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CONTENTS

SUMMARY: PRIORITY SCIENTIFIC PROBLEMS AND PROPOSED CARIBBEAN DRILLING INITIATIVES

The 53 participants of the Workshop on Caribbean Problems and ODP Drilling Initiatives appraised scientific problems of the Caribbean region for which ocean drilling is a necessary approach. The following eight problems, given below without ranking, are considered first priority on the bases of global thematic content and filling crucial knowledge gaps in Caribbean geologic evolution.

- **Paleogateways of the Caribbean:** existence and tectonic evolution of Jurassic and Cretaceous seaways in the rifting and drifting of North and South America.
- **Paleoceanography of the Caribbean:** oceanographic evolution of Jurassic and Cretaceous seaways between Atlantic and Pacific oceanic realms.
- **Origin of the Caribbean plate:** native Caribbean or exotic origin of oceanic lithospheres of the Caribbean plate.
- **Cayman Trough:** oceanic crustal formation, deformation, and magma genesis at a major transform plate boundary and the kinematic history of the modern Caribbean-North American plate boundary.
- **Caribbean oceanic plateaus:** magmatic processes, history of formation, tectonics, and geographic origin of thickened oceanic crust that resulted from widespread Cretaceous midplate volcanism in the Venezuelan and Colombian Basins.
- **Sediment subduction and arc magmatism:** role of subducted sediment and related fluids in magma generation in the Lesser Antilles magmatic arc.
- **Mechanics of accretionary forearc development:** mechanics of accretionary wedge thickening, inner forearc tectonics and forearc basin-wedge interactions, episodicity of accretion in the Lesser Antilles forearc.
- **Fluids evolution in accretionary wedges:** generation, migration, residence times, and material and heat transport of fluids from and volume loss budget of the Barbados accretionary wedge.

A shipboard drilling strategy to acquire data for major advances in solution of these problems includes general sites shown on Figure S1 and listed with estimated drilling time in Table S1. The total drilling time to address adequately the recommended problems/sites is nine drilling legs (each 2 months).

Participants strongly advocate that ODP begin planning a 9-leg program of Caribbean drilling as soon as possible.

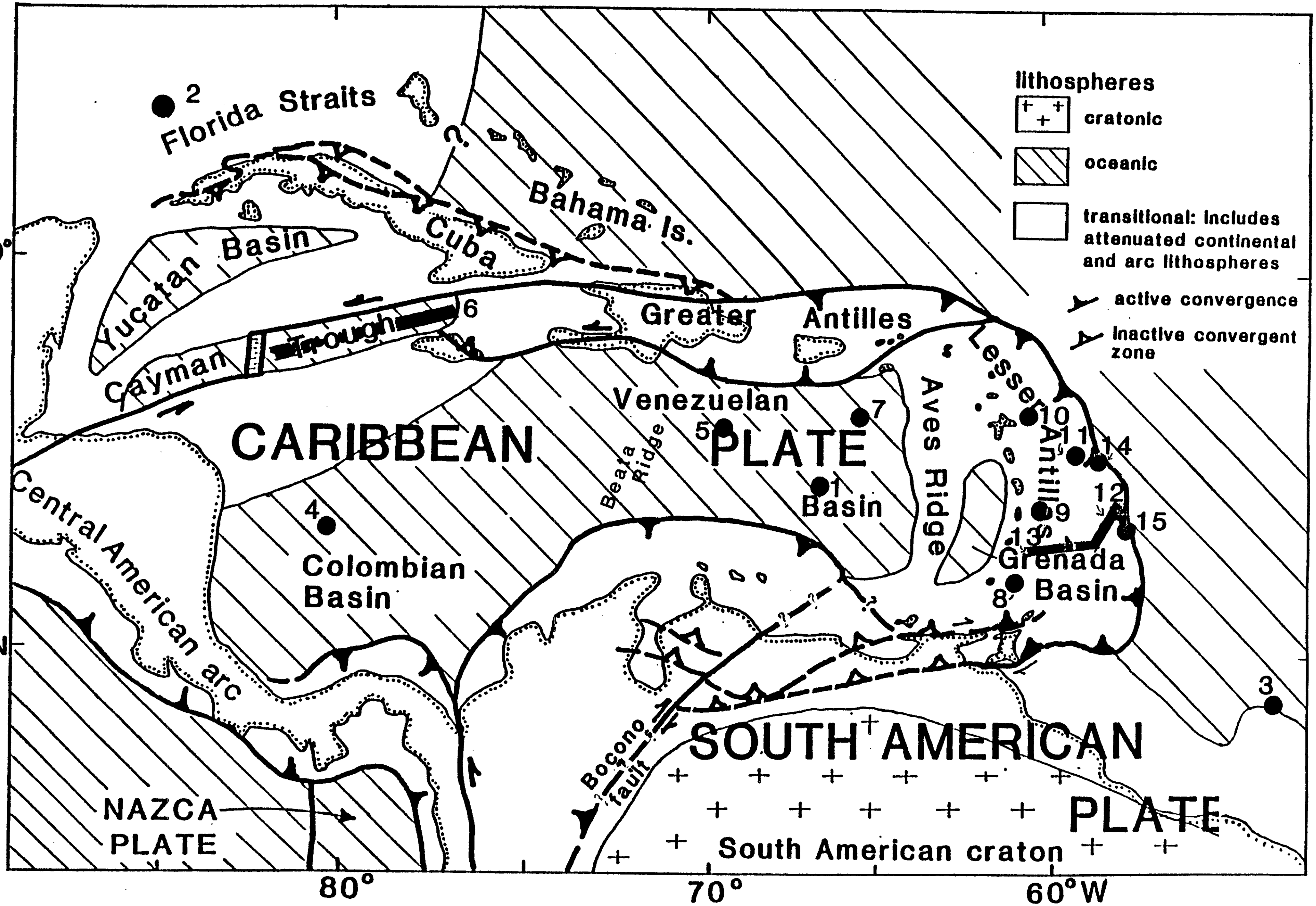

Figure S1: Sites recommended for ODP drilling to address priority scientific problems of Caribbean region; numbers refer to site listings of Table S1 and section IX.

Table S1: Site numbers on Figure S1, problems addressed, and estimated drilling time (in 2 month legs); summarized from section IX

	Site	Problem	Duration (legs)
1	SE Venezuelan Basin	paleogateways paleoceanography oceanic plateau Caribbean plate	1.0
2	SE Gulf of Mexico	paleogateways paleoceanography	0.5
3	Demerara Rise	paleogateways paleoceanography	0.5
4	SW Colombian Basin	paleoceanography oceanic plateau Caribbean plate	0.25
5	NW Venezuelan Basin	paleoceanography oceanic plateau Caribbean plate	0.25
6	Cayman Trough	crustal formation 2-d thermal subsidence basalt evolution Ca-NA plate history	1.0
7	NE Venezuelan Basin	oceanic plateau Caribbean plate	1.0
8-10	Lesser Antilles Arc Platform Flank	role of sediment subduction in arc magmatism	0.3 each
11	Barbados wedge northern	mechanics of accretionary wedges	0.5
12,13	Barbados wedge southern	mechanics of accretionary wedges	0.5 each
14,15	Barbados wedge southern and northern	fluids evolution in accretionary wedges	2.0
		total	9.0

I. CARIBBEAN WORKSHOP

A workshop to develop scientific ocean drilling initiatives in the Caribbean region was held at Oracabessa, Jamaica, November 17-21, 1987.

The goals of the workshop were as follows:

1. to provide an up-to-date assessment of major problems of the origin and evolution of Caribbean basins and bordering terranes, their structure and histories of motion, sedimentation, and water mass transfer.
2. to ascertain and prioritize the advances in understanding thematic and regional problems in the Caribbean region that can be made by ODP drilling.
3. to formulate and recommend a drilling strategy that can lead to solutions of high priority problems.
4. to identify and assemble a community of active scientists who will advance Caribbean studies under ODP by submission of specific drilling proposals or by the promotion of such submissions.

The workshop, convened by R. C. Speed, was attended by 53 geologists, geophysicists, and geochemists, identified in Table I-1, from 11 nations, including Colombia, Trinidad, Barbados, Jamaica, and Dominican Republic. Participants were asked to submit a brief of drilling sites and strategies before the meeting. A digest of this is in section VII. Participants and the meeting agenda were divided among four topics, as follows:

Tectonic evolution of plates and oceanic lithospheres
Chair: N.T. Edgar, Washington DC, US

Paleoceanography - sediment history - geochemistry
Chair: J.B. Saunders, Basel, Switzerland

Active margin and accretionary processes
Chair: G.K. Westbrook, Birmingham, UK

Magmatic processes, including arc, ophiolite, and intraoceanic
Chair: H. Sigurdsson, Rhode Island, US

Table I-1
PARTICIPANTS

	Panel
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Panels:
1. Plates and oceanic lithospheres
2. Paleoceanography - sediment history - geochemistry
3. Active margins and accretionary tectonics
4. Magmatic processes

The agenda (Table I-2) began with information exchange in formal plenary session. This was followed by panel meetings to define and prioritize problems that could be addressed by ODP drilling and were appropriate to the panel's scope. Panel membership is indicated in Table I-1. The panel deliberations were then distilled by panel chairmen and the convener to a roster of most important problems without internal ranking. These were presented in plenary session. The titles and organization of the roster were disputed as presented, and such matters were refined by an ad hoc committee (G. Draper, T. Donnelly, J. C. Moore, K. Klitgord) that did not include panel chairmen.

The most important problems as finally titled and organized are discussed in section IX together with an estimate of drillship time in units of 2 month legs (Summary and Table IX-1). Workshop participants strongly advocate that ODP dedicate a block of 9 legs to address the important tectonic, paleoceanographic, magmatic, and sedimentologic problems presented in this report.

Table I-2
AGENDA

Nov. 17 8:00 PM Introductory presentations

Conference goals and tasks	Speed
Ocean Drilling Program: guidelines, specifications for drilling, proposals, procedures	Buffler
History of marine drilling in the Caribbean and Gulf of Mexico: DSDP-IPOD-ODP	Hay

Nov. 18 and AM Nov. 19

Panel 1: Tectonic evolution of plates and oceanic lithospheres — Chairman: Terry Edgar

Keynote speakers:

Klitgord:	Constraints on the kinematic evolution of the Caribbean
Pindell:	Caribbean tectonic evolution

Others:

McCann:	Modern Caribbean plate motions
MacDonald	Caribbean paleomagnetism
Gose:	Is there a rigid Caribbean plate: paleomagnetic constraints
Jackson:	Jamaica Passage
Speed:	Nonrigid Caribbean plates and CA-SA collision
Schlanger:	Pacific-Caribbean connections from paleo-oceanographic and volcanic inferences
Frisch/Meschede:	Suspect terranes at the SW margin of the Caribbean plate
Salvador:	Southern boundary of the Caribbean plate: fact or fantasy?
Rosencrantz:	Yucatan Basin and Cayman Trough
Perfit:	Evolution of the northern Caribbean plate boundary
Draper:	Untitled truths
Avé L'Allemant:	Allochthoneity of the Venezuelan Basin
Larue:	Puerto Rico Trench
Hall:	Magnetic anomalies in the Colombian and Venezuelan basins
Mauffret:	Northern boundary of the Caribbean basin
Buffler:	Jurassic tectonics in the SE Gulf of Mexico

Panel 2: Paleoceanography—sediment history—geochemistry
Co-chairmen: John Saunders

Introductory presentation:

Saunders:	Synthesis of knowledge and problems

Others:

Keller:	Caribbean paleoceanographic and sedimentologic history
Droxler:	Carbonate platforms on the active Nicaraguan Rise
Peterson:	Deep circulation in modern Caribbean and paleoceanographic record

Panel 3: Active margin and accretionary tectonics — Chairman: Graham Westbrook

Introductory presentation:

Westbrook	Accretionary tectonics around the margin of the Caribbean

Others:

Behrmann:	Volume balance of sediments at the Lesser Antilles convergent margin
Kellogg:	Amagmatic accretion and subduction in southwest Caribbean

Panel 4: Magmatic processes (including magmatic arcs, ophiolites, and intraoceanic)
Chairman: Haraldur Sigurdsson

Introductory presentation:
Sigurdsson

Others:

Meschede:	Ophiolitic complexes of Costa Rica and interpretation as oceanic terranes

Posters:

Pindell:	*Caribbean tectonic evolution*
Edgar:	*Formation of the Cayman Trough*
Hay:	*Evolution of the Caribbean in a global context*
Burke:	*Evolution of the Caribbean*
Burkart:	*Possible correlations of granitoids between Central America and Caribbean Basin*
Donnelly:	*Paleoceanography of the Caribbean and tectonic history*
Mascle.	*New geological map of the Caribbean*
Mann:	*New info in the Greater Antilles*
Buffler:	*Structure of oceanic crust in the eastern Gulf basin*
Smith:	*Growth of the forearc basin and slope basins of the Lesser Antilles*
Bouysse:	*Evolution of the eastern Caribbean island arc system*

Nov. 19 PM: **Individual panel meetings** to address problems, drilling strategies (sites, objectives, and specifications in priority) and recommended related research.

evening: Scientific presentations — posters

Nov. 20 AM: **panel meetings:** continue activity of Nov. 19; preparation of reports
PM: reports of panel chairs to plenary session

Nov. 21 AM: **plenary session:** overall Caribbean strategies for ODP and other research

Departure by mid-day.

II. BACKGROUND AND INTRODUCTION TO CARIBBEAN TECTONIC EVOLUTION

R. C. Speed, Convener

This report begins with a highly generalized review of the Caribbean region and what is known of its tectonic evolution with the objectives of a context for the problems set forth in succeeding sections and background for the unfamiliar reader. The review is not restricted to problems that can be solved by drilling.

Geographic Focus: The region addressed in the workshop is bounded by the following elements (Fig. II-1): cratons of North America and South America, on the north and south, respectively; the oceanic Cocos and Nazca plates on the west; and oceanic lithosphere of the Atlantic basin on the east. The workshop focused mainly on the following physiographic and tectonic features of the Caribbean (Fig. II-1):

1. central Caribbean ocean basins, the Venezuelan and Colombian Basins,
2. peripheral small oceanic basins, the Grenada and Yucatan Basins and Cayman Trough,
3. transitional lithospheres of arc, continental, and uncertain origin that surround and/or lie between these oceanic basins and whose Cenozoic and Mesozoic evolutions are related to those of Caribbean oceanic basins,
4. western edges of Atlantic lithosphere that are related to Caribbean evolution: downgoing lithosphere at the Puerto Rico Trench and below the Lesser Antilles forearc and that attached to passive continental margins at the Bahamas and northeastern South America.

The Gulf of Mexico and Central American arc are logically within the Caribbean realm and were considered in discussions to maintain a comprehensive view of the tectonic, sedimentologic, and water mass evolution of the region. Owing to the relatively high level of past and present investigation of

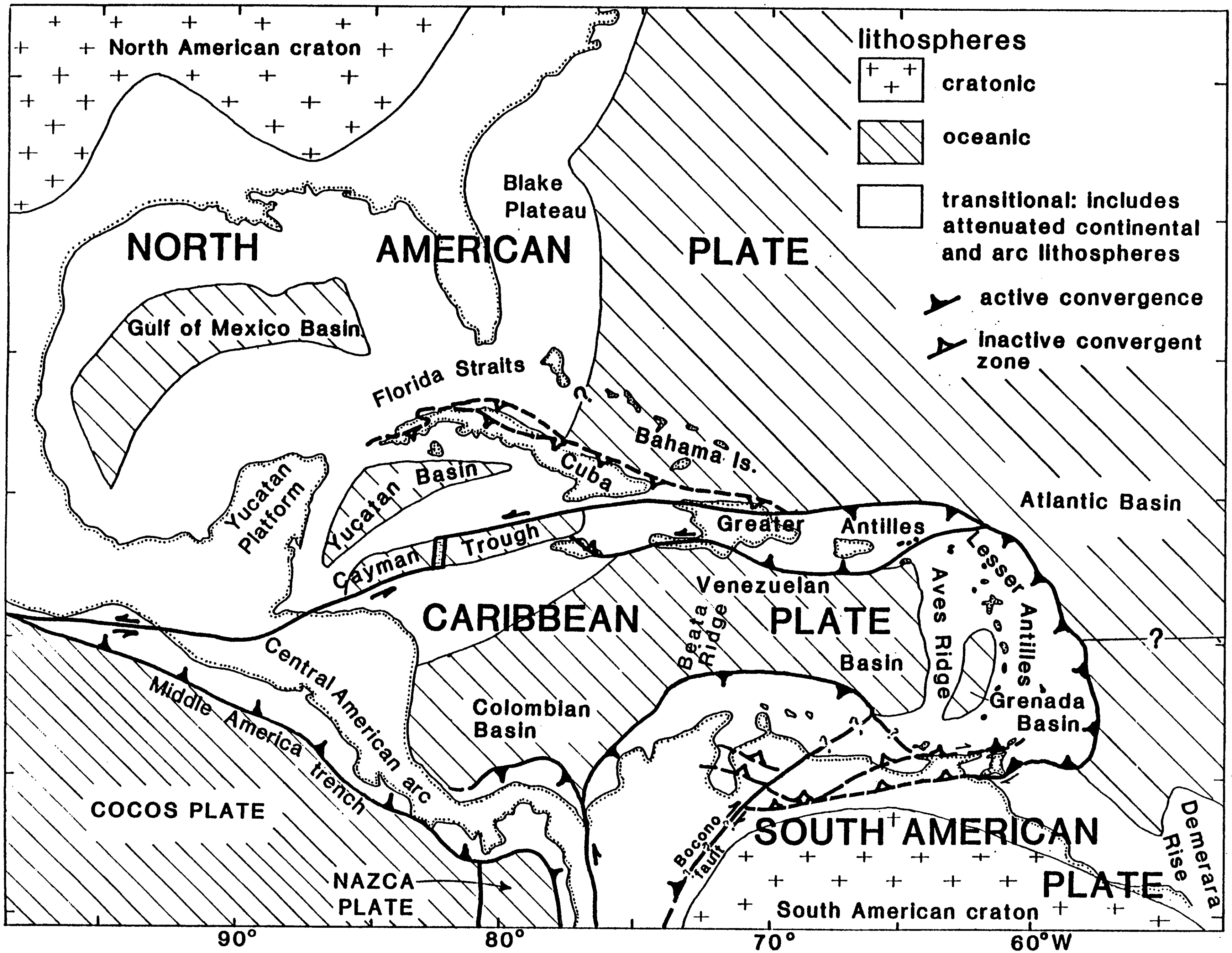


Figure II-1: The Caribbean region: geography and possible array of plates, zones of major modern displacement rates (solid lines), and lithospheric types.

these two features through DSDP and other auspices, they were given lower priority in considerations of new drilling initiatives.

Existing Data: Existing data on the Caribbean region come from onland (island and borderland) studies of geology and geophysics, marine geophysics, seismicity, plate kinematics, and marine drilling (mainly DSDP and ODP), coring, and dredging (see reference listing).

DSDP and existing ODP drilling (Fig. II-2) in the large Caribbean basins consist of Leg 4 (only 3 holes), Leg 15 (8 holes), and Leg 68 (only hole 504), a total of 12 holes. Legs 78A and 110 concentrated in a restricted area at the toe of the Barbados accretionary prism. The Gulf of Mexico - western Bahamas subregion has had Legs 1, 4, 10, and 77, comprising 26 holes. Although the Caribbean basin legs, particularly Leg 15, made a number of vital findings (Edgar, Saunders et al., 1973), the depth of penetration and core recovery were generally small, owing to difficult section and other impediments. Given this and the complexity of the Caribbean basins, the region is considered underdrilled. Compared to other oceans, the lack of highly successful DSDP/ODP drilling in the main Caribbean basins has hindered progress in understanding the development of the Caribbean relative to that in simpler and more popular oceans.

The abundance of well-studied onland tracts within and bordering the Caribbean, however, presents unparalleled opportunities for rapid strides in understanding the Caribbean when integrated the results of new ODP drilling in Caribbean basins.

Lithospheres: The possible distribution of types of lithospheres of the Caribbean and adjacent regions shown in Figure II-1 can be interpreted from sources in the reference list. The cratons of North America and South America are cored by Precambrian rock that has undergone little deformation in Phanerozoic time (last 700 ma). Between the cratons are lithospheres of certain and probable oceanic origin and others called transitional (Fig. II-1). Transitional lithospheres include continental crust that was stretched and diked in the Mesozoic; arc crust of Cenozoic and/or Mesozoic age built on terranes of oceanic, arc, or continental origin; and oceanic crust in obducted and subducted slices as well as arc

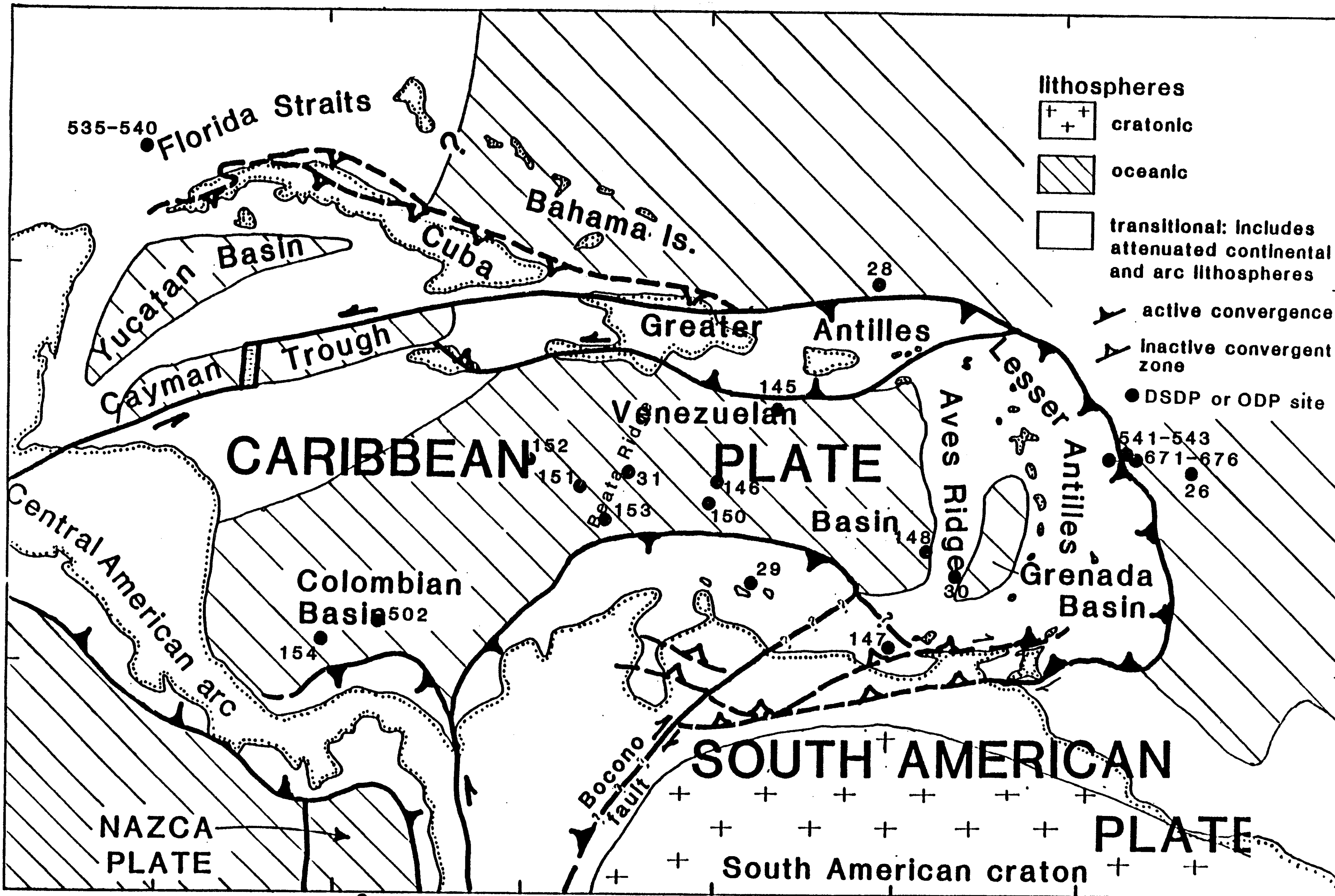


Figure II-2: DSDP and ODP holes in the central Caribbean Basins and adjacent tracts.

substrates.

The oceanic lithospheres of the Gulf of Mexico Basin (Late Jurassic), Yucatan Basin (pre-Oligocene), and Cayman Trough (Cenozoic) (Fig. II-1) appear to have crusts of normal thickness, whereas those of the Colombian and Venezuelan Basins (Coniacian or earlier) and the Grenada Basin (Eocene or earlier) have crusts that have wide areas of abnormally great thickness (12 km) together with patches of normal thickness. In the Colombian and Venezuelan Basins, the areas of thick crust, here called oceanic plateaus, contain at highest basement levels basalt of Late Cretaceous ages (Edgar, Saunders et al., 1973). It is a question whether the oceanic plateaus are built on older lithospheres or developed during initial lithospheric generation. None of the oceanic lithospheres of the Caribbean region has a well resolved magnetic fabric that can be interpreted with certainty in a context of seafloor spreading despite important attempts by Ghosh et al. (1984) and earlier workers.

Plates: The Caribbean region comprises three plates (Fig. II-1): Caribbean (Ca), North American (NA) and South American (SA). Ca and NA converge against the Cocos or Nazca plates at their western margins at the Middle America trench. A large microplate, composed mainly of northwestern SA, moves with a northerly component relative to the main SA plate.

The NA and SA plates are currently in relative motion about a pole in the central Atlantic (Fig. II-3) with convergence at small, westward-increasing rates in the Caribbean region. (Ladd, 1976; Minster and Jordan, 1978; Pindell et al., 1988; Argus and Gordon, 1988). Because of the proximity of the NA-SA pole to the Caribbean, however, the uncertainty in the pole position causes large uncertainty in convergent rates at all positions in the Caribbean. The existence and position of a discrete boundary between NA and SA are unknowns; a broad diffuse zone of convergent displacements is a likely alternative.

The Caribbean plate is generally poorly defined as to the positions of its boundaries, relative velocities with surrounding plates, and the extent of its internal rigidity. The Cayman Trough (Fig. II-1) contains the only modern spreading center contacting the Caribbean plate and is thus the only site the plate's relative velocity can be determined by reliable methods (MacDonald and Holcombe, 1978; Minster and Jordan, 1978; Rosencrantz et al., 1988; Stein et al., 1988). The long transform faults and related seismicity of the Cayman Trough give a good local Ca-NA direction (N80E) and Euler pole position, but the rate is much less precise owing to difficult magnetic correlations and complex ridge structure. The latest estimate is ≤15 mm/yr over the last 26 ma (Rosencrantz et al., 1988) whereas other estimates are as great as 40 mm/yr at times in the late Neogene.

Away from the Cayman Trough, the Caribbean plate is defined locally by seismicity and more generally, by Quaternary deformation in the transitional lithospheres surrounding the Colombian and Venezuelan Basins (Fig. II-1). Such phenomena indicate both convergent and strike slip motion. Seismic zones dipping below the Caribbean exist at the Middle America trench (Molnar and Sykes, 1969; Stein et al., 1988) and below the northern Lesser Antilles from Martinique north (McCann and Sykes, 1984; Wadge and Shepherd, 1984). Elsewhere, earthquakes give either no definition of a boundary zone or local movement zones of great complexity, both of which occur in the southern Caribbean and Greater Antilles (Kafka and Weidner, 1981; McCann and Sykes, 1984).

Ca-NA motions can in principle be exported from the Cayman Trough using the rigid plate assumption, and extended to the eastern and southern Caribbean, using Ca-SA = Ca-NA + NA-SA. Assuming rigid plates, generally eastward transport is predicted of the Caribbean relative to all points in NA and SA at uncertain but small rates; specifically, convergence is predicted S80E for Ca-NA in the northern Antilles and S77E for Ca-SA near Trinidad. It is a question, however, whether the assumption of rigidity is valid. For example, some focal mechanisms of thrust earthquakes in the northern Lesser Antilles suggest Ca-NA convergence of N65E (Sykes et al., 1982), about 30° from the Cayman-derived predicted direction. Further, the central Caribbean basins contain extensive faults and lineaments which probably originated by active or Cenozoic tectonics rather than by seafloor spreading. Moreover, there is no evident throughgoing zone of strikeslip faulting between Ca and SA. At the opposing limit to the rigid hypothesis, all or parts of the Caribbean plate may in fact be an assembly of

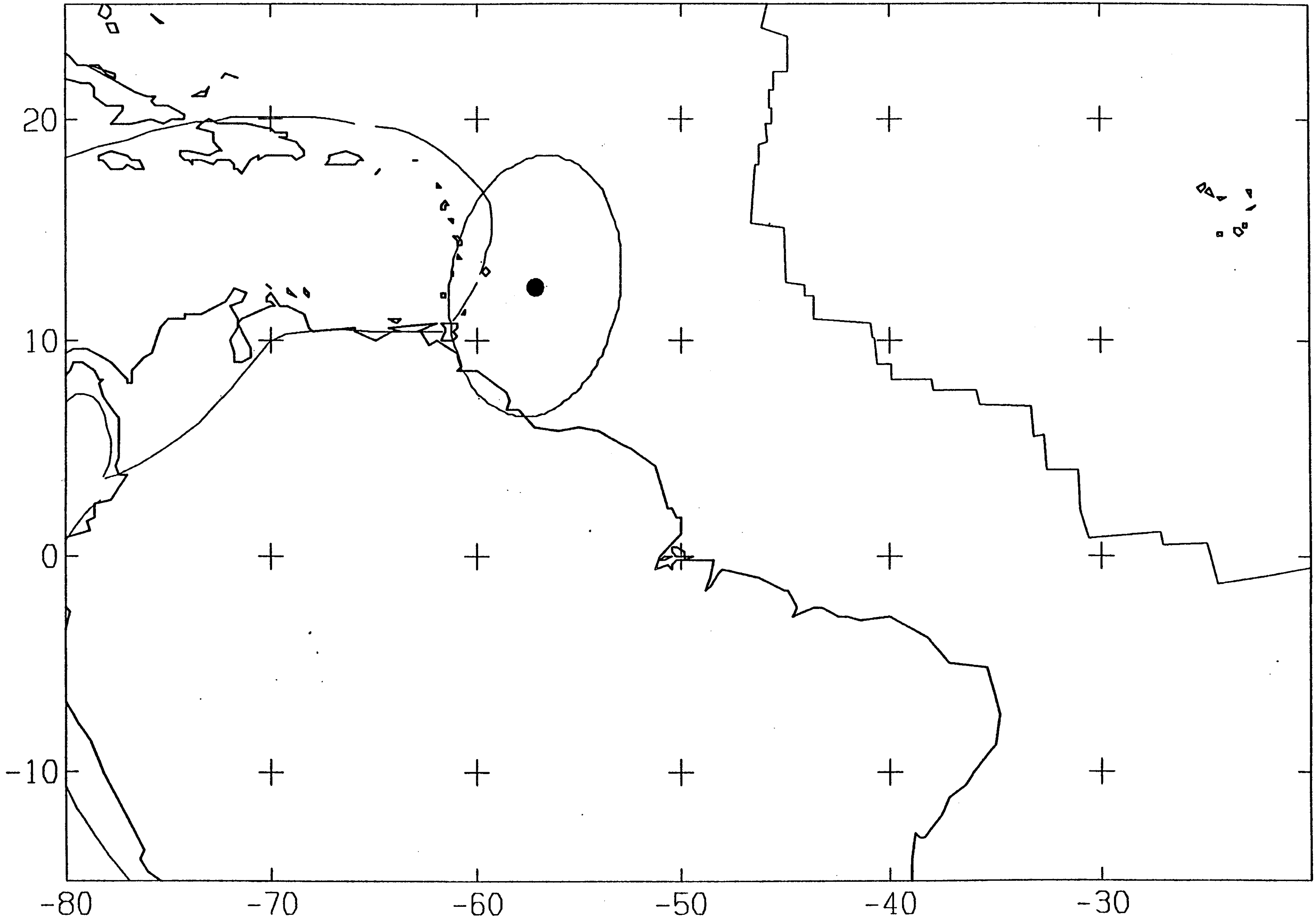


Figure II-3: NA-SA rotation pole for last 3 ma (dot) and 1 σ ellipse, calculated from NUVEL 1 global motion model (D. Argus and R. Gordon, unpub., 1988); SA moves clockwise with respect to fixed NA at 0.3/yr angular speed.

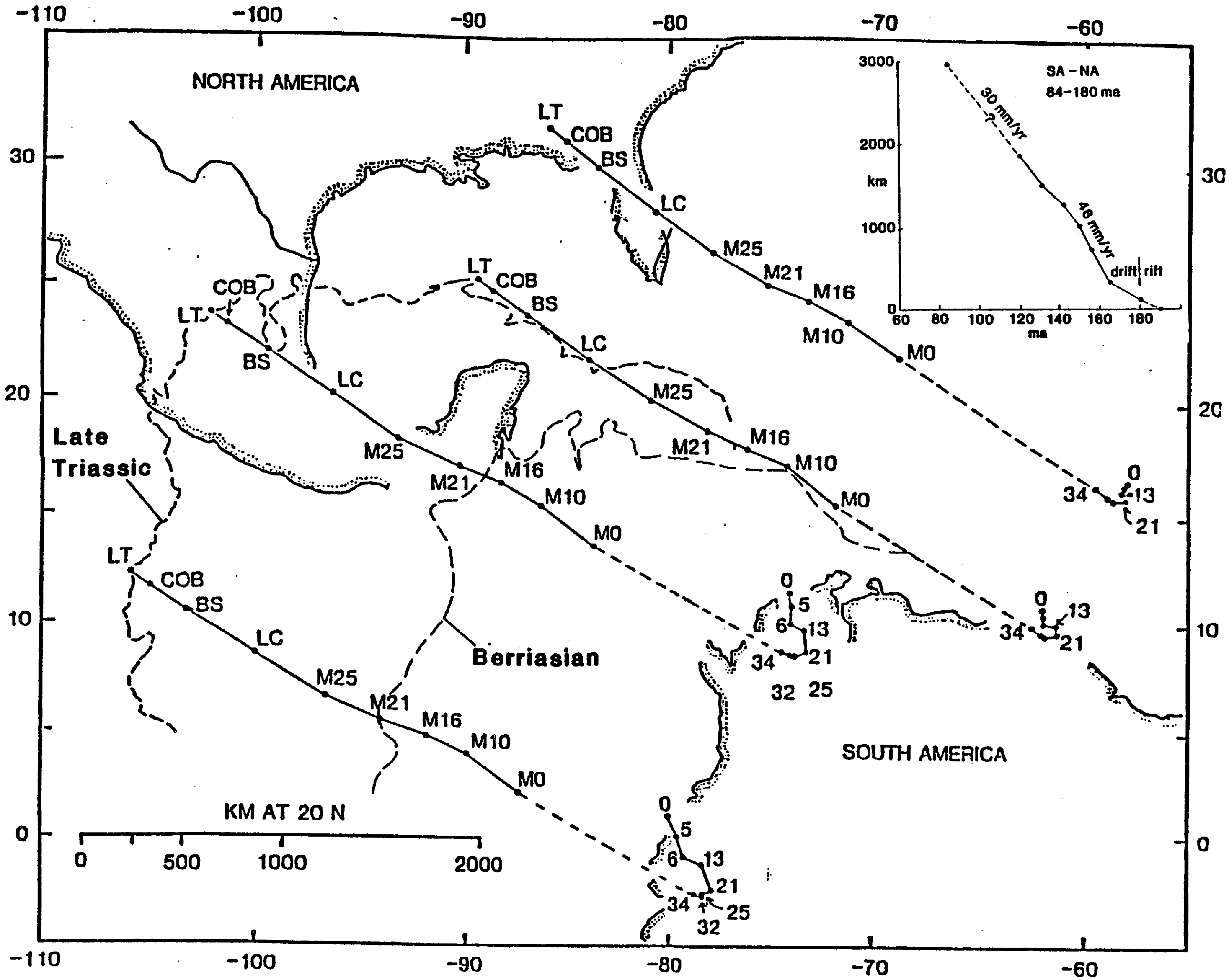


Figure II-4: Displacement-time paths of four points attached to the South American plate relative to North American plate from breakup of Pangea to the present calculated by Pindell et al., 1988. LT: late Triassic; COB: onset of central Atlantic drifting; BS: Blake Spur anomaly; LC: late Callovian (170 ma); M: pre-quiet interval magnetic anomalies; M21: Berrasian; MO: early Aptian (119 ma); LA: late Albian (linear interpolation); numbers: post-quiet interval magnetic anomalies; 34: Cenomanian (84 ma); 25: late Paleocene (50 ma). Time scale from Palmer (1983).

microplates.

Tectonic History: The tectonic evolution of the Caribbean region can be viewed in two ways: first, the growth and progressive reconfiguration of a huge gap between the North and South American plates in Mesozoic and Cenozoic times, and second, the result of processes that occurred within the gap and between the gap and the Atlantic and Pacific basins to the east and west. It is interesting that the evolution of the gap boundaries, hence the geographic context of the Caribbean region is relatively well known, whereas the evolution of lithospheres within the gap is not. A number of comprehensive models for both evolutionary paths exist: Freeland and Dietz, 1972; Walper and Rowett, 1973; Malfait and Dinkelman, 1973; MacDonald, 1976; Ladd, 1976; Stephan et al., 1980; Sykes et al., 1982; Pindell and Dewey, 1982; Ghosh et al., 1984; Burke et al., 1984; Beets et al., 1984; Mascle et al., 1985; Klitgord and Schouten, 1986; Pindell et al., 1988; Pindell and Barrett, 1989. In the following, however, stress is put on unknowns with views toward needed investigations.

The Mesozoic generation of the North and South American plates from Pangea and the subsequent motion of these plates set a 3-stage evolutionary framework for the Caribbean. The first stage is the breakup of western Pangea beginning in Late Triassic time and extending well into the Jurassic (Fig. II-4). The second is the southeastward drift of SA relative to NA at an average 30-40 mm/yr and the major growth of the Caribbean region from mid-or later Jurassic time to a mid-Cretaceous age between Aptian and Campanian. The third stage, from the end of stage 2 within the Late Cretaceous to the present, is marked by small and varied relative displacements of NA and SA, hence, only minor reconfiguration of northern and southern margins of the Caribbean region (Fig. II-4). Such data come from onland studies of the rifted margins of the American plates (Pilger, 1978; Thomas, 1985) and from Atlantic fracture zones and magnetic isochrons which yield NA-Africa + Africa-SA finite rotations and displacement paths vs. time (Ladd, 1976; Sclater et al., 1977; Klitgord and Schouten, 1986; Pindell et al., 1988).

Analyses of the relative displacement histories of the North and South American plates have evolved to a well resolved data set that is a constraint to Caribbean evolutions. It is important to note, however, that uncertainties exist in the plate rotation analyses, leaving an imprecision in plate positions and orientations through time that is not yet quantified. The principal uncertainties are 1) the kinematics of SA and northwestern Africa in Early Cretaceous time; 2) motions during the Cretaceous magnetic quiet interval; and 3) basic positioning of magnetic lineations and fracture zones (Stock and Molnar, 1982). The upshot of the uncertainties is that the reconstructed positions of NA and SA are imprecise to an unknown amount at each rotation stage and that an unspecified range of paleogeographies, which includes that of Figure II-4, exists for the boundaries of the early Cenozoic and late Mesozoic Caribbean region.

Stage 1: The reconstruction of Pangea and an understanding of the controls of its Paleozoic assembly are one of the basic goals of earth science. A perpetual question is the arrangement of NA and SA and other Paleozoic terranes in western Pangea (Bullard et al., 1965; Le Pichon and Fox, 1971; Ross, 1979; Pindell, 1985; Vander Voo et al., 1976; Klitgord and Schouten, 1986) and whether or not Paleozoic oceanic lithospheres existed between NA and SA or within their suture zone. As noted, reconstructions using finite rotations provide only general paleogeographic limits of continents' positions in Pangea. The absence of recognized Paleozoic ophiolite and related sediment in the Caribbean region is good evidence (Pindell and Dewey, 1982; Burke et al., 1984) that Pangea was probably fully continental. A more open question is the origin and times of emplacement within the Caribbean of pieces of transitional lithosphere of prebreakup ages and whether these are native to the NA-SA gap or entered the gap from other sites in Pangea or from sites outside Pangea.

The distribution, timing, and directions and magnitudes of transport of breakup tectonics in western Pangea are vital ingredients to an accurate reconstruction and to an understanding of the early development of the Caribbean region and its seaways. The breakup is recorded by rifting and magmatism beginning in Late Triassic and ending by Late Jurassic time in the Gulf Coast (Salvador, 1987;

Buffler et al., 1985; Winker and Buffler, 1988) whereas in northern South America, breakup phenomena, sparsely known, are recognized no farther back than Middle Jurassic (Maze, 1984; Feo-Codecido et al., 1984). Was the breakup south-propagating? Breakup structures in the Gulf Coast are generally interpreted to indicate no regionally uniform direction of transport and heterogeneous or sequential deformation (for example, Pilger, 1978). Does this reflect a succession of varied early extension directions or, on the other hand, control of breakup structures by inherited (Ouachitan?) structures above a uniformly extending ductile zone? How far did the two cratons separate in the breakup before the onset of drifting, and was the breakup direction similar or dissimilar to the succeeding drift vector of SA relative to NA?

A solution to the problem of Pangean breakup will bear not only on early Caribbean history but also on global themes of the causes and mechanisms of long continental transforms, control of rift-drift zones by pre-existing structure, and possible changes in asthenospheric flow during the transition from rifting to drifting.

Stage 2: Magnetic isochrons at the margins of the central-north Atlantic suggest the onset of seafloor spreading and resolvable drift of SA relative to NA in the Middle Jurassic, at a time that corresponds to the continent-ocean boundary (COB) or Blake Spur anomaly (BS) (Fig. II-4; Klitgord and Schouten, 1986; Pindell et al., 1988). Rotation poles for the second stage of Caribbean evolution suggest fairly steady separation of the American plates in a NW-SE direction of about 3000 km over 50-100 my at 30 to 60 mm/yr (Fig. II-4).

In contrast to the relative certainty of the history of expansion in Late Jurassic and Early Cretaceous times of the northern and southern boundaries of the Caribbean region, there is much uncertainty about the kinematics, mechanisms, and timing in the development of the lithospheres that now or did occupy the Caribbean region. This uncertainty has two stems:

1. Did the motions within the Caribbean region follow a) streamline flow in which all material (newly formed oceanic crust and fragments of transitional lithospheres) followed small circles to

the NA-SA rotation pole; this is illustrated in the model of Klitgord and others (1984) (Fig. II-5) which hypothesizes a series of small circle fracture zones extending from the Atlantic into the Caribbean region; or b) turbulent flow within the horizontal in which there were local rotations about poles other than the NA-SA Euler Pole and in which convergent and strike slip motions may have existed locally as well as divergent ones?

2. Were the second stage displacements in the Caribbean region restricted to native materials (locally generated oceanic lithosphere, Pangean fragments, and possible arcs), or did such displacements include tectonic exchanges of lithospheric fragments between the Caribbean and Pacific and/or Atlantic realms? If the flow were streamline, the lithospheres are all native whereas turbulent flow was likely to have included exchange.

Regardless whether streamline or turbulent, the second stage flow in the Caribbean region was divergent with high obliquity (45°) relative to its northern and southern boundaries. This implies that even in the simplest flow model, rifting and early drifting had high ratios of transform to normal opening relative to other major oceans such as the Atlantic.

Seafloor spreading during stage 2 can be confidently postulated in the Gulf of Mexico Basin and off northeastern South America at the Demerara Rise (Fig. II-1) from local stratigraphic and geophysical evidence. The Gulf of Mexico Basin apparently began and finished spreading in Late Jurassic time; its spreading direction is uncertain but all geologists who have addressed the Gulf Basin's origin postulate rotation of one or more of its boundaries during spreading (Hall et al., 1982; Pindell, 1985; Salvador, 1987). Further, the Yucatan terrane and other transitional lithospheres at the southern margin of the Gulf Basin are thought from stratigraphic evidence to have been in place by the end of the Jurassic (Salvador, 1987; Winker and Buffler, 1988). Therefore, aside from the Gulf of Mexico Basin of 400 km length in the NA-SA drift direction, stage 2 expansion of the Caribbean region must have included another approximately 2500 km NW-SE of spreading and stretching between the that and northern South America (Fig. II-4) (Pindell et al., 1988). The loci of such displacements have not

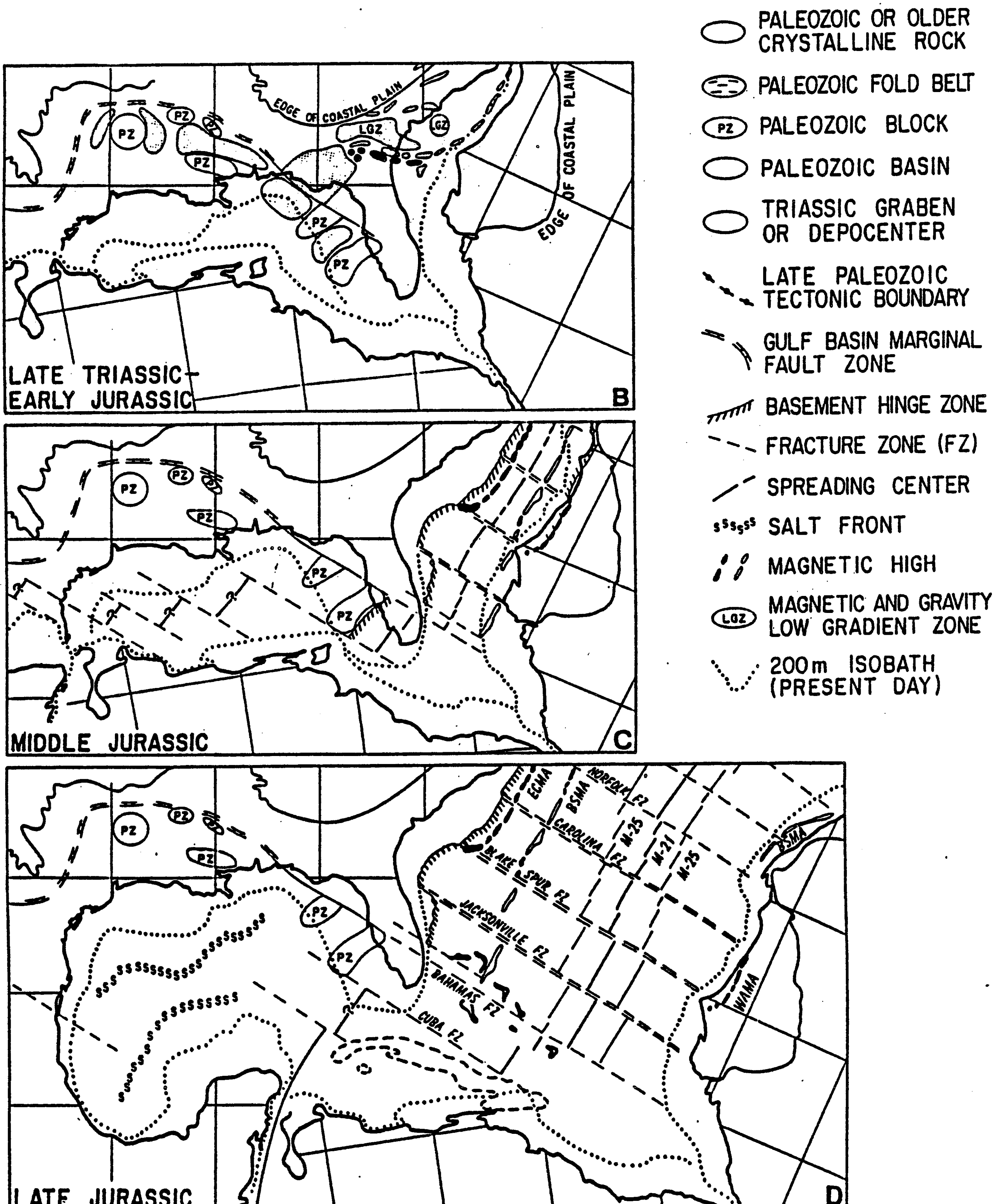


Figure II-5: Early drift stage model of Caribbean region (Gulf of Mexico and Florida Straits) assuming oceanfloor spreading paths follow small circles to the NA-SA rotation pole, after Klitgord et al., 1984.

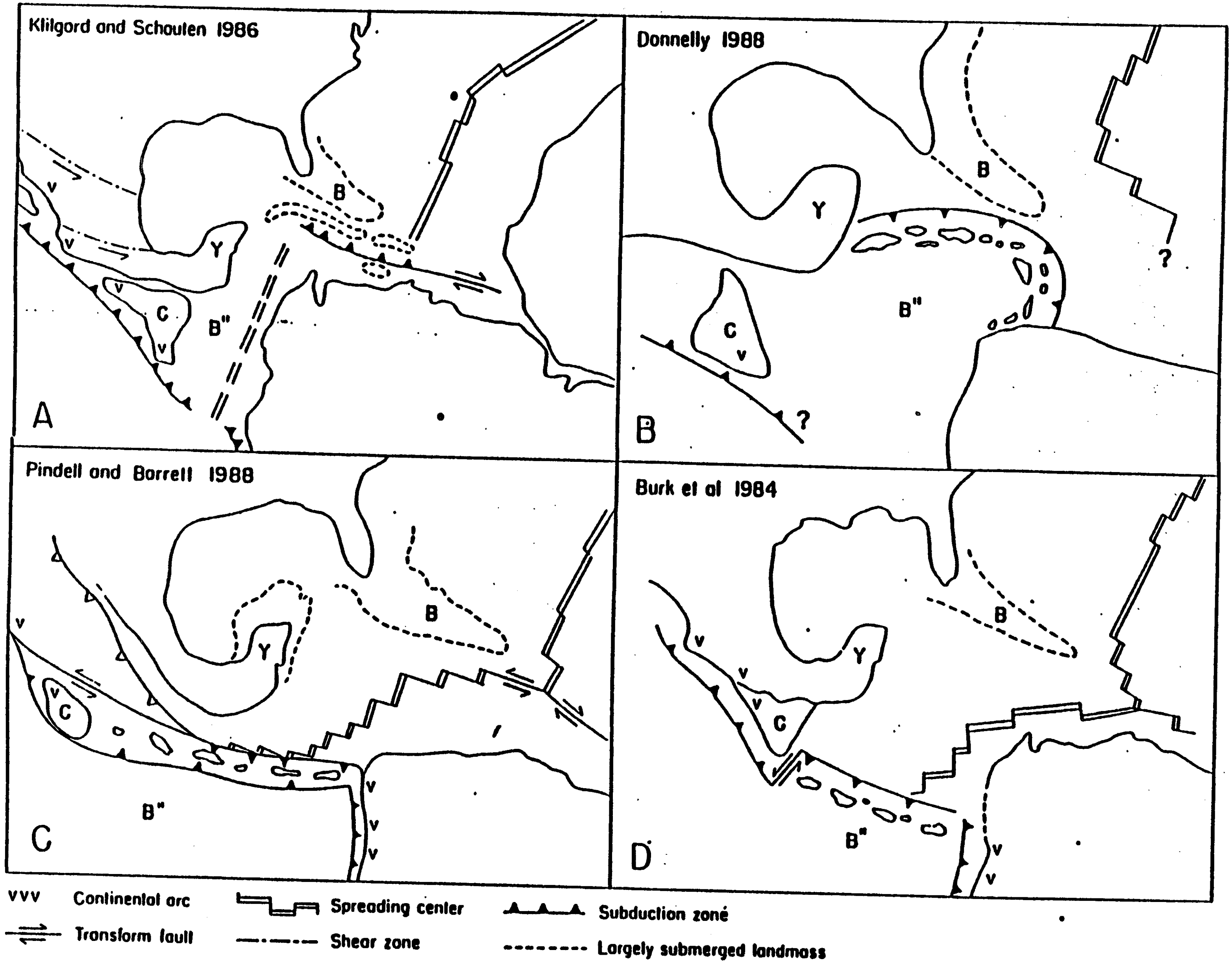


Figure II-6: Four different stage 2 reconstructions of the Caribbean region. A and B (Klitgord and Schouten, 1986; Donnelly, 1988) show today's Colombian and Venezuelan Basin lithospheres (B") as native to the Caribbean. C and D (Pindell and Barrett, 1989; Burke et al., 1984) show such lithosphere as exotic to the Caribbean. Compiled by Perfit and Williams (1989).

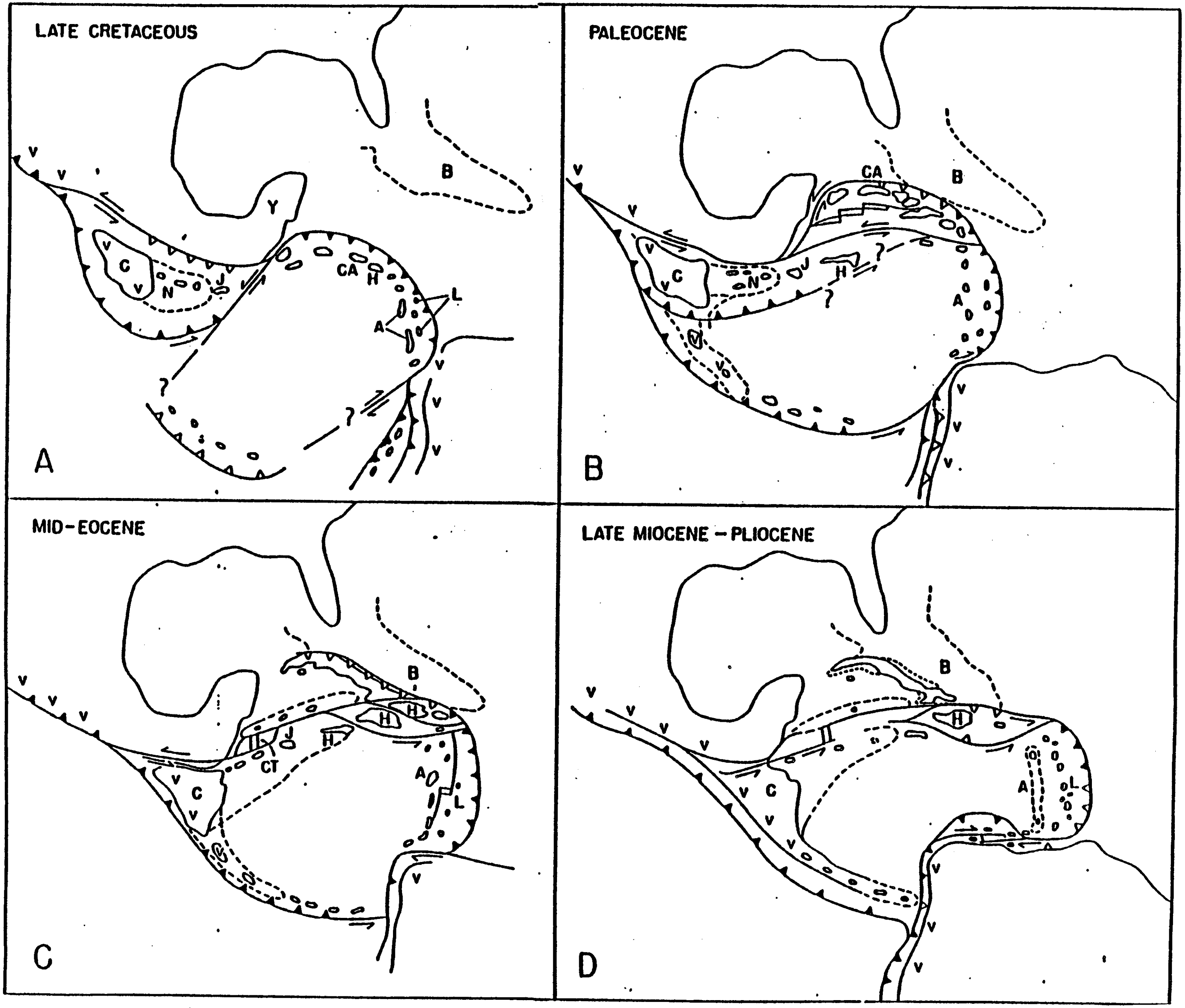


Figure II-7: Model of Caribbean with large transport in stage 3, incorporating ideas of Perfit and Heezen (1978), Burke et al. (1984), Wadge et al. (1984), and Pindell and Barrett (1989), presented by Perfit and Williams (1989).

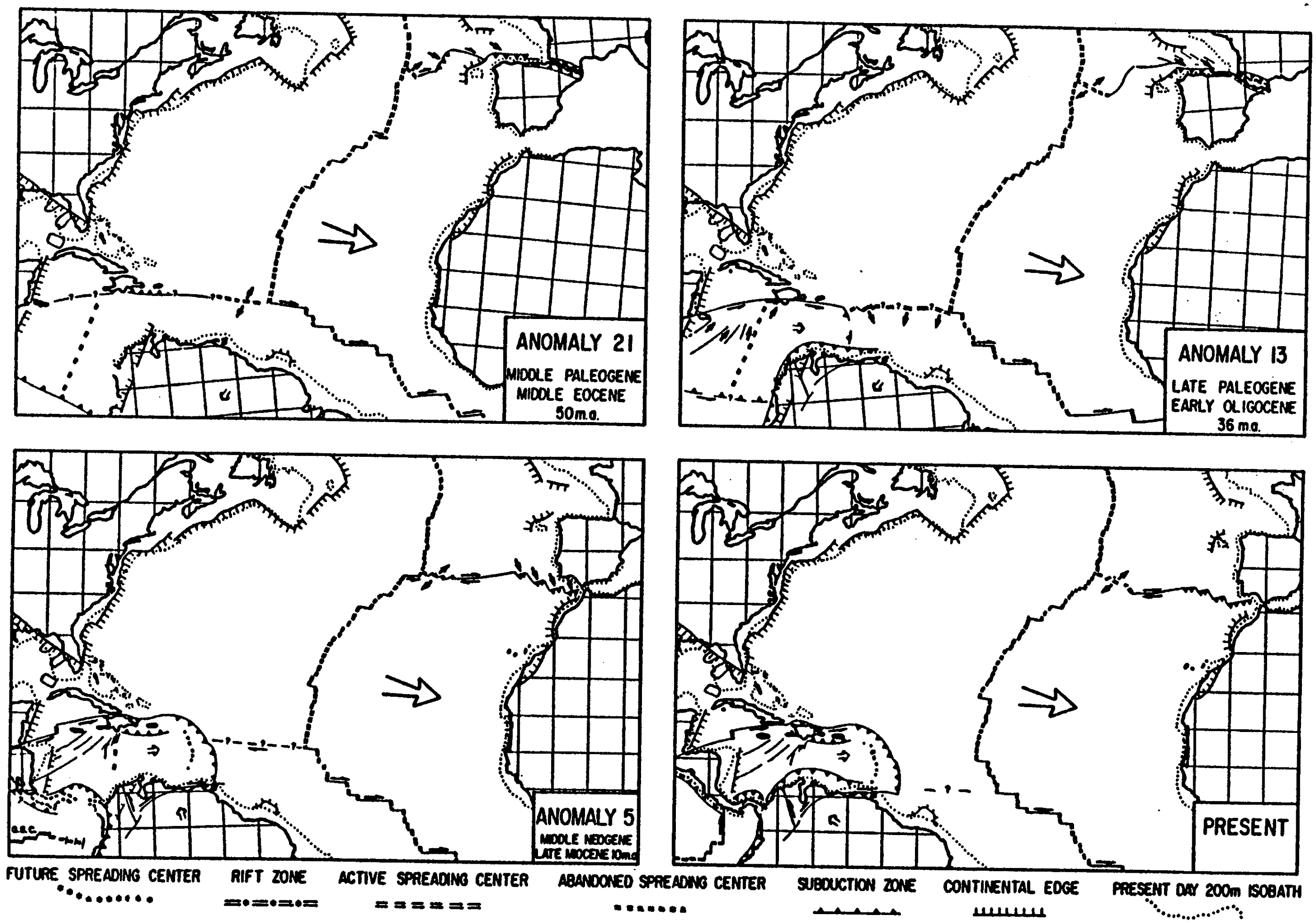


Figure II-8: Model for later stage 3 Caribbean tectonic evolution assuming small displacement of Caribbean plate relative to North American plate, from Klitgord and Schouten (1986).

been identified and may not be fully recognizable owing to possible total subduction below exotic lithospheres during stage 3. Nonetheless, the possibility of turbulent motions in stage 2 is indicated by the varied orientation of rifts in the Gulf Coast, paleomagnetic data of eastern Mexico (Gose et al., 1982), and features of the Gulf of Mexico Basin.

A fundamental question to Caribbean evolution is the role of the oceanic lithospheres of the Colombian and Venezuelan Basins during stage 2. Did they form by progressive spreading in stage 2, culminating in development of the oceanic plateaus, perhaps by diffuse midplate volcanism, at the end of stage 2? Or, did these lithospheres form totally with the advent of the oceanic plateaus late in stage 2? Or, are these lithospheres fully exotic and transported in during stage 3? Figure II-6 shows alternative conceptions of stage 2 paleogeographies of the Caribbean, A and B depicting native origins of oceanic lithospheres and C and D, exotic.

Transitional lithospheres of the Caribbean region south of the Gulf of Mexico Basin that are clearly older than or perhaps contemporaneous with the end of stage 2 exist as far south as Cuba. South of Cuba, stage 2 lithospheres are sparsely identified except for the Chortis terrane, obducted mafic and ultramafic complexes of Central America, the Greater Antilles and northern South America, and the La Desirade igneous complex of the Lesser Antilles. The region south of Cuba includes other complexes that may be stage 2, say pre-Albian, but their dating is uncertain (examples: Water Island of the Virgin Islands; La Rinconada of Margarita; El Tambor of Guatemala; mafic terranes of Hispaniola). It is a question whether the transitional lithospheres from Cuba north were wholly or partly native in stage 2 and if exotic, where they came from. For those older transitional lithospheres south of Cuba, the question is the same but moreover, whether some or all of them arrived during stage 3 from Pacific realms. In particular, do transitional lithospheres of probably ancient arc affinity indicate that subduction occurred in the southern Caribbean region during stage 2, implying rates of spreading within Caribbean basins exceeded the rate of expansion of the Caribbean region?

Stage 3: The third and final stage, which began some time between base Aptian and base Campanian, has only minor relative movement of NA-SA (Fig. II-4). Thus, the northern and southern boundaries of the Caribbean region were nearly stationary in this interval. The principal tectonics are the generally eastward transport of the Caribbean plate (or plates) relative to the American plates (Fig. II-1).

An uncertainty of great importance in Caribbean tectonic evolutions is the magnitude and duration of eastward transport of the Caribbean plate, or more particularly, its velocity history. If the transport has been small, the Caribbean plate is composed largely of native lithosphere (with respect to stage 3). In this case, a record of stage 2 tectonics, paleogeography, water mass transfers, and biotic development may exist in much of the Colombian and Venezuelan Basins and bordering terranes. If, on the other hand, transport has been large (>1000 km), much or all of the Caribbean plate is exotic in stage 3 and a fragment of the Farallon plate derived from Pacific realms (Malfait and Dinkelman, 1973). In this case, only the younger part of stage 3 Caribbean events and conditions is recorded in the Colombian and Venezuelan Basins, and it is not clear how far back the younger part extends. Figures II-7 and II-8 show time series models of Caribbean plate arrangements during stage 3, the first for large transport and the second, small.

The potentially most well resolved gauge of the movements of the Caribbean plate with respect to Americas is the oceanic lithosphere of the Cayman Trough (Fig. II-1). However, its spreading history is complicated, and magnetic data available to the scientific community are a modest sample, such that disparate interpretations have emerged. Moreover, it is not certain that the Trough's early opening was in the pullapart mode that exists today or that the Cayman Trough records the full Ca-NA displacement (Sykes et al., 1982). MacDonald and Holcombe (1978) reckoned from magnetics about 275 km of seafloor spreading since late in Miocene time but that opening of the Trough may have begun in the Oligocene (see also Wadge and Burke, 1983 and Perfit and Heezen, 1978). In contrast, Rosencrantz et al. (1988) interpreted 1100 km beginning in the Eocene from magnetics, and Rosencrantz and Sclater

(1986) estimated an Eocene onset from bathymetry and heat flow. Near the western end of the Ca-NA boundary zone in Guatemala, Burkart et al. (1983, 1988) found 130 km left slip on the Polochic fault since 10ma, giving a minimum displacement for the full zone. Donnelly (1989) argued that Motagua fault zone has had little displacement since the Cretaceous. Moreover, no zones of large Tertiary lateral displacement between the Caribbean and South America have been identified. It is evident that an improved understanding of the transport history of the Caribbean plate and the Cayman Trough in particular is a basic need.

If the Cayman Trough and modern Ca-NA boundary originated in Eocene time, what were the tectonics of the Caribbean region in the 40 to 70 ma preceding stage 3? One manifestation of such tectonics may be the widespread arc terranes of Late Cretaceous age, including those of the Greater and northern Lesser Antilles (Cuba to Guadeloupe); northern Venezuela and the Venezuelan Antilles (Aruba-Villa de Cura-southern Aves Swell-Margarita); and in the Chortis-Nicaraguan Rise-Jamaica tract. The Greater and Venezuelan Antillean arcs appear to have collided beginning in latest Cretaceous or early Paleogene with the northern and southern borders, respectively, of the stage 2 Caribbean; the collisions appear to be diachronous, younging eastward, and the arcs have paleomagnetic declinations that accord with eastward simple shear relative to their boundaries (Malfait and Dinkelman, 1973; Maresch, 1974; Pindell and Dewey, 1982; Burke et al., 1984; Stephan et al., 1980; Gose, 1986; Beck, 1987; MacDonald, 1988; Skerlec and Hargraves, 1980; Speed, 1985).

If the Late Cretaceous arcs are native to the Caribbean region, they may record divergence and convergence that was perhaps unrelated to the small relative motions of NA and SA. If, on the other hand, the arcs are exotic and derived from the Pacific, they record the onset of the relative eastward transport of the Caribbean plate before the Cayman Trough developed, conceivably related to the cessation of rapid drifting of NA vs. SA at the end of stage 2. If the Late Cretaceous Antillean arcs are exotic, were they initially a single arc at the leading edge of the early Caribbean plate?

The oceanic plateaus of the Colombian and Venezuelan Basins have many of the same tectonic questions as do the Late Cretaceous arcs. If they are exotic, they presumably record midplate volcanic events in the eastern Pacific. The widespread existence of such events in the western Pacific is well known, but their mechanics are not (Larson and Schlanger, 1981). If native, they may record Late Cretaceous midplate volcanism of more global extent than that documented in the western Pacific.

The stage 3 Caribbean region also includes many features that are certainly or probably native by virtue of their Cenozoic ages. These included such major structures as the Beata Ridge, Aves Ridge, Hess Escarpment, central Venezuelan Basin fault zone and others, none of whose tectonics is clear. The origins of the Grenada Basin and the Yucatan Basin are controversial, whether backarc spreading, trench jump, or other; both are vital to an understanding of Caribbean plate evolution.

Finally, the Cenozoic Lesser Antilles and Central American arcs are certainly native although in both, only the youngest rocks are *in situ*. The Lesser Antilles records the underflow of the Atlantic lithosphere and perhaps, the edge of continental South America below the leading edge of the Caribbean plate. The forearc of the Lesser Antilles changes markedly along the trend of the arc from Grenada to the Virgin Islands because of the northward diminution in thickness of incoming sediment (reflecting increasing distance from SA) and because of varying obliquity of convergence from 0 to near 90°. The Central American arc records the underflow of the Cocos ± Nazca plates below the Caribbean and the emergence of the Panamanian isthmus in mid-Cenozoic time.

Major Thematic and Regional Problems: The discussion below centers on major Caribbean problems that are at the forefronts both of global scientific themes and of understanding Caribbean evolution. The context is general and based largely on the preceding analysis. The succeeding panel discussions and recommendations focus on aspects of these problems whose solutions are best approached by ODP drilling.

1. Reconstruction of Pangea: An ultimate goal of Caribbean science is the establishment of the pre-Late Triassic positions and orientations in the Pangean supercontinent of the cratons of NA, SA, and Africa and of continental transitional lithospheres and microplates that now exist in the Caribbean region. Of particular interest are the path through western Pangea of the Ouachitan-Alleghanian collision zone, its late Paleozoic tectonic evolution, and its relationship with the contemporaneous proto-Pacific margin of Pangea. Such information is necessary to constrain theories why all the continents coalesced fully, if briefly, as Pangea.

2. **Oblique rifting and the breakup of Pangea:** The orientations of the boundary zones between rifted and unrifted NA and SA (stage 1) and the length of the Gulf of Mexico Basin (Fig. II-1) are substantially oblique to the NW-SE separation direction of NA and SA in stage 2 (Fig. II-4). This implies oblique rifting during breakup of Pangea over a huge region, unless stage 1 underwent different extension from that of stage 2. If oblique rifting occurred, two fundamental thematic questions follow: 1) what caused the obliquity and specifically, how was it influenced by earlier structures of the Ouachitan suture zone and Early Cambrian passive margin?; and 2) what were the kinematics and mechanisms of regional oblique rifting? The first theme relates to the mechanics of structural reactivation, the longevity of major displacement zones under succeeding tectonic regimes, and the perpetuity of the individual continents. The second considers the generation of structures (e.g. rifts and transforms) and the degree of nonconservation and local rotation in motions (e.g. diking, rotating blocks, local convergence) of a strongly oblique breakup in comparison with a nonoblique one such as in the central Atlantic. Moreover, it is important to improve our knowledge of the breakup history (e.g. did breakup begin uniformly in NA, SA, and intervening transitional continental lithospheres? did it propagate N to S? or was it irregularly distributed in time and space?). Further, what was the total displacement between the cratons of NA and SA taken up by continental stretching and diking?

3. **Oblique separation of major plates and evolution of lithospheres in the gap between NA and SA:** In the second stage of Caribbean evolution, the NA and SA cratons drifted farther apart, roughly 3000 km, from their positions at the end of stage 1. The plate edges at least through the Jurassic appear to have been substantially oblique to the cratonal transport direction. The kinematics and mechanisms of gap-filling in oblique divergences are a global problem that can be addressed in the Caribbean. Did Caribbean spreading centers tend to migrate toward normality with the transport direction and did the ratio of transform to rift boundaries diminish with progress in stage 2? Was the flow

field in the widening Caribbean region streamline or turbulent? If turbulent, was there exchange of lithospheres with or migration of lithospheres in from the Pacific or Atlantic, and did subduction occur in the Caribbean? How much of the stage 2 cratonal displacement was taken up by spreading, how much by further stretching and diking, and how much by microplate or major plate insertion? Where did the continental transitional lithospheres (Yucatan-Campeche-Cuba-Florida Straits; Chortis-Nicaragua Rise) and older Cretaceous arc terranes of the Caribbean come from?

The Caribbean region is perhaps unique globally as a site to study oblique divergent phenomena if the stage 3 Caribbean plate is not far-traveled. This is because of the unusual situation where the boundaries of the expanded region are approximately known with time and where subsequent tectonics may not have greatly altered the record of divergence. For example, the Mediterranean probably underwent comparable oblique divergence in the Mesozoic but Africa and Eurasia underwent major Cenozoic convergence and partial collision, consuming and disturbing the products of earlier divergence.

4. Insertion tectonics and the origin of the Caribbean plate: The characteristics and origin of the modern Caribbean plate are a major unsolved problem of plate tectonics. One possible origin, by large eastward motion of Pacific lithosphere relative to the American plates (Fig. II-7), affords an opportunity to investigate in the Caribbean a little appreciated type of tectonic behavior, here called insertion tectonics.

A first order task is to define today's Caribbean plate more precisely: the positions of bounding zones of major displacement, the relative velocities across them, and the internal rigidity and displacement zones. It is important to pin down the late Neogene spreading rate at the Cayman Trough and to assess if Ca-NA velocity at the Cayman can be extrapolated via Euler poles to the Lesser Antilles and to Ca-SA. Moreover, the plate's history needs much study: total displacement and duration of the Cayman Trough, and the existence of CA-NA displacement zones concurrent to and adding to that of the Cayman Trough. Did the Caribbean plate move with an eastward component before the Cayman

Trough developed, perhaps even as early as stage 2, as suggested in Figure II-7?

A most fundamental question is whether the total eastward transport of the Caribbean plate is small, such that native lithospheres exist between Cuba and SA, or large, such that lithospheres older than about mid-Cenozoic between Cuba and SA are exotic as far east as the present Atlantic.

In the case of small transport, the objective is to understand the tectonics of the Cuba-SA interval in stage 3 which led to generation of oceanic lithosphere, numerous Late Cretaceous arcs, and collision of arcs with deep basin margins.

In the case of large transport, the Caribbean plate largely originated in the Pacific and is a product of insertion tectonics. Are such tectonics related to the expanding gap between diverging major plates with a possibly mutual convergent boundary outside the gap (here at the Pacific margin). If so, are insertion tectonics a predictable phenomenon globally such that a Caribbean investigation will lead to recognition of this elsewhere? Alternatively, the insertion may have been late in stage 3 and not clearly related to the stage 2 divergence. If so, what precipitated such motions?

5. Atlantic-Pacific connections and Caribbean paleogeographic evolution: The paleogeography of the Caribbean region from breakup of Pangea to the present has been a major control in communication of water masses and biota between the Atlantic and Pacific. Such control is thus basic to advances in paleontology, paleoceanography, and paleoclimatology. Data are needed that indicate the positions and ages of deep basins (floored by oceanic lithosphere) that were continuous between Atlantic and Pacific and, moreover, the existence and sill depths of shallow marine seaways across the Caribbean.

6. Origin of oceanic plateaus and the evolutions of the Colombian and Venezuelan Basins: The lithospheres of the Colombian and Venezuelan Basins are the core of the Caribbean plate (or plates), and it is a major question whether they are mainly native to the Caribbean or far-traveled from the Pacific. Another question is whether these lithospheres include an older crust that lies below the oceanic plateaus and was a product of spreading in Jurassic or Early Cretaceous times or whether the oceanic plateaus formed during the initial lithosphere generation. If the lithospheres are far-traveled, the Caribbean oceanic plateaus are probably transported samples of Late Cretaceous midplate volcanism peculiar to the Pacific. If the lithospheres are mainly native, the oceanic plateaus imply that midplate volcanism was not restricted to the Pacific plate and that such penecontemporaneous events could possibly have occurred widely. Thus, it is important to investigate Caribbean oceanic plateaus to understand what may have been a global event in Late Cretaceous ocean basins and the reasons for its occurrence. It is also important to understand the processes of such midplate volcanism: kinematics, amounts and directions of crustal extension, magma sources, and duration and the relation of these to plate boundary tectonics.

7. Processes in active forearcs and magmatic arcs and the evolution of the Lesser Antilles: Processes in growth, attrition, and defluidization of forearcs and in the transfer of sediment from forearc to the mantle and magma source areas are forefront scientific problems (COSOD, 1988). Such processes are perhaps better addressed in active Caribbean arcs, especially the Antillean arc from Tobago north to Puerto Rico, than elsewhere in the world. This is because certain controlling factors, obliquity of convergence and thickness and composition of incoming sediment, vary continuously between wide limits along the length of the Antillean arc. Moreover, the biostratigraphic control is hard to surpass. Existing studies (seismic, ODP drilling, onland work) have provided crucial initial strides in understanding offscrape mechanisms, controls of detachment, upslope transition in forearc deformation mechanism, positions of and gradients in fluid loss in forearcs, long extent of sediment underthrusting of the forearc, and forearc basin evolution. These studies should be expanded in the future in pursuit of a comprehensive theory of forearc behavior.

Further, studies of Lesser Antillean magmas suggest they contain at least a small proportion of melted sediment or supracrustal fluid and that such sediment arrives at the melting zone on the downgoing Atlantic slab (White and Dupre, 1985). This interpretation is possible because the compositions of magma and the bulk incoming sediment change concomitantly along the length of the arc. An expanded understanding of the role of sediments in Lesser Antillean magmatism is vital to global geochemical and sediment budgets.

Certain elements and phenomena of the Cenozoic evolution of the Lesser Antilles are poorly understood and need further investigation. Examples of these are the origin and age of the Grenada Basin, the structure of major crystalline blocks (La Desirade, Tobago, etc.) within the Antillean forearc, configuration of the Paleogene Lesser Antillean magmatic arc, origin of rapid Cenozoic subsidence of the south wall of the Puerto Rico Trench, and origins of different forearc basin structures north and south of St. Lucia.

III. TECTONICS PANEL REPORT

Chair: N. T. Edgar

Panelists: Ave L'allement, Behrmann, Burkart, Christofferson, Gose, Hall, Klitgord, MacDonald, Mauffret, Mann, McCann, Persad, Pindell, Rosencrantz

Summary

The Tectonics Panel considered as the principal tectonic problems of the Caribbean: 1) the Mesozoic evolution of the Caribbean region by rifting of Pangea, drifting of the Americas plates, and the development of seaways between the Atlantic and Pacific basins; and 2) the late Mesozoic and Cenozoic displacement histories and origin and origin of the Caribbean plate, especially at its northern boundary zone.

The panel believes ODP drilling can yield major strides towards solutions of these problems, as follows. Addressing Mesozoic seaway development, three sites are given first rank: southeastern Gulf of Mexico, Demerara Rise, and southeastern Venezuelan Basin (Fig. III-1). For the problem of Caribbean plate history, first priority sites are a series within the Cayman Trough (Fig. III-1). The tectonics panel places great importance on technological advances: oriented core, drilling through sands, and stress measurements; these are discussed in section VIII. The panel also considers new onland and marine investigations as vital complements to ODP drilling.

Introduction

The Caribbean region and its lithospheres (Fig. III-1) originated in Mesozoic and Cenozoic times principally by two tectonic processes: 1) rifting of Pangea, drifting apart of NA and SA, and generation of seaways between Atlantic and Pacific; and 2) development of the Caribbean plate and its eastward displacement relative to NA and SA. The Tectonics Panel concludes that advances in understanding the phenomena of two processes, here called Mesozoic seaways and Caribbean plate, are the basic goals of new investigations and that ODP drilling is required to make such advances.

Mesozoic Seaways

The tectonic units, kinematics, timing of events, and paleogeographic evolution of the Caribbean region in the Mesozoic are poorly known. The history of continental breakup, the positions and timing of spreading sites, and the positions and ages of deep and shallow seaways are uncertain. Reasons for this lack of knowledge are that DSDP drilling in the Caribbean south of the Gulf of Mexico (Fig. II-2) was mainly shallow and penetrated rocks no older than Coniacian. Moreover, there are inherent limitations in precision of plate tectonic reconstructions, and clear seafloor spreading signatures in Caribbean basins are lacking. It is evident from plate tectonic and other considerations (see Section II) that Lower Cretaceous rocks should be widespread in the Caribbean and that Jurassic rocks should occur at least locally. The distribution and nature of such rocks record the tectonics and paleogeography of seaway development and are vital to the reconstruction of Pangea. Such data will also yield advances in our thematic objectives of the processes and motions in strongly oblique rifting and continental separation. Thus, drilling should be designed to penetrate older Mesozoic deepwater strata that are native to the Caribbean region. Future drilling in the Atlantic should complement these efforts by drilling such strata at sites near the entrances to early Caribbean seaways.

There are two objectives in drilling these older strata: first, to date the breakup and subsidence that began seaway development; and second, to understand the positions and times of drifting and events in the formation of oceanic lithospheres and associated deep seaways.

Breakup and Subsidence

Our present knowledge of the positions and times of continental breakup and onset of seafloor spreading is as follows: Late Triassic to Middle Jurassic rifting and diking and formation of a broad region of thinned transitional lithosphere in the Gulf Coast; widespread evaporite deposition in the present Gulf of Mexico region (Fig. III-2) in the Callovian but with uncertain connections to the Atlantic and Pacific basins; Late Jurassic spreading and subsidence of the Gulf of Mexico Basin; establishment of Bahamian–circum-Gulf carbonate platform in Oxfordian(?) time; deposition of Jurassic redbeds

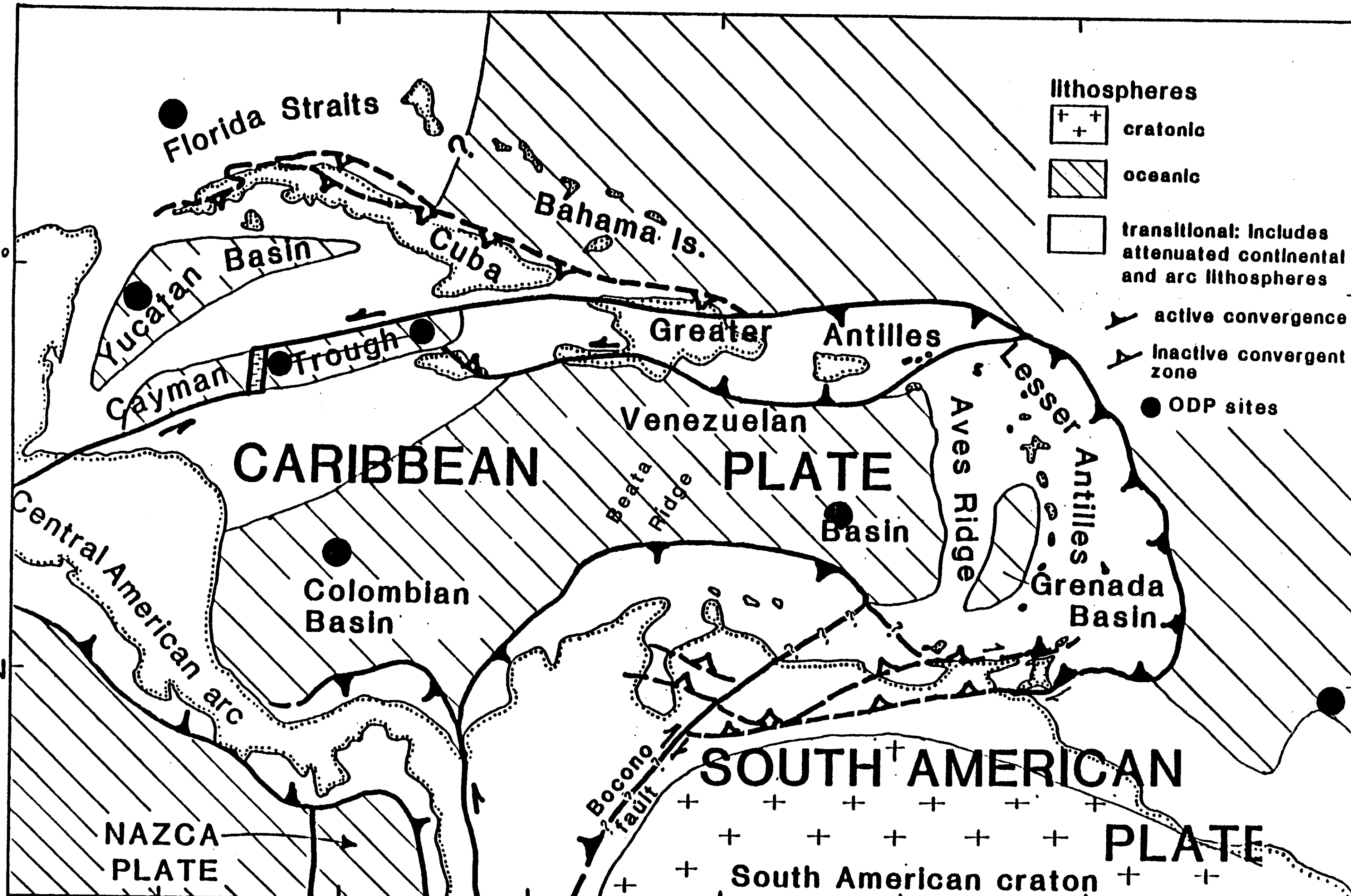


Figure III-1: Sites recommended for ODP investigation by the Tectonics Panel.

at the Demerara Rise and in graben of northern Venezuela; and deposition of Early Cretaceous evaporite and now-allochthonous Jurassic carbonates in Trinidad. A passive margin sequence of Middle and Upper Jurassic and Cretaceous rocks exists above Precambrian basement on Cuba, but it isnot certain whether or not such rocks are far-traveled with respect to the circum-Gulf Jurassic platform. Strata of the South Florida Basin and western Bahama Basin are known to contain only latest Upper Jurassic rock, and these were either sites of nondeposition or of erosion during rifting and drifting of the Gulf of Mexico region. Figure III-3 shows an admissible Mesozoic paleogeographic sequence that obeys these stratigraphic data and best fit NA-Af and Af-SA rotation poles (Klitgord and Schouten, 1986). The model is nonunique because of 1) the imprecision in positioning of seafloor data points; 2) the assumptions of streamline flow and the orthogonality, positions, and relative stability of rift-transform systems; and 3) the imprecision in dating older Mesozoic deposits.

To improve the data on rifting and early opening, we identify two promising deep water locales that are likely to contain requisite sedimentologic records (Fig. III-1).

1) **Southeastern Gulf of Mexico:** This is an area of transitional lithosphere (Figs. III-1, III-4), probably greatly stretched and diked continental crust between the Yucatan terrane on the west, Florida block (which was part of North America in the Triassic) on the east, and Cuba (Paleogene collision zone) on the south. DSDP Leg 77 drilling and seismic data (Buffler, Schlager et al., 1984; Schlager et al., 1984) indicate rifted crystalline basement and extensive Lower Cretaceous strata (Fig. III-4). The data also indicate accessible significant local thicknesses of strata below drilled Lower Cretaceous that are likely to include Jurassic and perhaps older deposits (Fig. III-4). Such strata might be correlative with Jurassic rocks in the collision belt of onland Cuba which indicate large but poorly documented subsidence in the Jurassic. The importance of the southeastern Gulf site is in the potential to time the onset and duration of rifting and postrift subsidence on the south side of the Gulf of Mexico in an area without younger tectonic overprint. Did rifting here carry on during and after that of the Gulf in response to latest Jurassic NA-SA opening? When did a major seaway south of the Gulf begin?

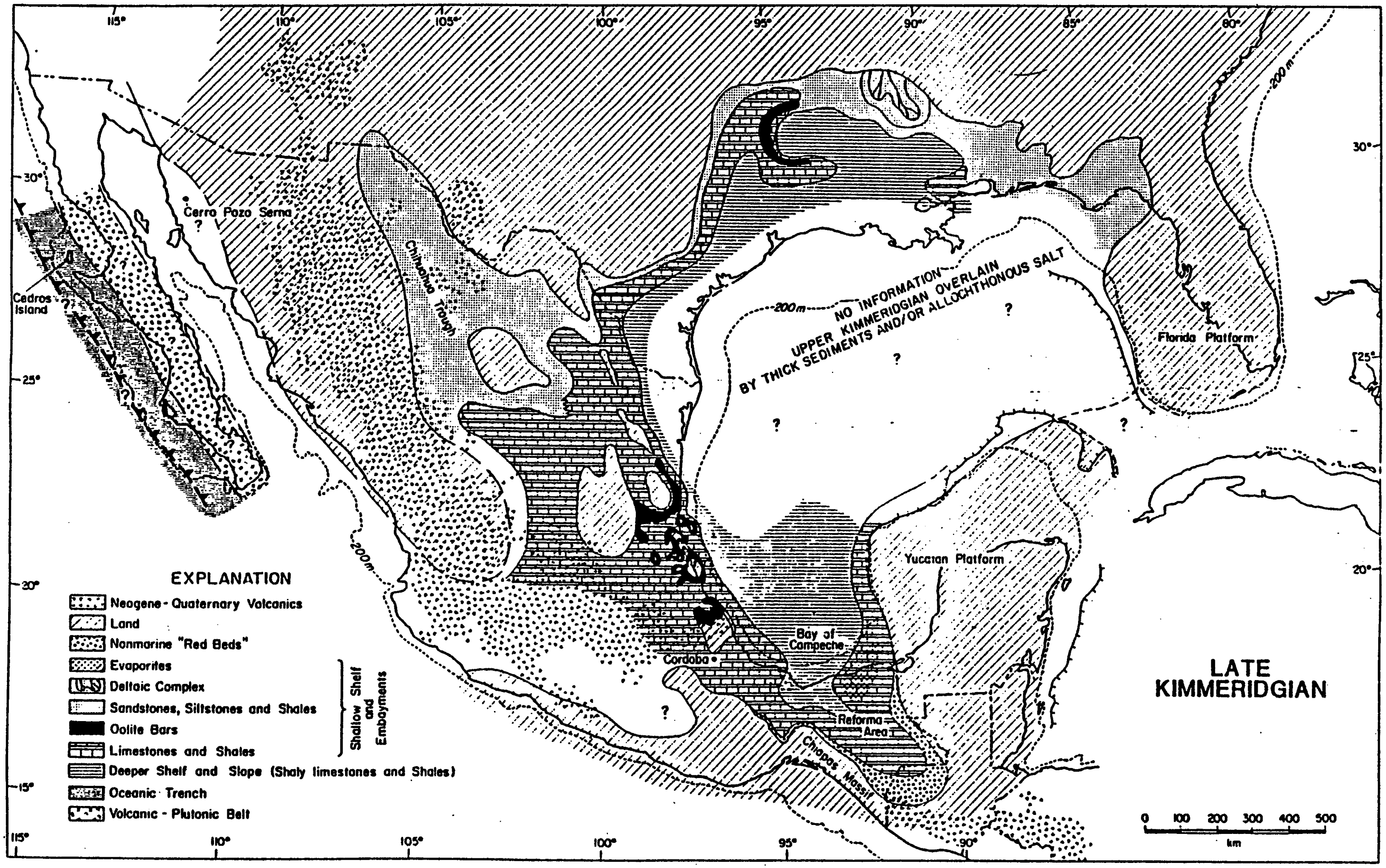


Figure III-2: Gulf of Mexico region and known and inferred extent of Late Jurassic deposition, from Salvador (1987); distribution for other Late Jurassic substages similar to late Kimmeridgian.

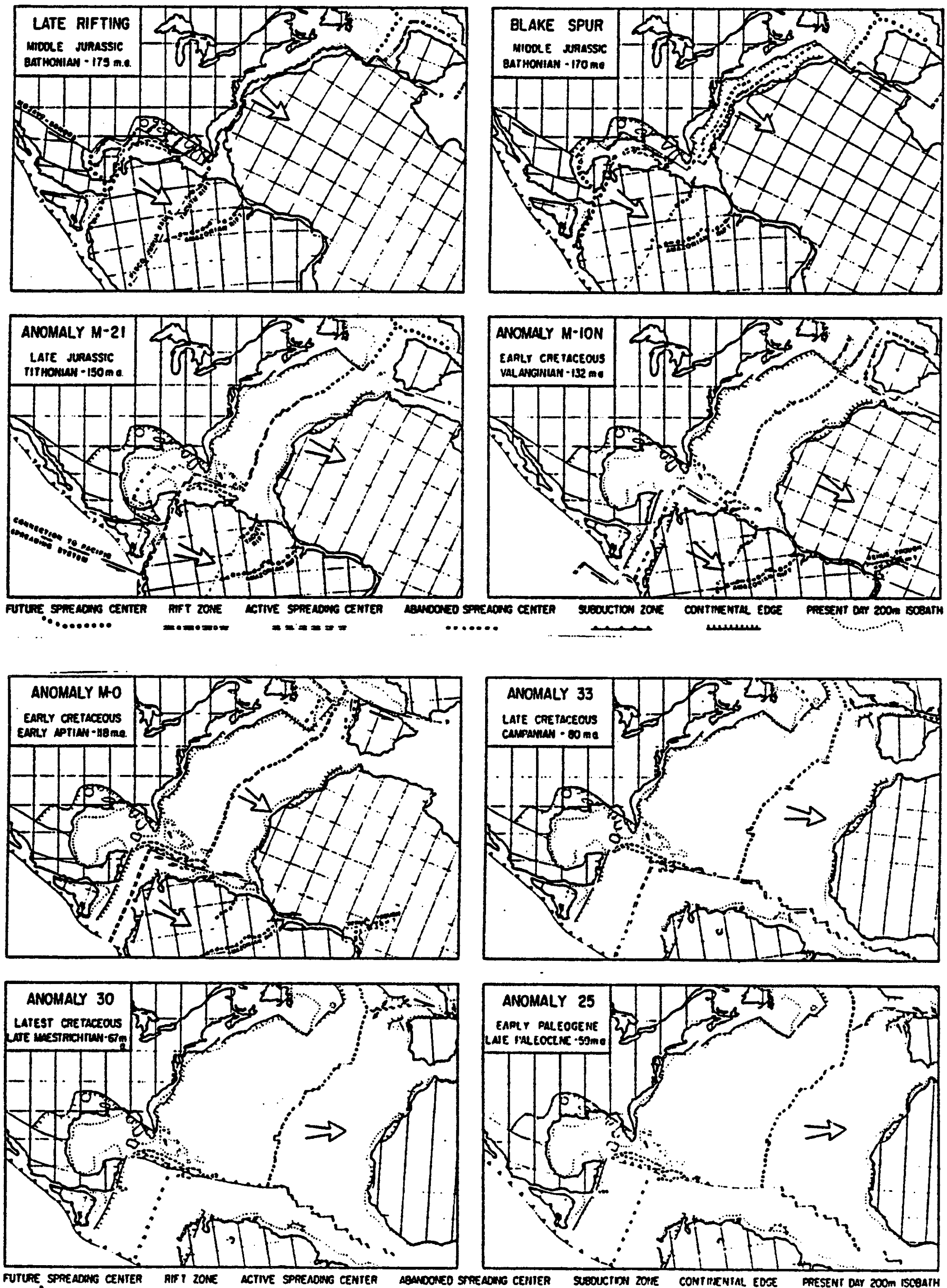


Figure III-3: Possible paleogeographies of the Caribbean region during early drifting, from Klitgord and Schouten, 1986.

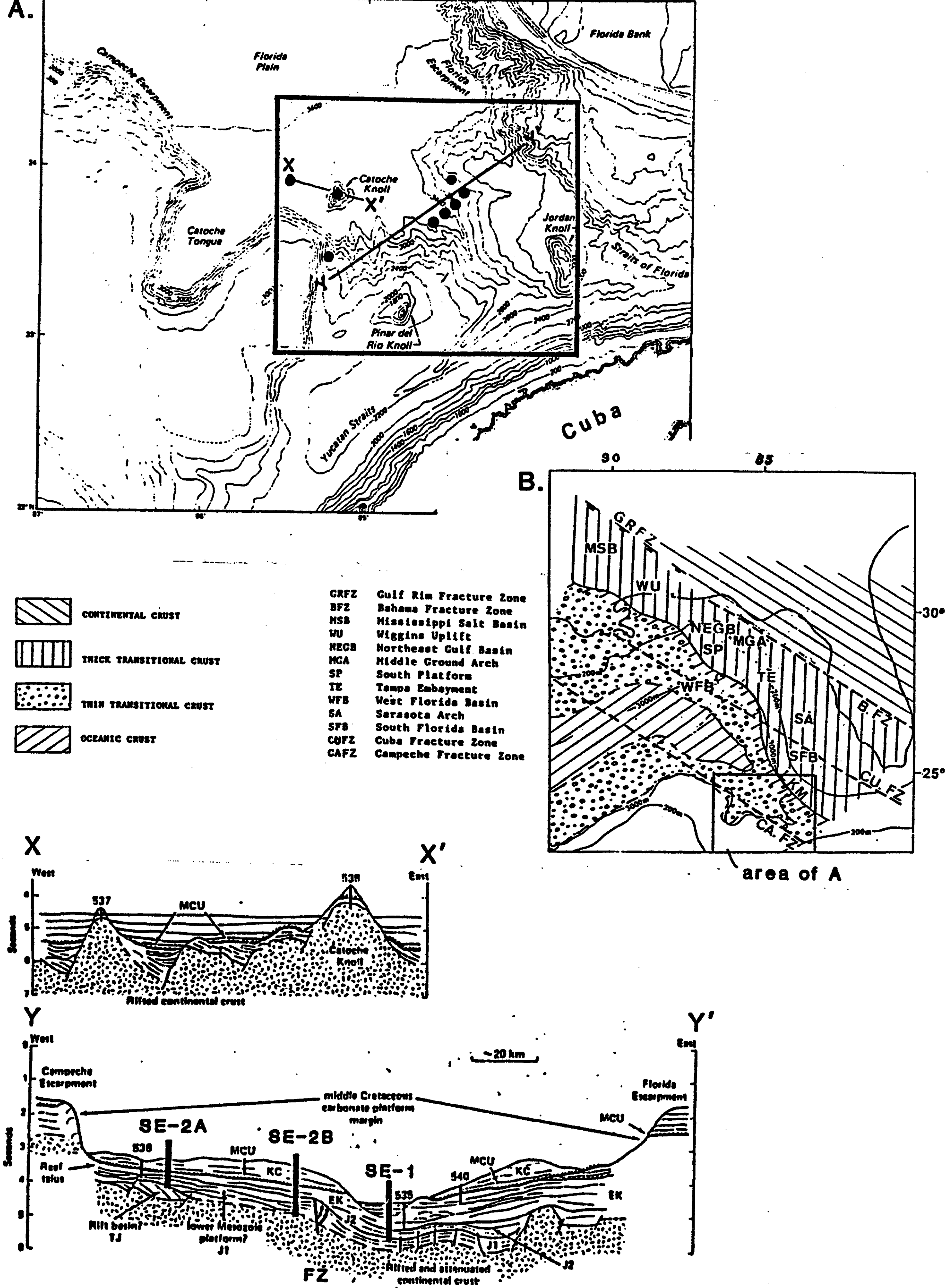


Figure III-4: Southeastern Gulf of Mexico target for ODP drilling (box); sections from Schlager et al., 1984, showing Leg 77 holes; MCU is mid-Cretaceous unconformity; TJ is possible Jurassic and/or Triassic strata; J1 and J2 are inferred - Jurassic units; SE are proposal holes (see Section VII-2).

Holes in this area may also supply data indicating whether streamline or turbulent motions occurred in the Jurassic by fault block geometries and paleomagnetics. Further discussion of this area is in section VII-2.

2) **Demerara Plateau:** The Demerara Plateau (Fig. III-1) is a salient of continental South America at the early Mesozoic passive margin with Atlantic oceanic lithosphere east of the Caribbean plate. Drilling and seismic data (Fig. III-5; A. Mascle, written commun., 1988) indicate a shelf sequence as old as Berriasian and a thick subjacent section of undated strata above basement that is probably Precambrian. At the toe of the plateau, there exist an outer rise, Mesozoic? volcanics, and the continent-ocean boundary together with an arch of the sub-Valanginan strata (Fig. III-5, sections). Dredge hauls (Fig. III-5, LDGO dredgehaul) from the toe yielded red beds thought to be Jurassic by palynology (Damuth and Heezen, 1969). According to the model of Figure III-3, the Demerara Plateau may have been continuous before NA-SA drift with North America near Florida and the southeastern Gulf of Mexico. Because strata of this site are certainly native to the Caribbean region and have not undergone subsequent strike-slip or collisional tectonics, they should provide crucial information on the positions and timing of rifting and drifting of NA-SA. Specifically, the question should be answered whether stretching and drifting propagated N to S; whether rifting started synchronously in NA and SA, ending in a major central ocean; or whether rifting had a greater duration in SA than the Gulf of Mexico region.

Complementary drill sites that help define the Atlantic entrance to early Caribbean seaways need to be considered. A prime candidate is near the junction of the Blake and Bahama escarpments west of DSDP 534 which penetrated Callovian strata. Such a hole may also record initiation of the Bahama carbonate platform.

Drift Phase

Our objective here is to understand the timing, positions, and mechanisms of opening of the Caribbean region between Yucatan and South America, presumably mainly by seafloor spreading from

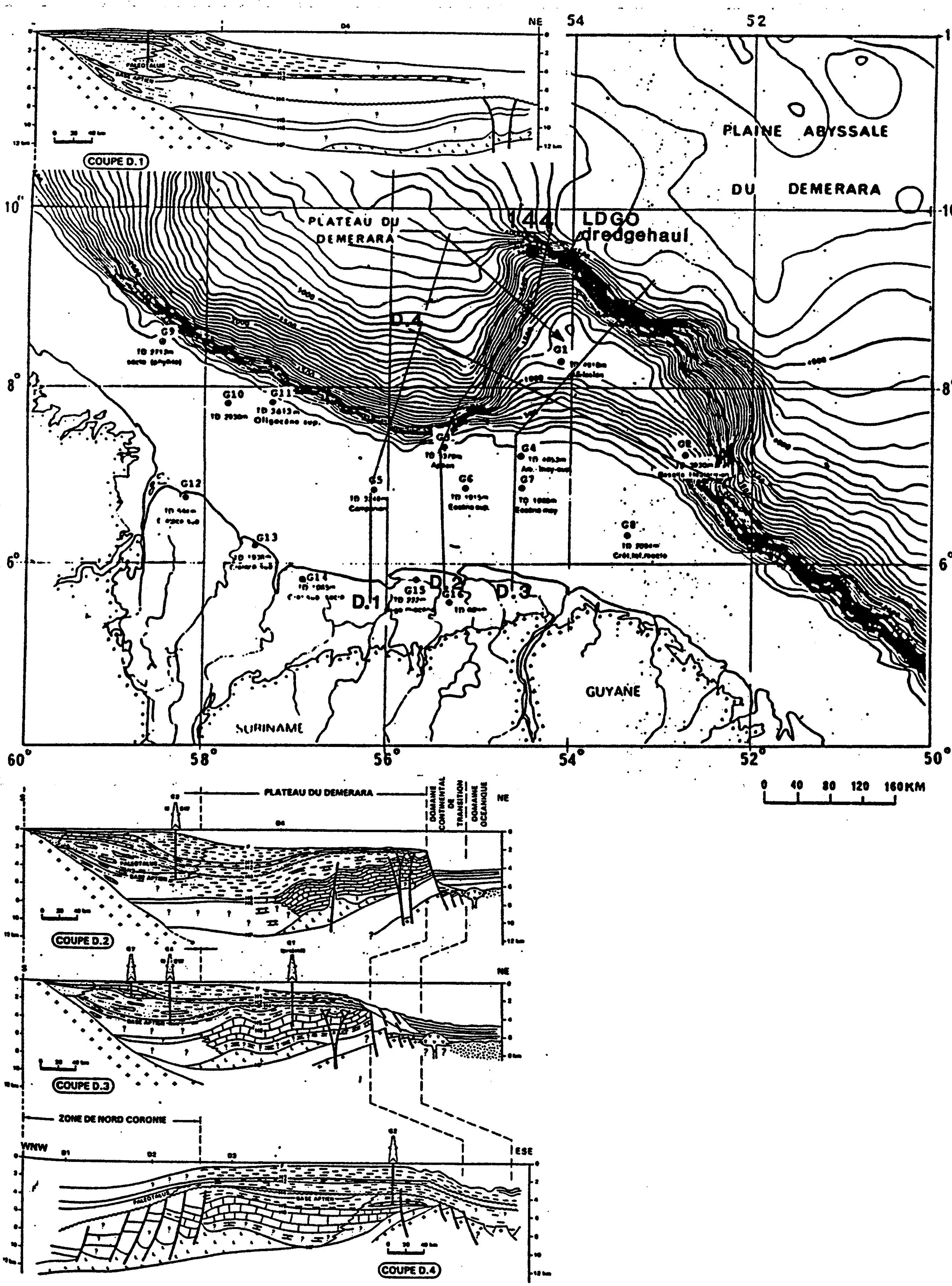


Figure III-5: Demerara Plateau target for ODP drilling; data supplied by A. Mascle (written comm., 1988); map: bathymetry, wells (G), edge of Precambrian shield, and cross section traces; cross sections: H1 - base upper Miocene; H4 - base Albian; H5 - Hauterivian; H6 - Valanginian; crosses - Precambrian; V - volcanic; random dashes - oceanic crust.

Late Jurassic to a time in the Late Cretaceous (Aptian to base Campanian). An associated objective is to understand the tectonics of oblique continental separation, discussed earlier. Questions are: Was a wide deep seaway connecting Atlantic and Pacific created in this interval? Did the present lithospheres of the Colombian, Venezuelan, and(or) Yucatan Basins partly or fully floor such a seaway? Or did this interval include a number of seaways, some or all of whose lithospheres have been consumed by intra-Caribbean subduction and(or) subduction below the Caribbean plate? The last question poses the fundamental issue whether or not all the Mesozoic terranes between Yucatan and SA came from the Pacific as a far-traveled Caribbean plate. If the Caribbean plate has small displacement and Caribbean oceanic lithospheres are native, drilling in the Venezuelan, Colombian, and Yucatan Basins could elucidate a drift phase history.

The oceanic plateaus of the Venezuelan and Colombian Basins are a major consideration because their Late Cretaceous basalt series would have to be drilled through to test the existence and character of older Caribbean strata and crust. Seismic data suggest that sedimentary reflectors and normal oceanic crust exist below the plateaus, and this would be valuable to test (Stoffa et al., 1981). It is preferable at the outset, however, to drill sediment sections where oceanic plateaus do not occur. These may exist in three areas, as follows:

1) **Southeastern Venezuelan Basin:** Current knowledge of the distribution of oceanic plateaus (anomalously thick, smooth surfaced oceanic crust) and normal crust (normally thick, rough surfaced oceanic crust) in the Colombian and Venezuelan Basin is shown in Figure III-6. The most extensive recognized patch of normal crust is in the southeastern Venezuelan Basin (ruled pattern, Fig. III-6B) where a typically rough top of crust is overlain by up to 2 km of sediments, far in excess of sediment thicknesses on the oceanic plateaus. Such sediments, heretofore undrilled, may contain a continuous section to early Mesozoic strata and a record of Jurassic and Early Cretaceous environments, provenance, and bathymetry of central Caribbean basins. It should be noted that the correlation of Coniacian horizon smooth B'' (Fig. III-6C), the top of the adjacent oceanic plateau, with the top of the normal

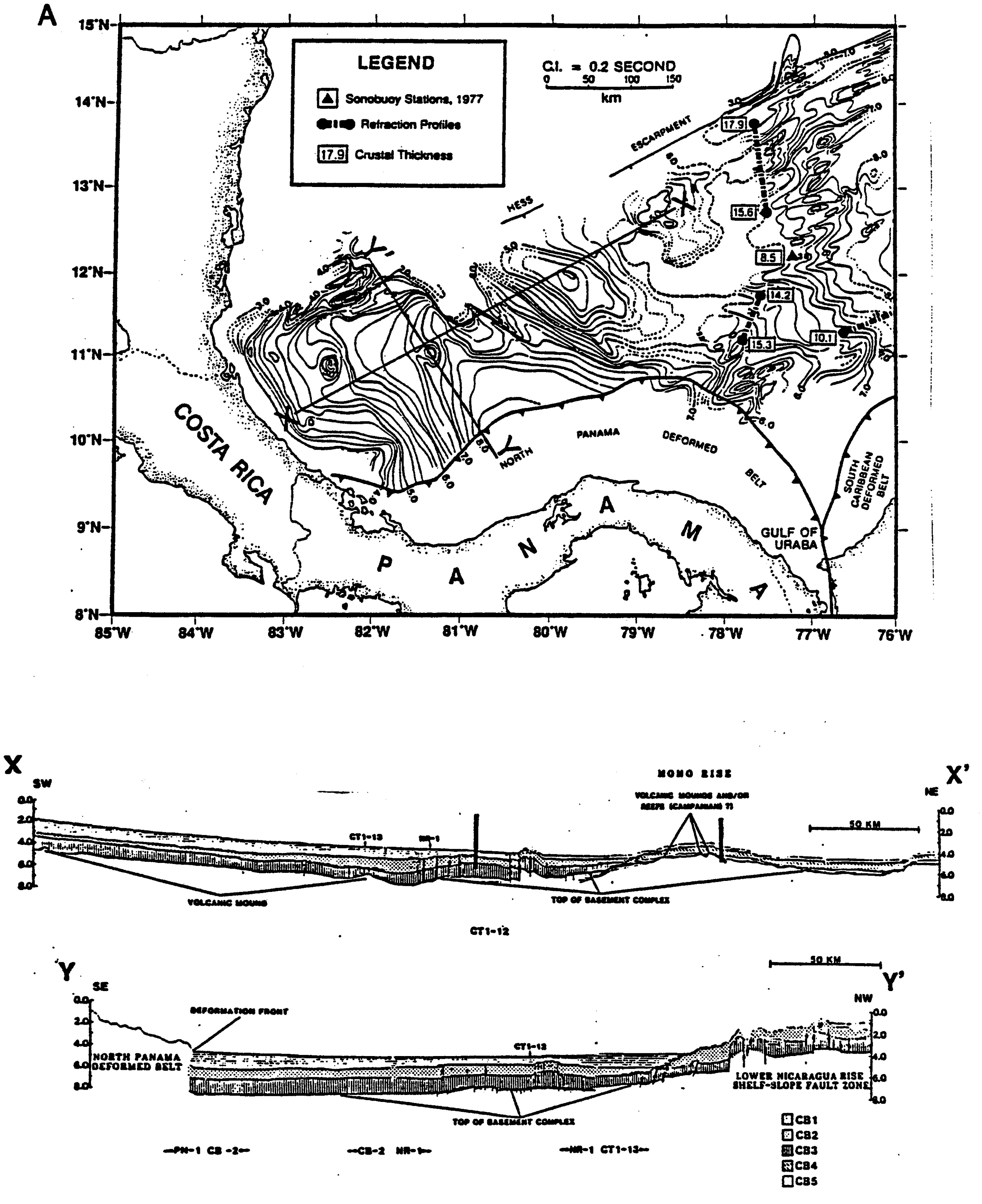
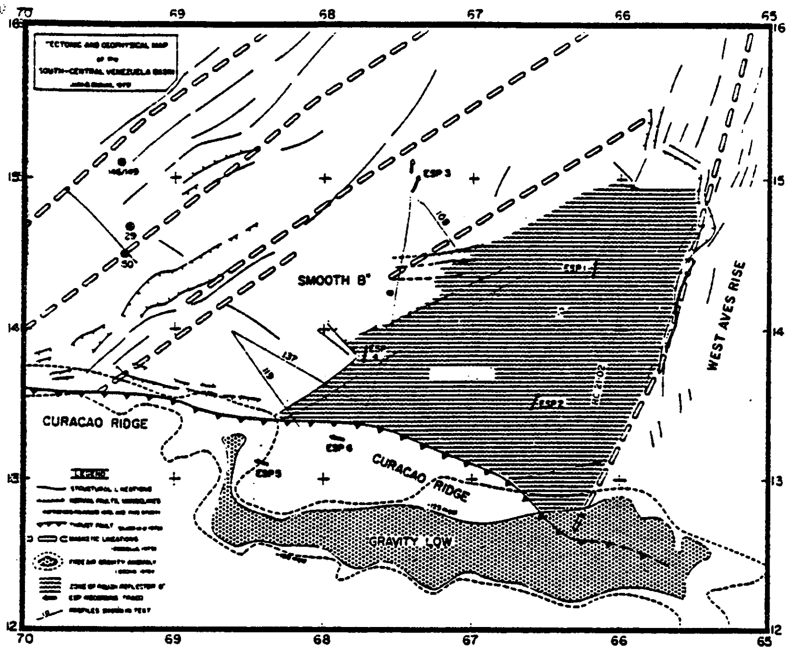
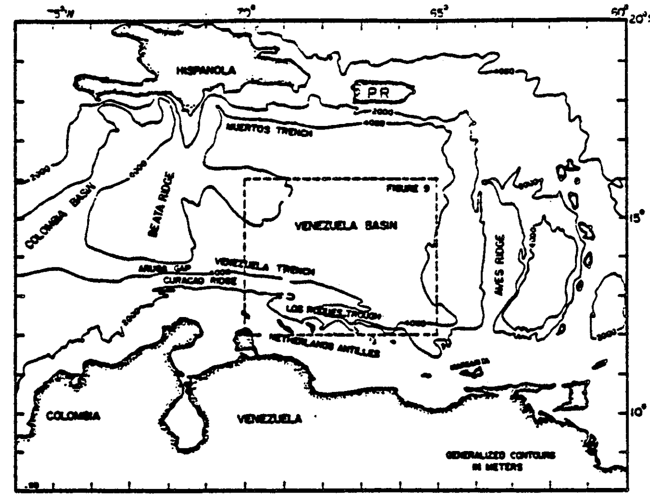


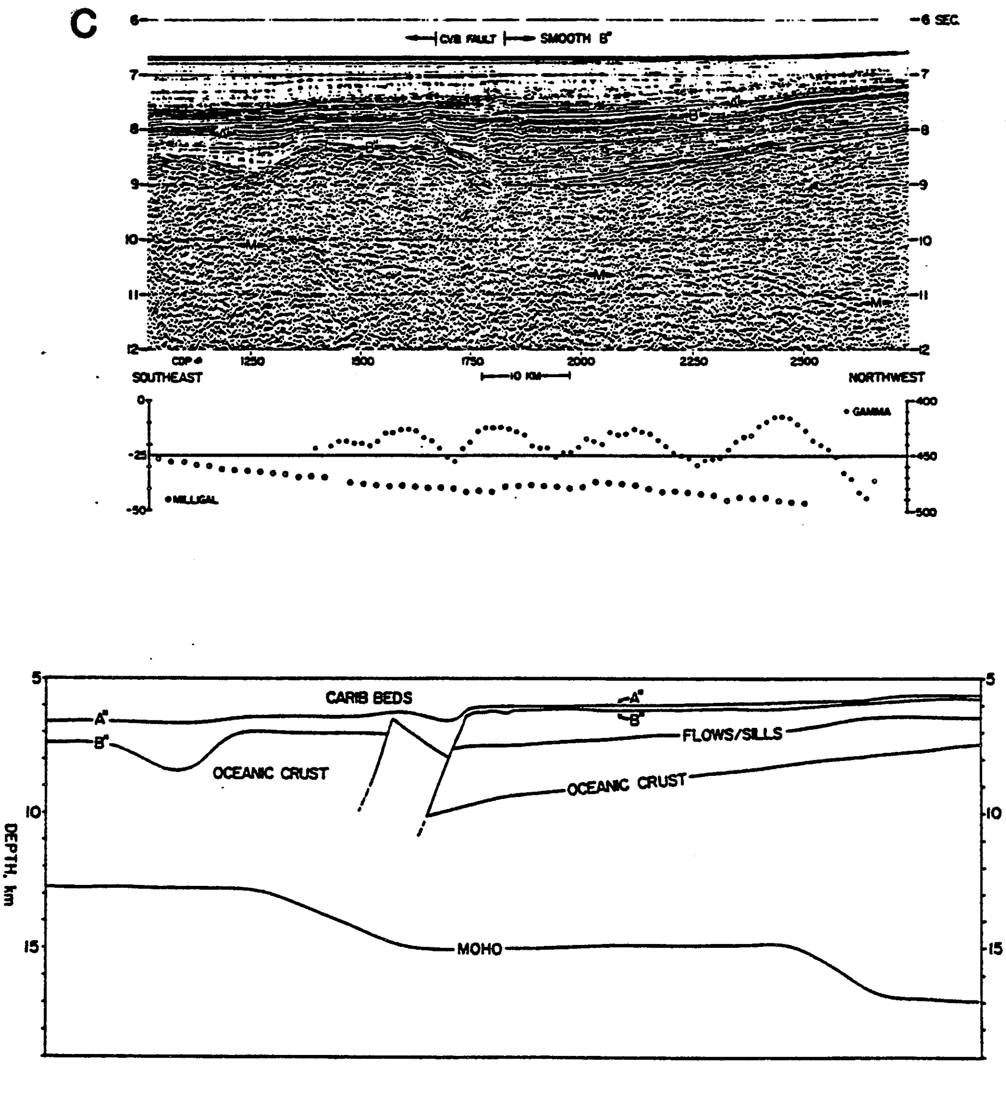
Figure III-6: Crustal structure of Venezuelan and Colombian Basins; A) Colombian Basin, contours of two-way travel time to acoustic basement and crustal thicknesses in km (boxes), from Bowland and Rosencrantz (1988); B) map of southeastern Venezuelan Basin target for ODP; areas of oceanic crust with normal thickness in horizontal line pattern and oceanic plateau without pattern (called smooth B"); C) seismic section and line drawing of Line 108 across oceanic plateau - normal crust boundary (CVB fault) from Diebold et al., 1981; correlation of B" across CVB is doubtful.

B


SMOOTH B"
WEST AVES RISE
CURACAO RIDGE
GRAVITY LOW
ESP 1
ESP 2
ESP 3
ESP 5
ESP 6
LEGEND


HISPANOLA
P R
MUERTOS TRENCH
BEATA RIDGE
COLOMBIA BASIN
VENEZUELA BASIN
FIGURE 9
AVES RIDGE
ARUBA GAP
VENEZUELA TRENCH
CURACAO RIDGE
LOS ROQUES TROUGH
NETHERLANDS ANTILLES
COLOMBIA
VENEZUELA
GENERALIZED CONTOURS IN METERS

C


6 SEC.
CVB FAULT
SMOOTH B"
CDP #
1250
1500
1750
2000
2250
2500
SOUTHEAST
NORTHWEST
10 KM
GAMMA
MILLIGAL
CARIB BEDS
A"
B"
FLOWS/SILLS
OCEANIC CRUST
MOHO
DEPTH, km

crust (rough B'') may not be valid.

The area of normal oceanic crust may be only slightly or, on the other hand, greatly displaced with respect to the adjacent oceanic plateau, and either one or both could be far-traveled or native Caribbean. If both crusts are native Caribbean, drilling to the normal crust should indicate 1) the history of seaway development in the region between the southern Gulf of Mexico and the South American margin; 2) whether or not the Late Cretaceous plateaus are built on an older normal oceanic crust; and 3) a record in its Cretaceous sediments of the evolution of the adjacent oceanic plateau. If, however, both crusts are far-traveled, drilling in the normal crust should indicate items 2) and 3) above and the first record of early Mesozoic conditions of the Farallon plate, which came from Pacific realms. Moreover, the history of sediment provenance, faunal provinciality, and paleomagnetic latitudes and declinations in strata of the normal crust may be the best of all evidence whether or not the Caribbean plate is of Pacific origin.

2) **Colombian Basin:** Seismic studies in the Colombian Basin (Fig. III-6) indicate it contains major oceanic plateaus and intervening tracts of normal crust (Bowland and Rosencrantz, 1988). The patches of normal crust are alternative sites to that of the southeastern Venezuelan Basin.

3) **Yucatan Basin:** The Yucatan Basin contains normal oceanic crust of age known only as Eocene or older and possibly Jurassic or Cretaceous (Fig. III-7) (see also section VII-1). It lies between the Eocene collision belt of Cuba and the Cenozoic transform plate boundary at the Cayman Trough (Fig. III-7) and was a product of ocean basin formation before either the Cuban or Cayman tectonic events. The Yucatan Basin crust may be a piece of early Caribbean oceanic crust trapped behind the younger Caribbean plate boundary or a crust locally generated by early Cenozoic spreading (Malfait and Dinkelman, 1972; Dillon et al., 1973). If the Yucatan Basin crust is early Caribbean, it probably contains a locally complete sedimentary record of the early drift phase without superposition of an oceanic plateau.

Caribbean Plate

The first order problem is whether the present Caribbean plate is native to Caribbean region and its oceanic lithospheres a product of local seafloor spreading or, alternatively, of exotic origin from Pacific realms.

This may be best studied at the Cayman Trough with the goal of understanding whether Ca-NA displacement at their present boundary has been large (>1000 km), indicating a mainly exotic origin, or small permitting a native origin, as discussed below. Moreover, the Cayman Trough is an important tectonic feature in its own right, representing one of the largest pullapart basins at a transform boundary and permitting study of processes of lithospheric formation.

If the plate displacement at the Cayman boundary is small (say, <600 km), the succeeding question is whether lithospheres of the Venezuelan and Colombian Basins were native or exotic in pre-Cayman time. This question may be addressed by crustal ages and paleomagnetic latitudes of crusts of those basins and by faunal provinciality of suprajacent Mesozoic sediments, discussed below.

The consequences of large and small total eastward Caribbean plate displacements (present plus pre-Cayman plates) are as follows:

1) **Large (>1500 km) displacement:** Native Caribbean lithosphere of pre-Campanian age may not exist south of Yucatan and Cuba, having been totally subducted by the incoming plate. The Caribbean plate in this case had pre-Cayman movement and is probably composed fully of lithosphere from the Pacific. It would probably be a remnant of Mesozoic Farallon plate which was an eastern complement to the Pacific plate (Engebretson et al., 1984). It would of course be of great importance to plate tectonics to know if this is true. Drilling in the Colombian and Venezuelan Basins may then provide the only direct record of Mesozoic events and transport of the Farallon plate because everywhere outside the Caribbean, Farallon lithosphere of Mesozoic age has apparently been fully subducted. Moreover, if the Caribbean plate is in fact a Farallon fragment, we would have a preserved example of insertion tectonics. We could then investigate the mechanics of such plate tectonics, particularly the stability of a subduction zone bordering a

widening region between separating large plates (Fig. II-4).

2) **Small (<500 km) displacement:** In this case, all but the westernmost lithospheres of the Caribbean are native, and a pre-Eocene or mid-Tertiary Caribbean plate may not have existed. Drilling in Caribbean basins would tell the story of the evolution of Caribbean seaways. The existence of Mesozoic arc terranes in the Caribbean would indicate that the drift phase in Caribbean opening was more complex than seafloor spreading at the same rate as continental separation. Such indications of intra-Caribbean subduction might be explained by seafloor spreading in excess of NA-SA drift or by irregularities in relative NA-SA motion that are unresolved in Atlantic data.

   Further, the oceanic plateaus would be at least partly of Caribbean origin, implying a more global distribution of Late Cretaceous midplate magmatism than is currently recognized. It would then be of great importance to investigate the tectonics of oceanic plateau development, in the contexts both of Caribbean evolution and global phenomenology.

3) **Intermediate Displacement:** In this case, eastern realms of the Caribbean may record indigenous events whereas western ones probably formed in the Pacific.

Cayman Trough

The first tectonic objective of ODP drilling in the Cayman Trough (Fig. III-8) are the rates and duration of seafloor spreading. MacDonald and Holcombe (1978) and Rosencrantz et al. (1988) analyzed marine magnetic anomalies within the Cayman Trough, and reached distinctly different conclusions. MacDonald and Holcombe (1978) contend that magnetic anomalies show that the Trough opened at a rate of about 20 mm/yr since 2.4 Ma, and at 40 mm/yr between 8.5 and 2.4 Ma, for a total displacement of 288 km. They argue that magnetic anomalies older than 8.5 Ma (anomaly 4A) cannot be reliably identified. Rosencrantz et al. (1988), on the other hand, argue that recognizable anomalies are present back to anomaly 20 (Middle Eocene). Their sequence of anomalies indicates that the Trough opened at about 30 mm/yr between the time of the Trough opening, estimated at between 45

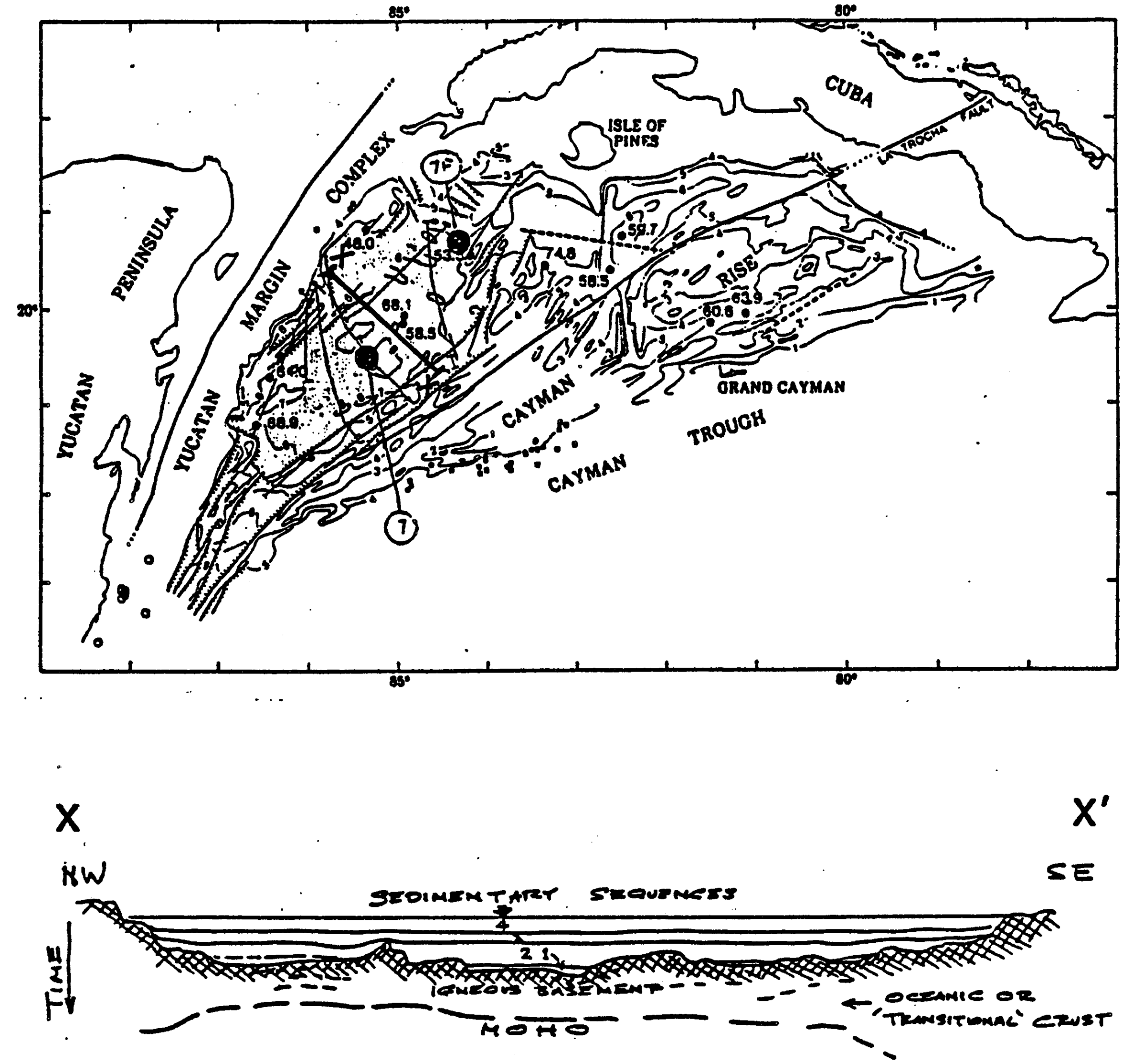


Figure III-7: Yucatan Basin. Contours show depth to acoustic basement in km; patterned area is oceanic crust; faults are heavy lines, seismic reflection traces are light lines; seismic refraction traces are heavy dashes; dots are heatflow; open circles are wells; big dots are proposed drillsites; seismic sequences 1-4 are all undated; from E. Rosencrantz (unpubl., 1988).

and 50 Ma (middle Eocene), and 30 Ma (late Oligocene), and at 15 mm/yr between 30 Ma and the present. They believe the total displacement is 1100 km. Sykes et al. (1982) argued for 1400 km displacement. Direct measurement of crustal age will resolve the difference between these interpretations and indicate whether there has been large or small displacement of the Ca plate relative to NA since the mid- or early Cenozoic (Figs. II-7, II-8).

An established opening history for the Cayman Trough has a number of applications to both Caribbean and global tectonic evolution and tectonic processes, as follows:

1) **Inception and evolution of small ocean basins:** The Cayman Trough has simple geometry and bathymetry (Fig. III-8). The basin is bounded along the northeastern and southwestern walls by transform faults connected across a spreading axis (Fig. II-1). The eastern and western margins of the basin are rifts. The western margin is buried beneath a blanket of sediment, but the eastern margin is sediment starved, exposing its structure. A full opening history of the basin, as described by magnetics and intrabasin age sampling, will permit reconstruction of basin geometry back to the time of initial spreading, with exact reconstruction of the relative positions of conjugate rift margins. Additional sites of the western and eastern rift margins which address the subsidence history of the margins will permit additional reconstructions of the rifting phase, particularly timing and duration of rifting. The Cayman Trough provides an opportunity to describe and quantify the full evolution of a small ocean basin. If the trough initially developed as a pull-apart basin along a preexisting plate transform boundary, then the history will provide insights into the development of these common tectonic features.

2) **Thermal evolution of small isolated ocean basins:** Within the Cayman Trough, basement depths are greater and crustal heat flow is less than predicted by subsidence-age and heat flow-age relationships for typical crust within large ocean basins (CAYTROUGH, 1979; Rosencrantz and Sclater, 1987; Rosencrantz et al., 1988). Both are consistent, however, with a crustal cooling model which accommodates lateral as well as vertical heat loss from the accreting lithospheric slab (Boerner and Sclater, 1987). This model expresses crustal subsidence and heat flow as functions of slab age and

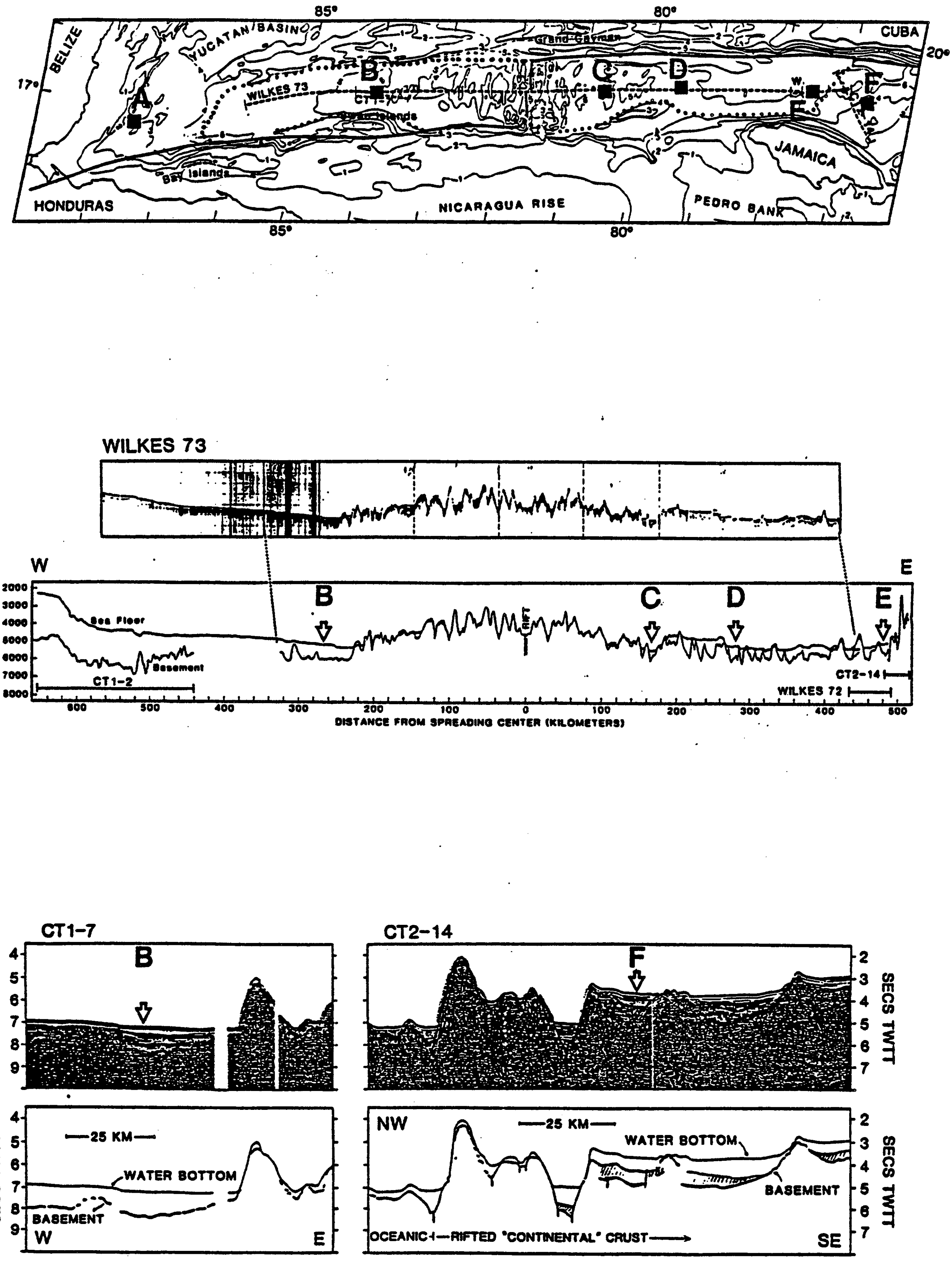


Figure III-8: Cayman Trough. A) bathymetric map showing seismic traces (dashed), major faults (solid lines), and edge of oceanic crust (dots), from Rosencrantz et al. (1988); squares are drill sites proposed in Section VII-16. B) Wilkes 73 single channel reflection section and line drawing. C) UTIG MCS sections and line drawings; hachured pattern in CT2-14 interpreted to be synrift sediments.

width. Sampled crustal ages, combined with existing bathymetric and seismic reflection information and new precise heat flow surveys, will directly test the validity of this analytical model, which has wide application to small, isolated ocean basins worldwide.

3) **Reconstruction of the kinematics of a transform plate boundary zone:** The northern boundary of the Caribbean plate consists of a 50 to 200 km-wide zone of transform and transform-related crustal deformation extending from the Pacific south of Chiapas, Mexico, to the Atlantic in the region of Anegada Island. The age of inception is uncertain. The Cayman Trough lies within this zone, and the Cayman spreading center has apparently recorded relative offset within this zone. Consequently, the basin opening history provides a kinematic framework from which to assess the timing and duration of tectonic events along the margin, which include both transpression and transtension as well as boundary zone fragmentation.

In summary, a series of holes along the length of the Cayman Trough is proposed that would penetrate and sample basin sediments and would continue into basement (Fig. III-8). The direct objective for drilling at each site would be to establish crustal age at each site to calibrate the rate history of and total displacement by spreading and to sample crust beneath each site to assess crustal formation processes.

Pre-Cayman Origin of Caribbean Plate

If the displacement of the Caribbean plate relative to NA at the Cayman Trough is small, a forefront question is then whether lithospheres of the Colombian and Venezuelan Basins were native to the Caribbean or were brought in tectonically by earlier, pre-Cayman movements of the Caribbean plate, as depicted in Figure II-6.

Exotic terranes could have entered the Caribbean south of Yucatan from Late Jurassic through Paleogene times and from any direction except from Atlantic sites where isochrons are preserved. Interpretations of Caribbean evolution that employ a pre-Eocene Caribbean plate, however, have easterly components of transport and Pacific origins of terranes (Mattson, 1969; Malfait and Dinkelman, 1972; Pindell and Dewey, 1982; Sykes et al., 1982) (Fig. II-6). This is based mainly on the possible correlation of Caribbean oceanic plateaus with contemporaneous plateaus in the western Pacific plate (Schlanger and Silva, 1981; Larson and Schlanger, 1981) and the thought that such midplate volcanism occurred across a Pacific-Farallon spreading center. Paleomagnetic data support pre-Eocene eastward motion if the Cayman Trough spreading began after or late in Eocene time, because declination anomalies of older Eocene or older age exist with appropriate rotation sense for boundary-parallel simple shear in collided arc rocks of the Greater Antilles and coastal South America (Gose et al., 1982; Skerlec and Hargraves, 1982; Stearns et al., 1982; MacDonald and Opdyke, 1972; Beck, 1988).

If lithospheres of the Colombian and Venezuelan Basins are far-traveled from the Pacific, they are likely to have large paleomagnetic latitudes that differ from contemporaneous latitude ranges in the Caribbean. This is because Farallon-NA convergence was right-oblique in the Cretaceous (Engebretson et al., 1985). Further, their lowest strata, presumably deposited at and near a spreading ridge, would contain fossils of Pacific rather than Atlantic affinities and probably little trace of continent-derived sediment. If these lithospheres were native, the latitude anomalies should be zero or small, and they should contain Atlantic-type fossils and may include sediment from South America. Moreover, the age of oceanic crust of today's Caribbean plate would be another test if it were known widely. That is, if very early Cretaceous and Jurassic ages spanned the Colombian and Venezuelan Basins, a Pacific origin would be indicated because NA-SA opening between Cuba and SA requires spreading through Aptian and possibly to Campanian time (Fig. II-4). Plate tectonic models are not precise enough, however, to assert the absence of small amounts of Jurassic or Early Cretaceous seafloor spreading in the southern Caribbean, for example perhaps extending west along the South American Margin from the Demerara Rise.

A definitive test of the provenance of the lithospheres of the Colombian and Venezuelan Basins is hard to devise. Studies of drillcore from these basins as to crustal age, geochemistry of protocrust and oceanic plateaus, paleolatitude, and faunal affinities, however, are likely to point compellingly to either an exotic or native origin.

Sites recommended for this investigation are in the southeastern Venezuelan Basin and western Colombian Basins where crust of normal thickness has been identified (Fig. III-1). These same holes are to be employed for investigations of Mesozoic seaways. Further, this problem can be jointly addressed with that of the origin of oceanic plateaus in a hole through the plateau, either at the Beata Ridge or in the northeastern Venezuelan Basin (Fig. V-1).

IV. PALEOGEOGRAPHY - SEDIMENT HISTORY - GEOCHEMISTRY PANEL REPORT

Chair: J. B. Saunders

Panelists: Buffler, Burke, Duque-Caro, Droxler, Farfan, Hay, Hendry, Keller, Lozano, Meyers, Peterson, Robinson, Salvador, Schlanger

Summary

Studies of drillcore in sedimentary sections of Caribbean basins offer major opportunities to advance knowledge of: 1) the history of development and maintenance of Caribbean seaways; 2) the history of Atlantic-Pacific water exchanges and their influence on oceanographic and climate history, and diagenesis, biotic evolution; and 3) the detection of exotic lithospheres in the Caribbean region.

Core of Jurassic and Early Cretaceous strata from native Caribbean lithospheres may inform us of the time of onset and duration of continental breakup and of subsequent subsidence and spreading. The southeastern Gulf of Mexico, Demerara Rise, and Blake Plateau are high priority sites for these objectives (Fig. IV-1). Such strata may also indicate by compositions, fauna, flora, diagenesis, and hiatuses the early Caribbean history of Atlantic-Pacific water interchange. Jurassic and Cretaceous strata in the Colombian and Venezuelan Basins, on the other hand, may indicate if and when a pre-Cayman Caribbean plate arrived from distant Pacific realms.

For much of the Late Cretaceous to present interval, the Caribbean region has included one or more seaways, and it is vital to learn the paleoceanography and associated records of water composition, temperature, flow patterns, fauna, and flora of this duration. The importance lies in the role of Pacific and Atlantic water exchange in the well-established, dramatic changes in global circulation and climate from the Cretaceous and early Paleogene to the later Cenozoic. A profound example of such changes is the growth of the Central American isthmus in late Cenozoic time and its effect on circulation in the northern Atlantic and development of the Gulf Stream.

Prime targets for Late Cretaceous to Neogene stratigraphic sections are in the Colombian, Venezuelan, and Yucatan Basins, away from highs where scour is likely to have been intense. If the

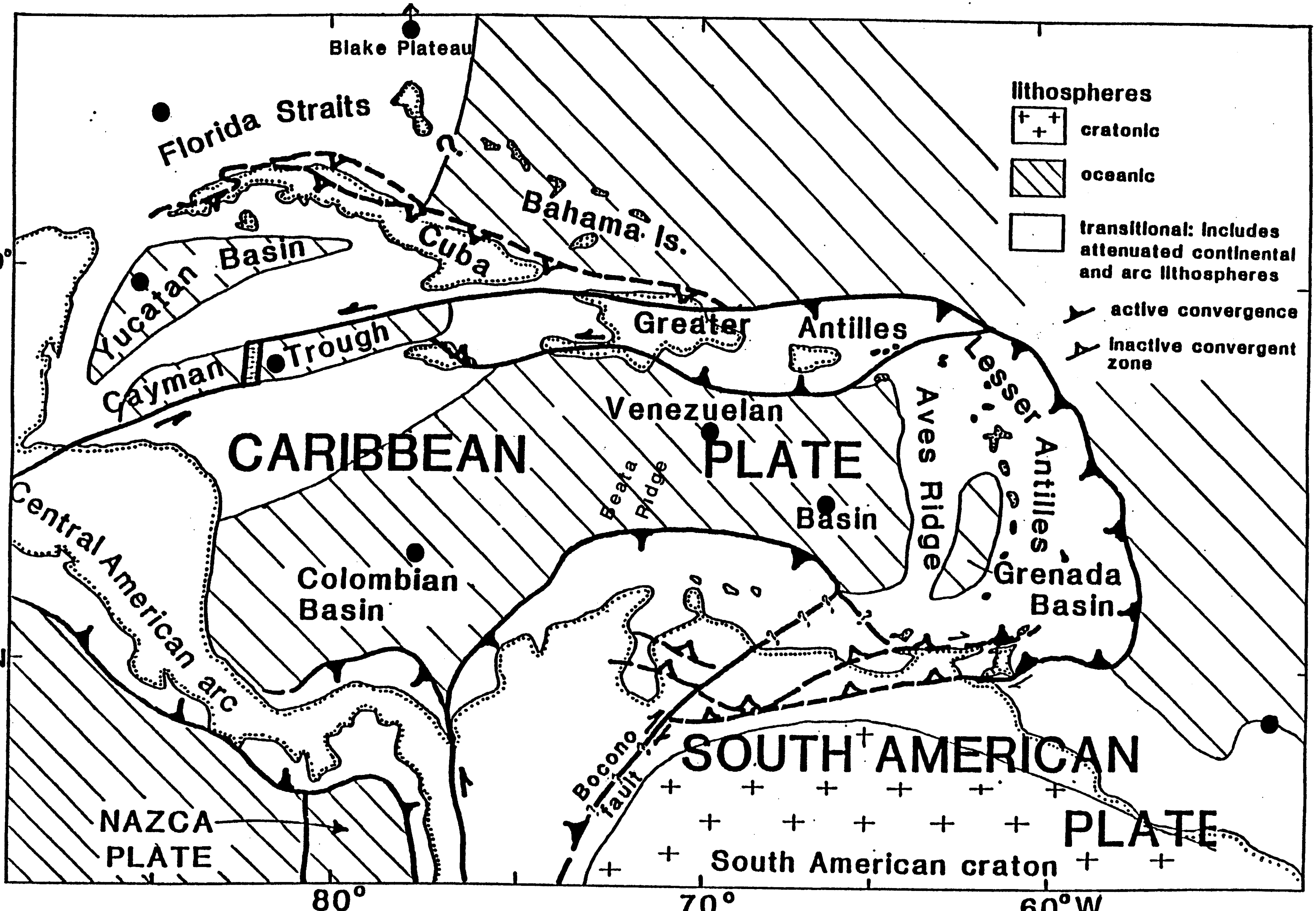


Figure IV-1: Priority sites of the Paleoceanography - Sediment History - Geochemistry Panel.

Caribbean plate traveled far in the Cretaceous, the goal of Cretaceous paleoceanography may not be attainable. If the Caribbean plate is far-traveled in Cenozoic time, sites in the eastern Venezuelan Basin should be drilled.

Introduction

The Paleontology-Sediment History-Geochemistry panel addressed the global and regional significance of Caribbean seaway evolution from the early Mesozoic to the present and drilling strategies in Caribbean strata to elucidate such seaway evolution. The major considerations are 1) the development with position and time of deep and shallow interconnections between Indo-Pacific and Tethyan-Atlantic realms; 2) the influences of such circulation changes on global and regional oceanographic and climatic history, and in particular chemistry, temperatures, and biological evolution; and 3) the possible detection of large tectonic transport of Caribbean lithospheres by faunal provinciality and sediment provenance and stratigraphic changes therein.

Strata of Caribbean basins have the potential to add greatly to our understanding of each of these goals. Unfortunately, previous drilling has not provided suitable core for inroads to date.

Jurassic Seaways

The distribution and nature of Jurassic rocks in the Caribbean region is crucial to understand the early development of seaways between the Atlantic and Pacific as Pangea broke up and NA separated from SA + Af.

Jurassic rocks are known to occur at the northern South American margin (Figs. IV-2): Tithonian carbonates in the tectonic complex of the Northern Range of Trinidad (Saunders, 1968); Bajocian or early Bathonian at Siquisique and Jurassic undifferentiated in the Espino graben, both in Venezuela and probably of rift-phase supracontinental origin (Muessig, 1984; Feo-Codecido et al., 1984); Jurassic red beds in the northern Andes which are in basins of either arc or rift origin (Maze, 1984); and red beds of possible Jurassic age dredged from the Demerara Rise (Damuth and Heezen, 1969). Jurassic strata are widespread in the northern Gulf of Mexico region (Fig. III-2) (Salvador, 1987; Winker and Buffler, 1988) and eastward into the Blake Plateau. They are suspected to continue south into the southeastern Gulf of Mexico and the Florida straits via DSDP drilling and seismic correlation (Buffler, Schlager et al., 1984; Schlager et al., 1984; Winker and Buffler, 1988). In central Caribbean realms, Jurassic is known only in the obducted Bermeja complex of Puerto Rico (Fig. IV-2) (Mattson, 1979), the La Desirade complex (Fig. IV-2) (Mattinson et al., 1980) and in Cuba (Case et al., 1984).

There are two drilling objectives for Jurassic strata: 1) to document the ages of first marine and first deep marine water ingress at sites that are most likely indigenous to the Caribbean; and 2) to supply evidence from fossils and sediments for or against large tectonic transport of terranes on which the sediments lie. In the latter objective, the strategy is to discriminate in strata above oceanic lithosphere an Atlantic or Pacific or other faunal provinciality and sediment provenance. Further, we wish to detect the existence and age of influx of sediments of South American cratonal origin as a gauge of proximity of sites to the southern Caribbean region vs. time.

There are three sites that satisfy the first drilling objective, namely, probably native, undisturbed marine Jurassic strata. Two of these are also priority sites of the Tectonics Panel and are discussed extensively in section III.

1. **Western central Atlantic** just east of the Blake Plateau (Figs. IV-1,3) where a deep marine Jurassic section would, perhaps, document the time of first entrance of Jurassic marine waters into the Caribbean from the North Atlantic.
2. **Demerara Rise** off northeastern South America (Figs. IV-1, III-5) where an inferred shelf to deep-marine Jurassic section would document the southern limit of a Jurassic Atlantic seaway, and link oceanic with land-based Jurassic sections along the present southern margin of the Caribbean.
3. **Southeastern Gulf of Mexico** (Figs. IV-1, III-6) to establish the nature, timing, and evolution of Jurassic marine seaways between the Gulf of Mexico and the central Caribbean.

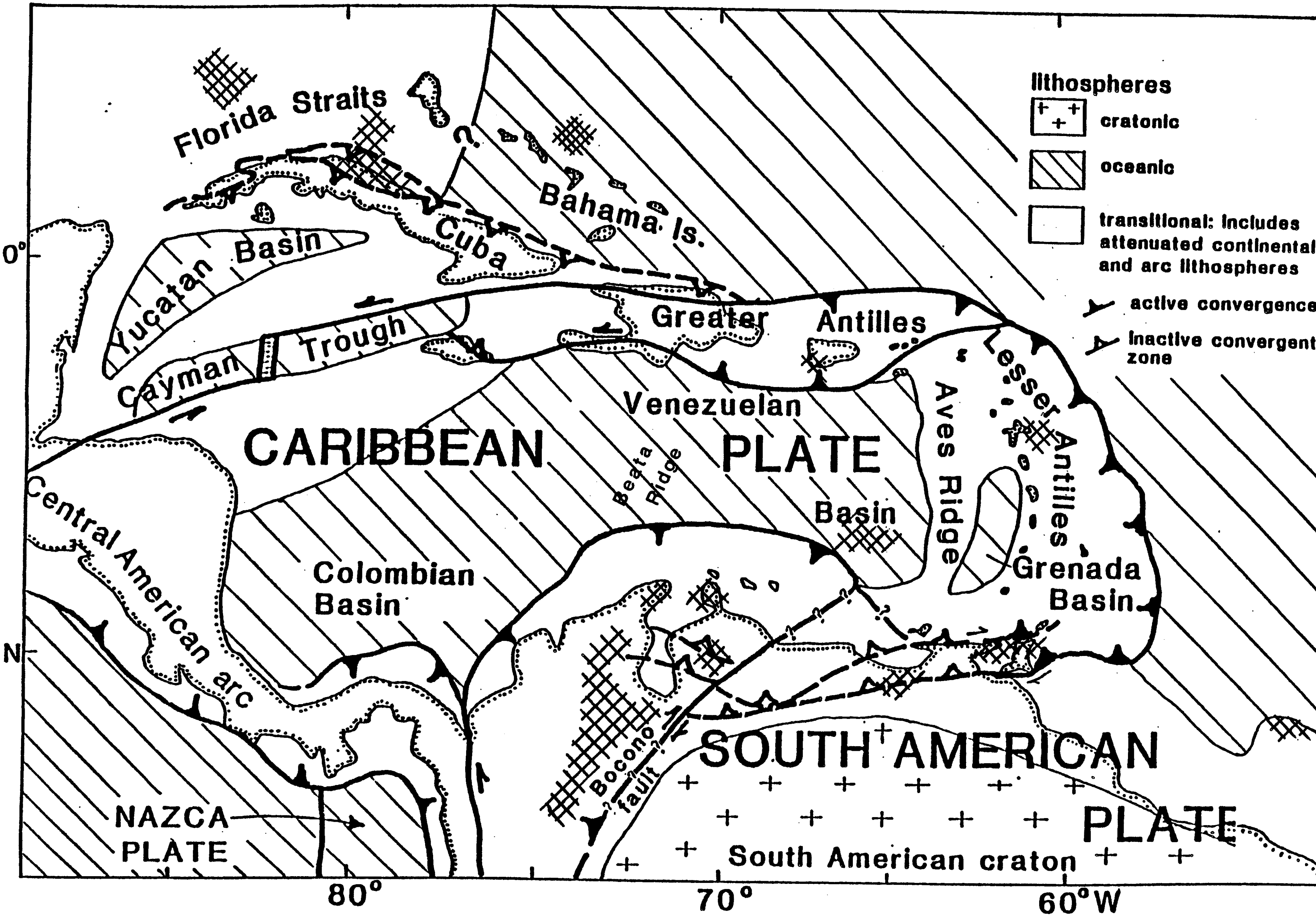


Figure IV-2: Known and inferred occurrences of Jurassic and Early Cretaceous rocks in the central and southern Caribbean region (cross-hatching).

The second objective can be attained in the Venezuelan and Colombian Basins in areas of normal crustal thickness (Figs. IV-1, III-4) and/or in areas of oceanic plateaus below the Late Cretaceous edifices. These were also recommended by the Tectonics Panel and are discussed in section III.

Ocean drilling would only be part of an integrated effort to reconstruct the Jurassic paleogeography and paleoceanography of the Caribbean-Gulf region. Prior to drilling, it will be necessary to compile all the information on pre-Cretaceous rocks around the rim of the Caribbean and on islands such as Cuba. For the same reason, the geophysical records need to be searched for reflections that suggest pre-Cretaceous strata.

Early Cretaceous Seaways

The stratigraphic record from Berriasian through Barremian is very poorly known in the Caribbean south of Yucatan and Cuba. Rocks of certain Early Cretaceous age have not been identified except at La Desirade (Fig. IV-2), the Demerara Rise (Figs. IV-2, III-5), the Virgin Islands, and Hispaniola. Evaporites of probable Early Cretaceous age exist in isolated occurrences in Trinidad and eastern Venezuela (Fig. IV-2), and no rocks below Coniacian have been penetrated by drilling in the Colombian and Venezuelan Basins.

The objectives of drilling Early Cretaceous sediments are the same as those for Jurassic strata, except that emphasis is on drift-phase subsidence and paleoceanography in possibly several major seaways. The study of Early Cretaceous fossils and sediments will complement that of Jurassic strata in discriminating large vs. small pre-Cayman transport of the Caribbean plate and may assist in dating such movements, if any.

To approach these objectives, sites are advocated in the Venezuelan and Colombian Basins where crust of normal thickness is encountered. A site in the southern Venezuelan Basin in the area of so-called rough B' (Fig. III-6) is particularly attractive. The Yucatan Basin is another Caribbean basin of apparently normal crustal thickness which may include a full Cretaceous section (Fig. III-7) (E. Rosen-

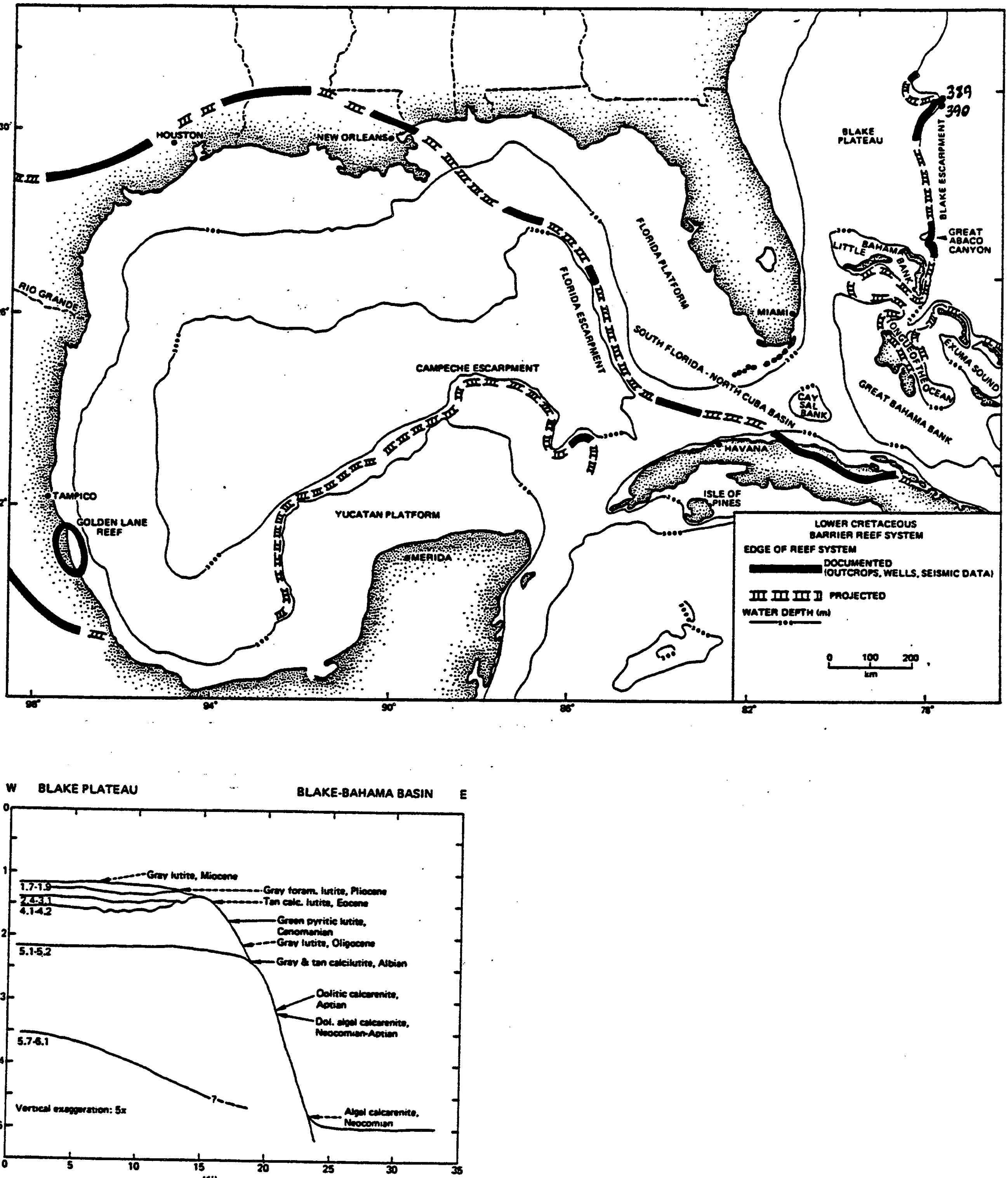


Figure IV-3: West-central Atlantic stratigraphy of the Blake Plateau.

crantz, writ. comm., 1988).

Paleoceanography and Faunal Evolution of the Late Cretaceous and Paleogene

The evolution of Caribbean seaways in this duration profoundly influenced Atlantic-Pacific oceanic circulation patterns and affected climate, faunas and floras. Yet, despite its global importance, few studies of Caribbean seaways have been undertaken. To understand the evolution of such seaways and their effects on global circulation, climate and biota, one or more key stratigraphic sections through Late Cretaceous and Paleogene sediments must be obtained. The results from Leg 15 were very incomplete, but they give important clues on where to aim for more complete documentation.

Major Oceanographic and Climatic Effects

Climate: During the Late Cretaceous through the Paleogene, major changes in the ecosystem resulted from a change from the warm, equable climate of the Mesozoic towards a climate and ocean circulation system that eventually led to the present regime (Fig. IV-4). The change from the Mesozoic to the Tertiary system was not gradual but involved dramatic, even catastrophic environmental changes that are still poorly understood. For instance, the late Maastrichtian climatic and environmental deterioration led to major extinctions followed by the K/T boundary mass extinction. The recovery period in surface productivity was prolonged and was followed by major changes in climate, oceanic circulation, productivity and evolution of microfossils during the late Paleocene to early Eocene. These fluctuations are illustrated in Figure IV-5. Understanding the conditions that led to these global changes is of primary importance in reconstructing ocean climate and atmospheric history.

Data gathered so far suggest climatic cooling during the early Late Cretaceous followed by isotopically lighter bottom waters during the late Maastrichtian (Lindinger and Keller, in press; Barerra, unpubl. data) that could have been caused by a major change in thermohaline circulation.

The K/T boundary event itself shows conflicting data, but overall cooling is implied for the earliest Paleocene with an unstably fluctuating climate. There was a general temperature rise during the

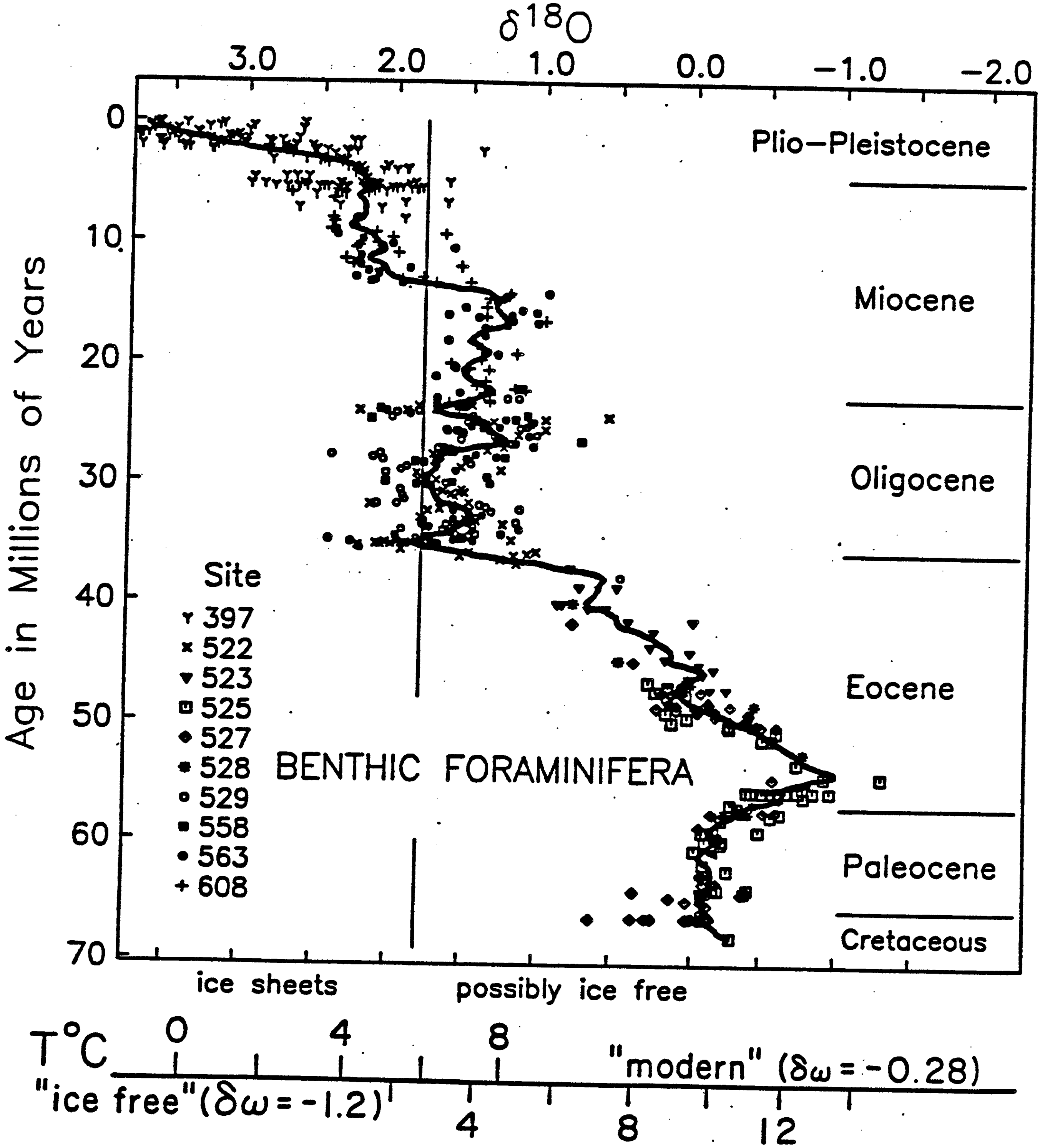


Figure IV-4: Bottom water temperatures vs age from composite benthic foraminiferal oxygen isotope record for Atlantic DSDP sites since 70 ma. The lower temperature scale assumes no significant ice sheets; upper scale assumes ice volume equivalent to present; from Miller et al., 1987.

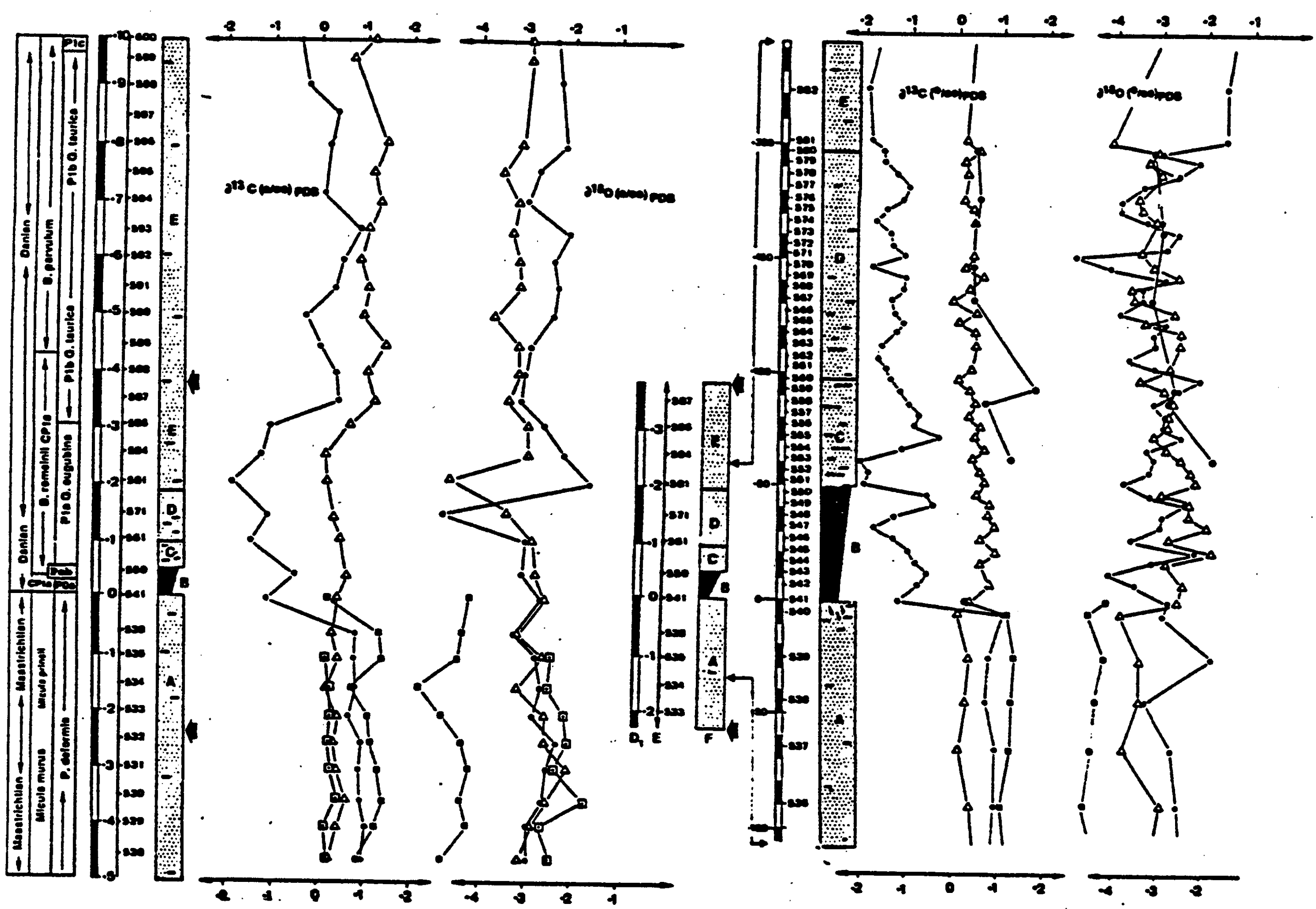


Figure IV-5: Carbon and oxygen isotopic changes with time in Cretaceous and Cenozoic at El Kef, Tunisia. Drop in productivity indicated by low carbon 13 at K/T boundary. Productivity was low and fluctuating in early Paleocene, and climate was unstable and fluctuating then as indicated by oxygen 18.

late Paleocene and into the early Eocene (Fig. IV-5). Stable oxygen isotope studies of well preserved faunas in the Caribbean could provide insights into the thermohaline circulation of Late Cretaceous oceans, production of warm saline bottom waters in low latitude marginal seas (Brass et al., 1982), and the climate regime between the Tethyan-Atlantic and Pacific oceans, as expanded below.

Productivity: Information on productivity fluctuations at different levels in the oceans can be gained by the carbon-13 isotopic values for planktic and benthic foraminifera and bulk carbonates. The relationship between oceanic productivity and atmospheric CO_2 is poorly understood. Yet it may be this interchange that drives the climatic system and is largely responsible for the long post-K/T boundary recovery period among marine microplankton.

Critical intervals to be studied are the K/T boundary productivity crash and prolonged recovery period (Gerstel et al., 1987; Arthur et al., 1987; Keller, 1988), the carbon-13 shift during the mid-Paleocene (Zone P2), and succeeding changes into the later Paleocene and early to late Eocene.

Cyclicity: Milankovitch cyclicity has been well established for the Pleistocene, but it is not well known whether similar orbital motions affected climate during the Cenozoic and Cretaceous. Studies of rhythmic bedding in the Appennines by Herbert and Fisher (1986) have shown a 100,000 year cycle and possibly a 400,000 cycle during the mid-Cretaceous. Similarly, a study of cyclicity in Albian outcrops at Piobbico in Italy shows clear 100,000 yr. orbital and 20,000 yr. precessional cycles (Fig. IV-6). This study shows that celestial motions similar to the present may have affected the climatic system at least since the Late Cretaceous. However, it also implies that the K/T boundary event may have disrupted this system for some time. At the present it is unknown whether Milankovitch cyclicity can be detected during the late Paleocene and Eocene, although rhythmic bedding at this time in Kryenhagen radiolarian cherts and shaly interbeds suggest that similar orbital effects existed.

The study of cyclic sedimentation in deep-sea sediments, the presence of Milankovitch cyclicity from Late Cretaceous through the Paleogene, and the possible disruption of this system for short periods of time is of key importance to an understanding of the evolution of climate and possibly of evolutionary changes of faunal and floral communities. The Caribbean can play an important role in this study by virtue of its geographic position.

The Faunal Record

Late Cretaceous: Studies of Late Cretaceous faunas and floras indicate that gradual extinction occurred through this time and that during the latest Maastrichtian, diversity was already significantly reduced. What caused this decline in diversity? Was it related to climatic and oceanic circulation changes? At present, good Late Cretaceous sequences with well preserved faunas are available from the Pacific (Sites 465, 577), South Atlantic (Site 528) and North Atlantic (site 605). A complete Late Cretaceous section in the Caribbean would allow comparison with these sites and demonstrate whether the Caribbean faunas and floras show either Pacific or Atlantic affinities.

The K/T Boundary: This event has been studied in many deep-sea as well as land sections. Recent studies in Texas (Brazos River - Jiang & Gartner, 1986; Keller, in prep.) show that the K/T boundary event may have had little impact in this region. Microfossils as well as invertebrate faunas disappear gradually during the Late Cretaceous. Planktic foraminifera that became extinct at the K/T boundary were already declining prior to the event.

In the deep-sea as well as in the Tunisian shelf sections and those of the Brazos River, about 10 species survived the K/T boundary. However, the Texas fauna shows important differences from those in Tunisia in that the surviving Cretaceous species in Texas are abundant and apparently thrive after the boundary. Did sheltered environments for Cretaceous faunas still exist in the Caribbean and Texas areas after the K/T boundary?

Early Paleocene: Zones P0 and P1 are usually condensed into a few cms. of clay deposition in the deep-sea. However, in shallow shelf sections these zones may be represented by as much as 3 m of sediment (Keller, 1988). The degree to which the CCD was raised due to the productivity decrease at this time could be investigated by placing a new hole in the region of Site 152 on the Nicaraguan Rise (Fig. IV-1), where the best results across the boundary have so far been achieved.

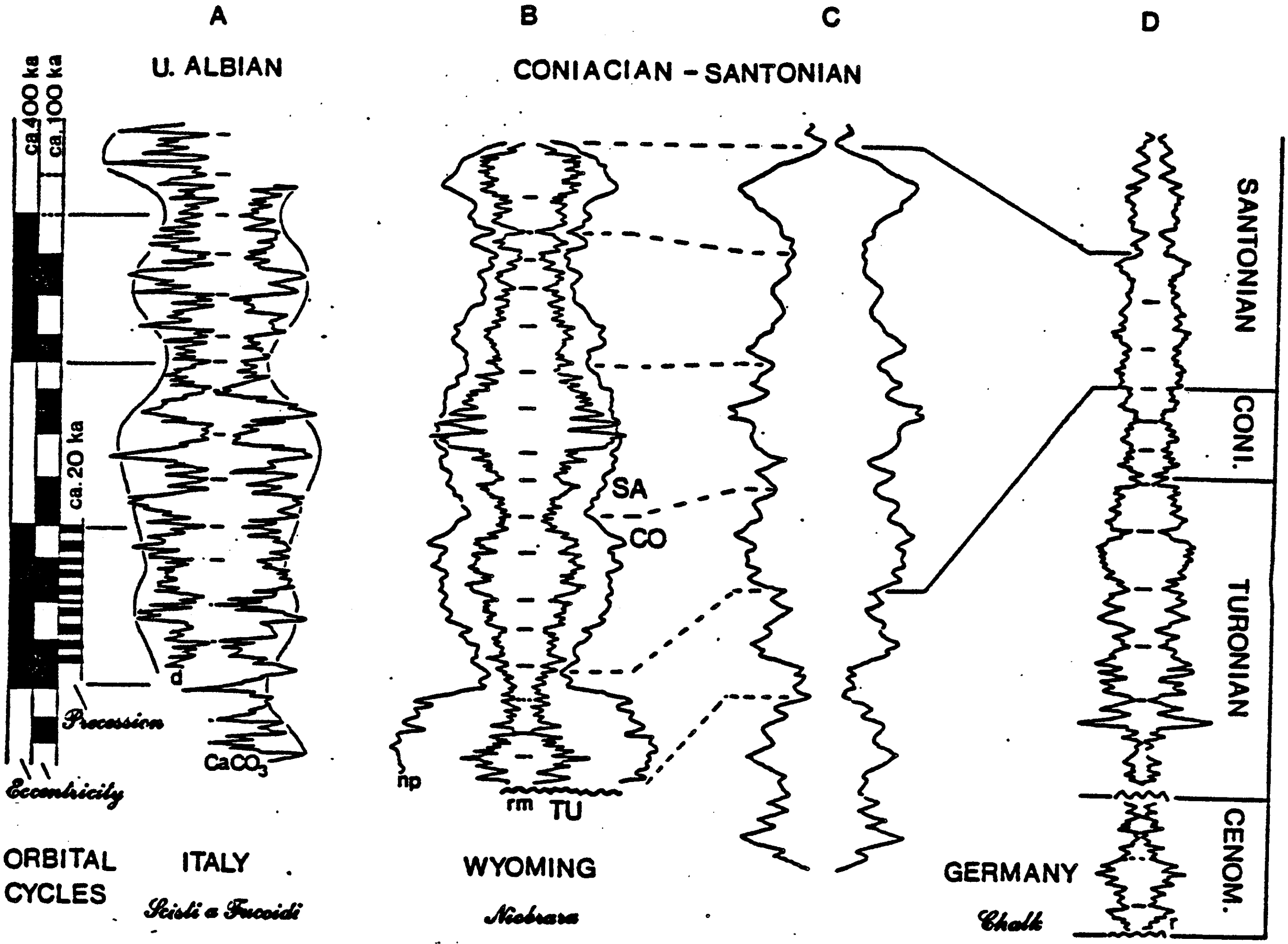


Figure IV-6: Signatures of "precession-eccentricity syndrome." The high-frequency signal is the precession-related (c. 21 ka) alternation of low-carbonate/high-carbonate bedding couplets; these are grouped into bundles corresponding to the 100 ka short-eccentricity cycle; envelope curve delineates the 400 ka long-eccentricity cycle. A: Albian, Italy from Herbert and Fischer, 1986; B: Late Cretaceous (Coniancian-Santonian) Niobrara Formation, Wyoming from Fischer, in prep.; C: enlarged segment of D, for comparison with B; D: Late Cretaceous (Turonian-Santonian) chalk of northern Germany (A. Fischer, in prep.).

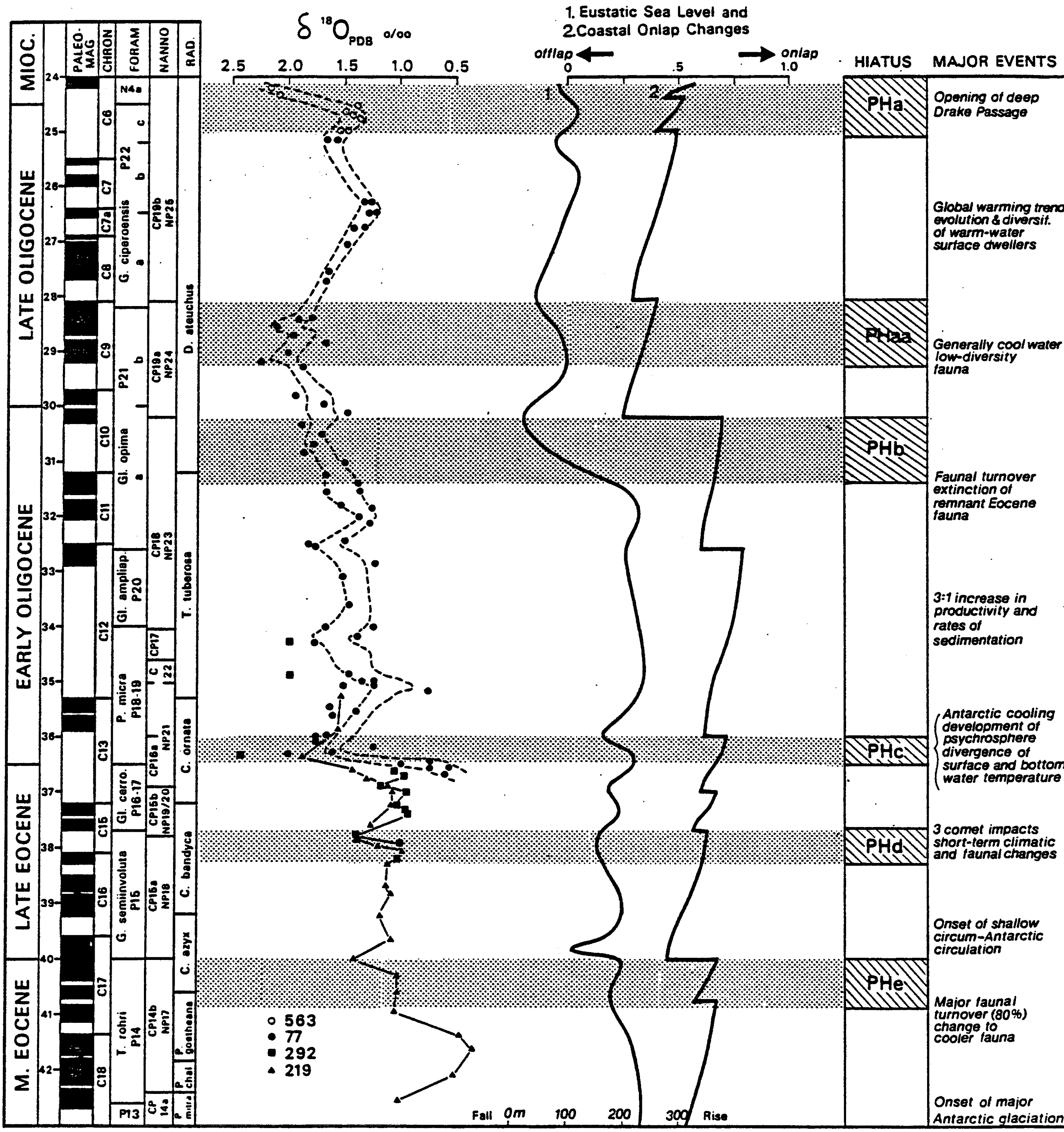


Figure IV-7: Hiatuses and major oceanographic and biologic events correlated with temperature and eustatic changes.

Middle-Late Paleocene - Early Eocene: Evolutionary radiation of Cenozoic planktic foraminifera after the K/T boundary event occurred during the middle and late Paleocene, and major faunal changes continued into the early Eocene. The climate warmed during the late Paleocene causing the maximum temperatures known in the Cenozoic to be in the early Eocene (Fig. IV-4). Thereafter, a cooling trend continued to the end of the Oligocene (Fig. IV-4). Oceanic productivity increased about 300,000 years (Zone P1b) after the K/T boundary event with a major shift in Zone P2 (Fig. IV-5). What caused the major climatic and productivity changes? Are there significant differences between the Caribbean, Pacific, and Atlantic records? Study of faunal provinces as well as oxygen-18 and carbon-13 studies of foraminifera can provide information on the evolution of the Caribbean province and its importance as a gateway between the Pacific and Atlantic through the Paleogene.

Hiatuses: Any section drilled in the Caribbean is bound to have hiatuses because of the Atlantic-Pacific current circulation through this seaway. The most extensive unconformities can be expected to occur on structural highs, which thus have to be avoided. Sites must be chosen above the CCD in the Caribbean basins to provide maximum information. Study of the global distribution of deep-sea hiatuses during the late Paleogene reveals that hiatuses generally correspond with climatic changes and eustatic sea level lowering, as illustrated in Fig. IV-7 (Keller, et al., 1987).

The distribution of hiatuses can provide information regarding flow paths of major oceanic currents, as well as the opening and closing of pathways within the Caribbean. Comparison of the hiatus distribution in the Caribbean with that of the Pacific and Atlantic will permit the tracing of oceanic circulation through the Caribbean seaway.

Drilling Objectives

It should be possible to recover a relatively complete stratigraphic record from a fairly stable region such as the southeastern Venezuela Basin (Figs. IV-1, III-6). However, the water depth should not be greater than 3500 m during the time of deposition and preferably shallower to insure well preserved calcareous microfossils. Possible locations are the flanks of the Venezuela Basin or the

Colombia Basin.

To obtain a complete enough section, it may be necessary to drill more than one hole at the site that is chosen, using new coring techniques able to get high recoveries in the difficult and varied lithologies.

Sedimentation and Diagenesis of Eocene Horizons A"

Seismic reflection studies in the Caribbean show a widespread strong reflector in the Colombian and Venezuelan Basins called A" (Fig. III-6) and correlated with the similar A reflection in the Atlantic (Ewing et al., 1967). A" was drilled on Leg 15 and shown to contain interbedded chert, limestone, and soft ooze of early and middle Eocene age (Edgar, Saunders et al., 1973). It has been impossible, however, to work out the stratigraphy, geochemistry, and diagenetic evolution of A" samples because the drilling procedures yielded badly disturbed core. The A" strata are a major objective of new Caribbean drilling because they are a product of heterogeneous diagenesis caused apparently by global or regional oceanographic changes. Understanding A" strata will also permit confident interpretation and correlation of reflector sets across major structures in the Caribbean, such as the boundaries between thick and normal crusts (Fig. III-6).

The problem of the diagenesis of siliceous and calcareous oozes has been sporadically investigated using samples of varying quality on a number of DSDP legs. However, given a suitable coring technology and a complete set of logs, it should be possible to obtain a complete section of the interbedded cherts, limestones, and soft oozes of A" and to make extensive extrapolations, as follows. It is known that A in the Atlantic is, in parts, a similar cherty interval but it is associated with an unconformity in the region of the continental margin. Using the new logging technology available on the **Resolution**, it should be possible to determine the seismic characteristics of A" in the Caribbean, particularly by analysis of velocity logs. It would than be possible to tackle the separation of the cherty interval from the unconformity in the North Atlantic, thereby contributing greatly to the knowledge of siliceous sediments and to the extent of the Eocene hiatus.

Using Caribbean locations to document cyclicity is particularly useful as the region constitutes the seaway between Atlantic and Pacific water masses.

Because of poor recoveries in Leg 15, the data with which to estimate the proportions or rates of accumulation of silica or other components are poorly resolved, yet this is critical to our knowledge of the mass balance of silica in the oceans (Miskel et al., 1985).

It appears certain that the alternation of lithologies that have been found to be so widespread in the oceans at this level reflects Milankovitch cycles in the Eocene. At the moment we know little about the faunal and floral response to the rapidly varying conditions highlighted by such cycles. Equivalent cycles are presumed to occur on land but have not been conclusively proved to date.

The test site should be in the Venezuelan Basin at a shallower depth than Site 146/149, which would require its placement some 50 km. to the northwest of that location (Fig. III-6). We should be prepared to drill a second hole at the chosen site if this is necessary to obtain an adequately complete section. In addition, it will be necessary to refine our knowledge of land sections that are thought to display equivalent rhythmic cycles. As regards, the effects of diagenesis on the calcareous and siliceous fractions of the sediments, new pore water studies must be made.

Neogene Paleoceanographic Record

The tectonic evolution of the Caribbean has played a fundamental role in controlling the exchange of surface, intermediate and deep waters between the Atlantic and Pacific Oceans. The development of physical barriers and the resulting impediments to water movement have allowed the chemical differentiation of the global ocean, setting up gradients in nutrients, salinity, and alkalinity between basins. Today, surface water entering the Caribbean comes through gaps in the Antillean arc and Aves Ridge. The prevailing trade winds pile up water against Central America resulting in a hydraulic head over the level of the North Atlantic which provides much of the driving force for the Gulf Stream. Below the surface layer, the basins of the Caribbean are largely isolated from the main-stream of Atlantic thermohaline circulation by a series of shallow sills (1600-1800 m) which control the downstream hydrography of the Caribbean deep waters. The Caribbean basins are thus filled with waters which have their origins in the mid-depth Atlantic, today's Upper North Atlantic Deep Water, and perhaps some Antarctic Intermediate Water. These waters affect depositional/preservational patterns in sediments of the deep Caribbean and leave a geochemical imprint on the benthic faunas.

Limited evidence to date suggests that the Caribbean basins have experienced a unique paleoceanographic history throughout the Neogene. Recent work on late Pleistocene sediments from the Caribbean has shown that carbonate dissolution patterns and the carbon isotopic record of benthic foraminifera are exactly out of phase with similar records from the adjacent deep Atlantic (Cofer-Shabica and Peterson, 1985, 1986, in prep.; Oppo and Fairbanks, 1987; Boyle and Keigwin, 1987). This reversal of the deep Caribbean signal on glacial-interglacial time scales has been linked to climatically-induced change in the vertical deep water structure of the open Atlantic. On much longer time scales, Leg 15 drill sites in the Venezuela Basin have allowed a very low-resolution reconstruction of Tertiary fluctuations in the Carbonate Compensation Depth (CCD) (Hay, 1985). Compared with CCD fluctuations in the Atlantic, those of the Venezuela Basin appear to have been much more frequent, rapid, and generally of greater amplitude. These relatively short (<2 Ma) and high amplitude (>600 m) bathymetric excursions of the Venezuela Basin CCD began suddenly in the mid-Miocene about 15 Ma ago. The relatively rapid onset of these cycles and their propagation through much of the late Neogene probably reflect some combination of tectonic (changing sill depth) or climate-related changes in the character of the water mass entering the basin, although changes in biological productivity may also have played a role.

Neogene sediments of the Caribbean basins offer a unique opportunity to assist in the reconstruction of the history of mid-water thermohaline circulation in the open Atlantic and to gain insight into the physical evolution of the Caribbean seaway through the careful comparison of sedimentologic, biotic, and geochemical records from each of the various basins. In particular, the western Venezuela

Basin (Fig. IV-1) and portions of the Cayman/Yucatan Basins (Figs. III-7, III-8) provide suitable target areas for sampling transects across a range of water depths. These basins are today separated from each other and receive their deep waters over different inlet sills. Both target areas should be APC-XCB-cored in depth transects consisting of a minimum of three double cored sites each. By following a transect strategy, we can make high resolution reconstructions of carbonate accumulation and dissolution history (a depth-dependent process), and examine the isotopic and faunal records in these respective basins. Comparison of Caribbean records with those from the adjacent Atlantic will lead to a better understanding of how the intermediate-depth Atlantic responded to major Neogene paleoceanographic and paleoclimatic events.

Because of the relative homogeneity of deep waters in the silled basins of the Caribbean, far fewer sites are needed to address the history of local deep waters than would be required in a stratified open-ocean setting. Thus, the proposed drilling program would require a minimum of actual site time in order to accomplish its objectives. In addition, time could be saved by coordinating an APC/XCB Neogene program with deeper penetration objectives.

Other Sites

The panel also recommends with lower priority drilling the northern Nicaraguan Rise with a view to the opening of a Cenozoic seaway between the Yucatan and Colombian and Venezuelan Basins during active transform motion at the northern NA-Ca boundary. The background for such drilling is in section VII (Droxler).

Correlative Studies

ODP drilling is our main concern, but other aspects need to be addressed. Before the **Resolution** reaches the Caribbean we have a chance to review our information on some aspects of the geology of the surrounding margins and of the islands. For this we would request funding to tackle certain key questions that we have yet to formulate in detail. A great wealth of information has already been gathered; some published but much in the files of oil companies. A Synthesis of the relevant parts of this will place us in the best position to interpret the new drilling results and to choose between the models of plate origin and microplate migration.

We need to concentrate particularly on the early history, from Triassic to early Paleogene. Subjects for study could include:

a) comparison of the Turonian to Santonian organic-rich sediments from Leg 15 for comparison with land occurrences of the same and earlier ages.

b) comparison of the Jurassic and Lower Cretaceous limestones of Cuba with those of Trinidad and eastern Venezuela to look for signs that these were laid down in geographic proximity.

c) comparison of the Cretaceous and Paleogene biota from earlier drilling with equivalents in North and South America and Central America. How similar are the faunas and floras, or to what extent do they differ? Do we see a Pacific provenance when we restudy the DSDP material already gathered?

V. ACTIVE MARGINS AND ACCRETIONARY TECTONICS PANEL REPORT

Chair: G. K. Westbrook

Panelists: Barker, Behrmann, Kellogg, Larue, Mascle, Moore, Payne, Smith, Speed, Tavaras

Summary

The Caribbean plate is rimmed by accretionary complexes along much of its margins, due to subduction of oceanic lithospheres of adjoining plates and of Caribbean oceanic lithospheres below peripheral terranes. Caribbean accretionary complexes provide unsurpassed opportunities for major advances in the global themes of accretionary wedge mechanics and evolution of fluids in accretionary wedges. It is possible to study by drilling all the major aspects of wedge mechanics in a single complex: wedge thickening mechanisms, kinematics, and materials changes; growth history of wedges and steady vs. episodic behaviors; tectonics of inner forearc regions, including wedge and forearc basin interaction; effects of oblique convergence; and forearc subsidence. The evolution of fluids in wedges: generation, flow rates and distribution, and controls by tectonism and vertical loading can be investigated concomitantly.

Introduction

The motions of plates around the present Caribbean plate have been such that most of its boundaries, with the striking exception of the Cayman Trough system, have some component of convergence across them. This has led to the development of Cenozoic, mainly Neogene, accretionary complexes around much of the Caribbean plate (Fig. V-1). The complexes occur at two types of subduction zones: exterior ones above downgoing oceanic slabs of adjacent plates (east of the Lesser Antilles between Puerto Rico and Trinidad, north of Hispaniola, and the Middle America Trench between Mexico and Panama) and interior ones where lithospheres of the Venezuela and Colombia Basins subduct marginal Caribbean lithospheres or microplates of arc and transitional character (south of Hispaniola and Puerto Rico, off northern Panama, Colombia and northwestern Venezuela). These margins vary greatly in their rates and directions of convergence and in the types of sediments accreted to them. Within a comparatively small geographical area, there is a wide diversity in the development of accretionary complexes.

The accretionary complexes of the Caribbean region are among the most intensively studied. Excluding the Pacific margin of the Caribbean plate, the Barbados Ridge complex in the Lesser Antilles forearc (Fig. V-2) has received the most attention. It was drilled in DSDP Leg 78A and ODP Leg 110 (Biju-Duval, Moore et al., 1982; Moore et al., 1982; Moore et al., 1987; Moore, Mascle et al., 1988), extensively explored by geophysical techniques (Westbrook, 1975; Westbrook et al., 1982, 1984, 1988; Brown and Westbrook, 1987; Mascle et al., 1985, 1988; Speed, Westbrook et al., 1984; Biju-Duval et al., 1982; Speed et al., 1988; Torrini and Speed, 1988) and onland (Speed and Larue, 1982; Speed, 1983). All these investigations have led to major advances in understanding two global themes.

1) **accretionary wedge mechanics:** thickening mechanisms, kinematics, and material properties changes; history of wedge growth by progressive deformation; forearc and slope basin development and interaction with the growing wedge; and structural effects of oblique convergence.

2) **evolution of fluids in accretionary wedges:** progressive compaction of wedge sediments by the expulsion of pore fluids and release by diageneses of fluids during accretion and subsequent thickening and deformation of wedges; fluid and heat flow rates, conduits; effects of underriding sediments - fluid sourcing and discharge paths; roles of fluids in wedge tectonics.

The global significance of these topics cannot be overstated because they provide a time-series analysis of active mountain-building and the major processes of thin-skinned tectonics and fluid accumulation. Although much has been recently learned, more investigations of accretionary wedges are necessary to arrive at comprehensive theories of accretionary tectonics and fluids evolution. We discuss below the main aspects of these two problems that can be approached by drilling, emphasizing

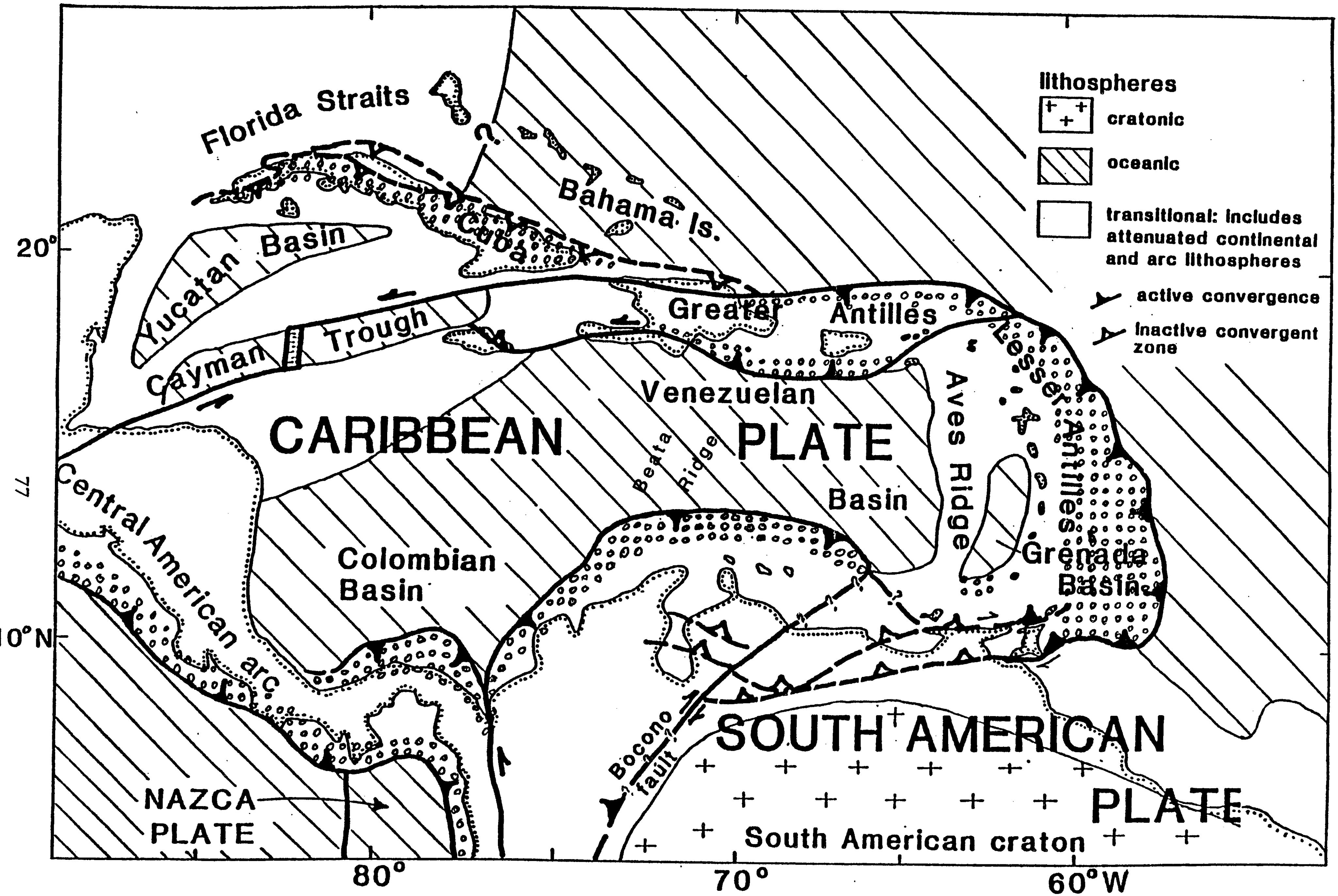


Figure V-1: Cenozoic accretionary complexes in the Caribbean region (open circles).

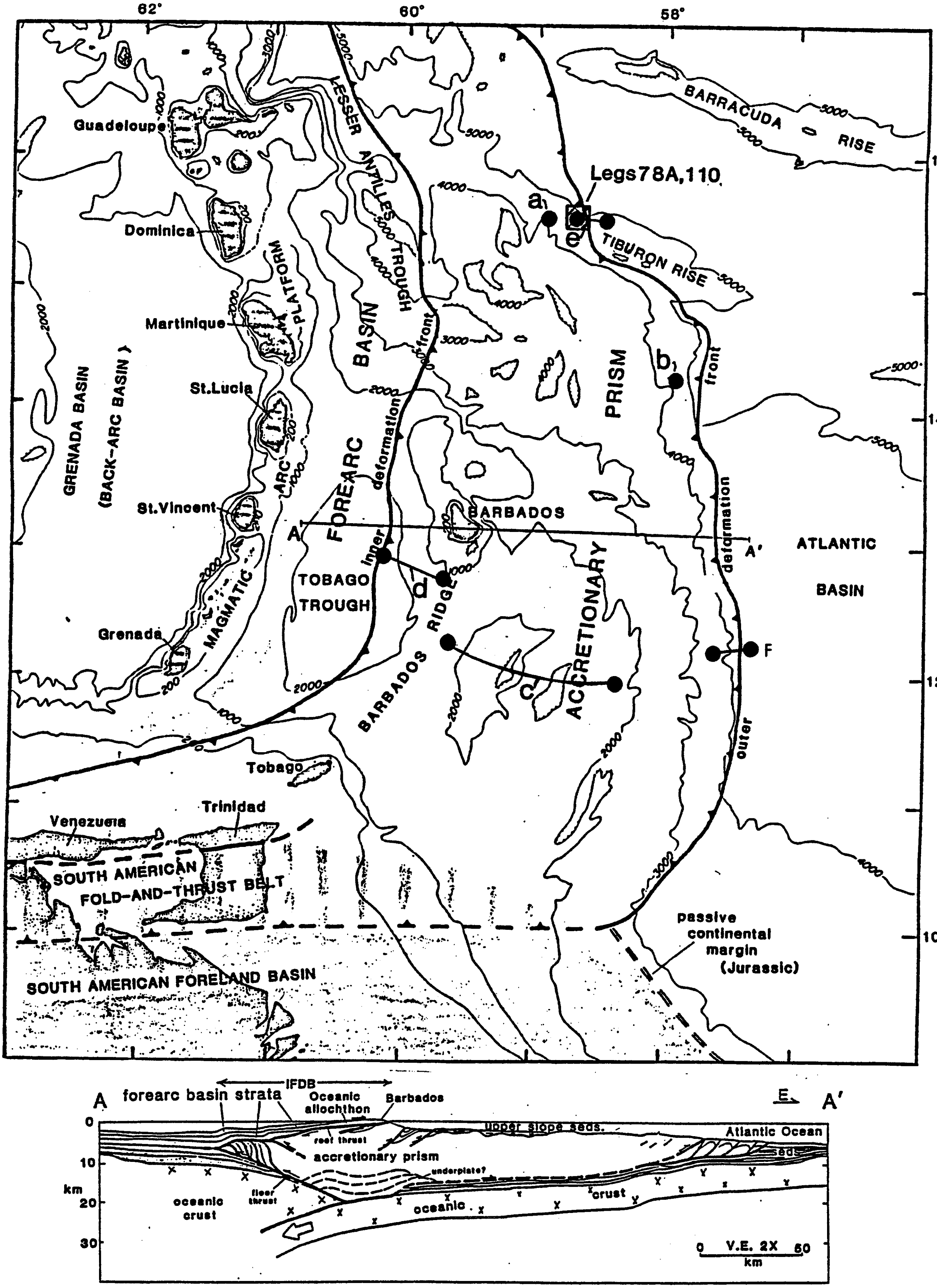


Figure V-2: Lesser Antilles forearc and Barbados Ridge accretionary wedge (=prism); recommended ODP targets indicated: a: test for underplating (duplexing); b: out-of-sequence thrusting; c: slope cover thickening, slope basin deformation, and episodicity of accretion; d: forearc basin-wedge interaction; e: fluids in low permeability prism; f: fluids in high permeability prism.

that Caribbean accretionary wedges offer perhaps the world's best opportunities for major inroads.

Accretionary Wedge Mechanics; Thickening, Growth History, and Interaction With Forearc Basin

Mechanics of Wedge Thickening: Accretionary wedges develop at active margins in response to plate convergence and offscraping of a part of the sedimentary cover from the incoming oceanic crust. Offscraping transfers to the wedge's leading edge a succession of thrust bound slices of sediment, each a few hundred to a few thousand meters thick. However, accretionary prisms usually grow to thicknesses of between several thousand meters and a few tens of km. The thickening cannot be explained solely by thrust imbrication during offscraping. Other processes of progressive thickening are active in the wedge behind the deformation front, as follows:

1) rotation of initially offscraped packets,

2) formation of duplexes below the wedge by deepening of the detachment in the underriding sediments,

3) development of late (or out of sequence) thrusts within the wedge,

4) incorporation ofsediments of slope basins and slope drape in the wedge by thrusting and folding.

All these processes have been recognized or inferred from the study of seismic profiles. Their magnitude, time of formation, and mechanics can be learned, however, only by deep drilling in areas already well surveyed by seismic profiling. Such investigations are not only of interest for accretionary tectonics but also for the understanding of the initial development of continental mobile belts.

The Lesser Antilles forearc at the eastern edge of the Caribbean plate, contains the Barbados Ridge complex which is one of the best surveyed accretionary wedges in the world (Fig. V-2). Several thousand km of multichannel seismic data (including high resolution as well as deep profile), Seabeam mapping, and Gloria survey allow recognition of the occurrence of all the tectonic processes previously described. Legs 78A and 110 of the DSDP program have yielded much data which, however, concern only initial accretion. A new set of holes (which would be achieved in a single leg) can immediately be proposed which would explain the different processes by which a wedge thickens upslope from the deformation front. Examples of drill sites that might be occupied are:

1) a deep hole 15 km arcward of the outer deformation front on the Leg 110 transect (near 674) to test the process of underplating (duplex formation) (Figs. V-2, site a; V-3A),

2) 2 holes in the central part of the Barbados Ridge would cross seismically well defined out-of-sequence thrusts (Figs. V-2, site b; V-3B),

3) holes along a transect as far upslope as Barbados (Fig. V-2, site c) would be devoted to the study the progressive deformation of the slope cover, and its incorporation to the prism, with the accompanying formation of slope basins (Fig. V-3C,3D,3E).

History of Growth of Wedges: Episodicity in Accretion: It is widely recognized that accretionary complexes do not grow in steady state. There are periods over which they have grown more rapidly than others. Variables controlling the rate of forward growth are rate of subduction, sediment thickness, and sediment type which influence the position of decollement surfaces and the shear stresses along them. A shallow-tapered accretionary wedge, which will have low shear stresses at its base, will grow forward more rapidly than a steeper angled wedge with higher shear stresses. The taper and shear stress are functions of pore fluid pressure, sediment permeability and compaction rate, and thus, the sediment is an important component of wedge growth.

To establish the importance of episodicity in the accretion process, we need to identify accretion rates and periods of fast and slow accretion in the past which could be correlated with changes in plate motions, sea level, and other aspects of the environment of accretion. The rate of forward growth of the accretionary complex, which is not the same as the rate of subduction, can be established for the growing tip of the wedge by examining the change in sedimentation between the trench floor and the uplifted accreted slices of sediment. Rates of growth further in the past can be obtained by drilling into the accretionary complex beneath the slope cover sequence to examine the age of the contact between the slope cover and the accreted rocks beneath. With allowance for shortening, which can be

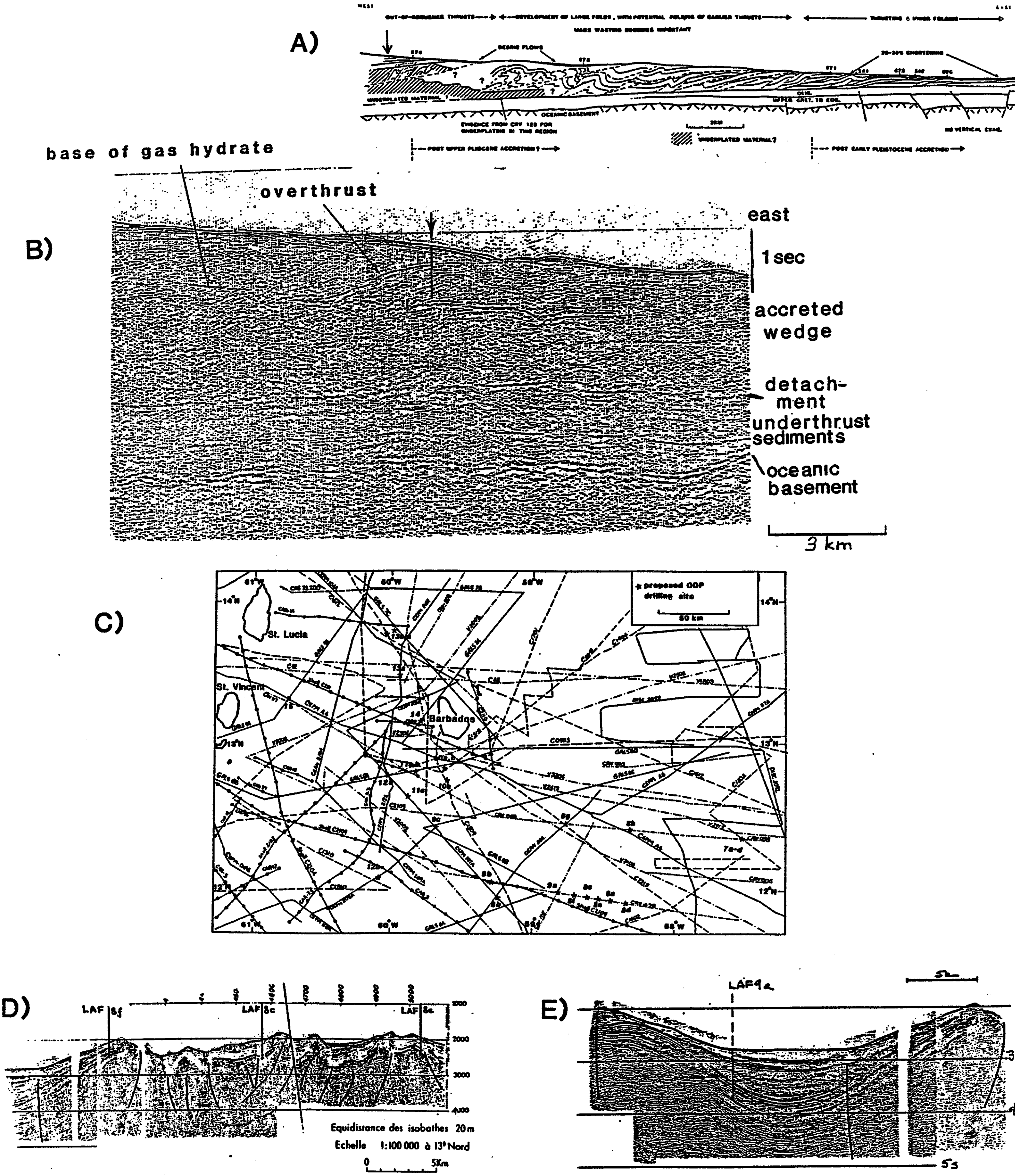


Figure V-3: Sections in Barbados accretionary wedge showing recommended sites: A) Legs 78A-110 transect: site to test for underplating (arrow); map location at a, Fig. V-2; B) site to test out-of-sequence thrusting; map location at b, Fig. V-2; C) track chart near Barbados; D) and E) sites to study deformed cover, slope basins, and episodicity; map locations Fig. V-3c.

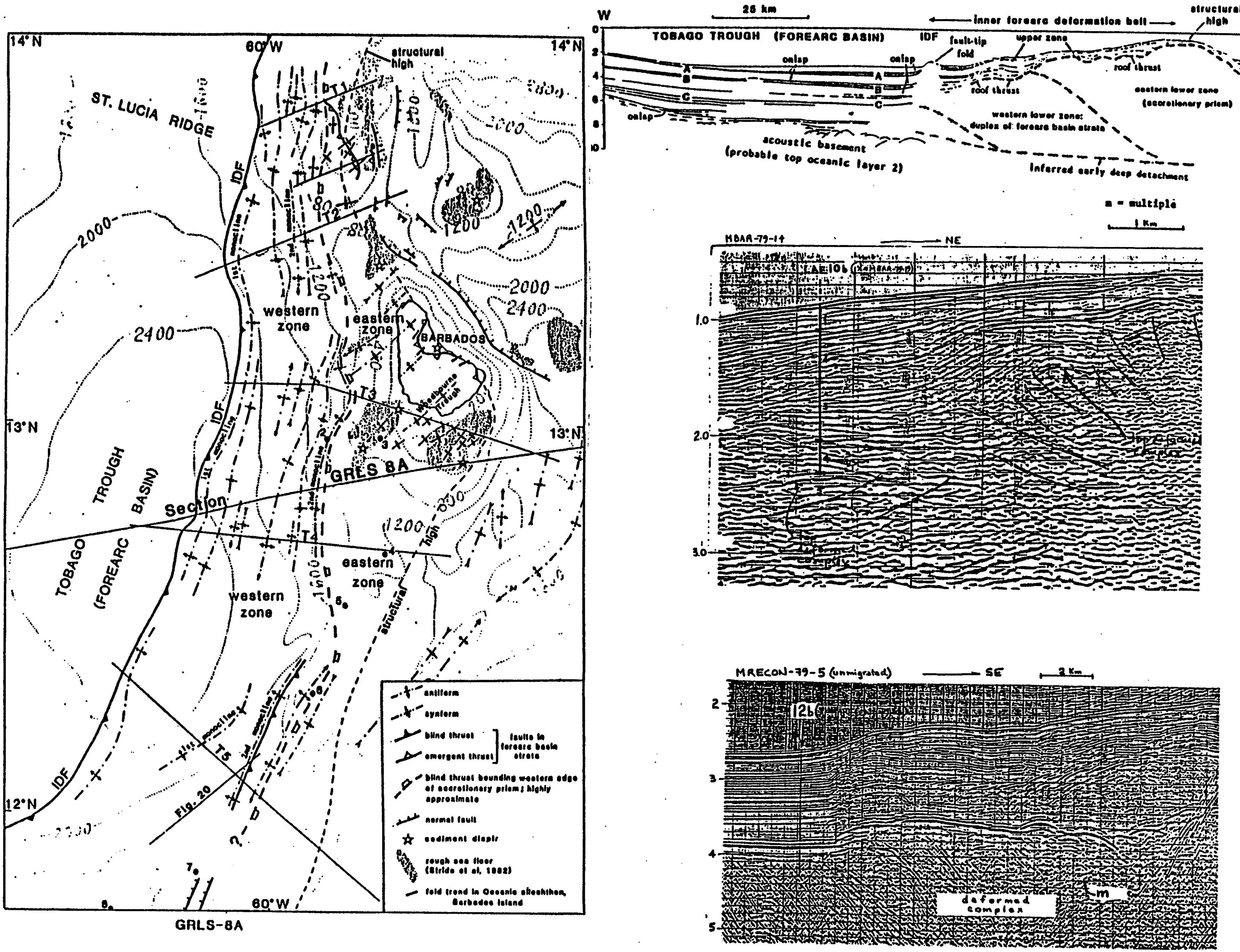


Figure V-4: Deformation belt in the forearc basin (Tobago Trough) accretionary wedge (Barbados complex) transition.

assessed from the deformation of the slope cover, the rates of forward growth of the complex in the past can be derived. Changes in accretion rate are also reflected in changes in the compaction state that show themselves as lateral velocity and density variations and produce variable response to deformation, displayed as variations in vergence and changes in the angle and sense of the surface slope of the wedge. Accretion rates are also reflected in heatflow anomalies near the front of the complex. For the Barbados Ridge complex, these data indicate that the outer part of the complex, varying in width from 20 to 80 km, has accreted more rapidly than the inner part. The Barbados Ridge complex has a well developed slope cover sequence deposited above the CCD, that can be well dated, and is very broad and probably at least 40 my old offering the possibility of resolving variations in accretion rate in some detail over a long period.

Interaction Between Wedges and Forearc Basins: A zone of young tectonism is recognized in the inner or arcward reach of many of the world's forearcs (examples: Lesser Antilles, Sulawesi, Sunda, Aleutian). In such zones, the seaward flank of the forearc basin (FAB) is deformed, either together with or against the arcward flank of the accretionary wedge (Fig. V-4). The widespread occurrence of such zones implies that their development is related to the growth of the accretionary wedge. In turn, such inner forearc zones may be presumed to contain vital information for an improved understanding of the growth dynamics of forearcs. Therefore, they form an important target for ODP.

Within such zones, however, the structure, kinematics, and timing of deformation are poorly understood. Alternative hypotheses include 1) the arcward translation and wedging of the accretionary wedge into the FAB, 2) collapse of FAB strata against the edge of a relatively rigid wedge, recording contraction of the forearc basin, 3) uplift and migration of the arcward edge of the wedge and consequent progressive deformation of FAB ahead of it due to growth of the wedge by offscraping and perhaps, underplating. Questions of timing address the onset of deformation in inner forearc zones relative to wedge evolution and whether such deformation had been steady or episodic.

The zone in the Lesser Antilles forearc, the Inner Forearc Deformation Belt (IFDB, Fig. V-4) is well defined in geographic extent and general configuration by marine geophysics. Interpretations of the internal structure and history of the IFDB are controversial (Westbrook, 1975; Westbrook et al., 1982; Biju-Duval et al., 1982; Speed, 1981; Speed and Larue, 1982; Mascle, 1986 Smith, 1987; Speed et al., 1988 Torrini and Speed, 1988), however, and Figure V-4 shows in cross section one of several possible solutions. The major unknowns are 1) the age and lithic kindred of reflector sets that occupy stacked fault and unconformity - bound packets within the IFDB, 2) the history of stacking of the packets, and 3) the position of the boundary in the IFDB between the deformed FAB strata and the original accretionary complex.

Such data can be obtained by ODP drilling in a single leg that includes few rotary holes that penetrate the seabed ≤1200m and several HPC holes (Fig. V-2, site e). The probability of useful findings is high because the region has a 1) dense array of existing MCS seismics, 2) strong probability of highly microfossiliferous rocks, 3) probability of diverse sediment provenances (pelagic, terrigenous, volcanogenic) to aid identification of lithic kindred, 4) outcropping accretionary wedge on Barbados, 5) extensive analysis of seismics by diverse authors (as above) to provide well-posed drilling targets and alternative models to test. Such factors cause the Lesser Antilles forearc to be the best, or at least one of the best, places in the work to investigate FAB - accretionary wedge tectonic interactions.

Oblique Convergence: Impinging upon the topic of wedge mechanics are two aspects of forearc tectonics that are well developed in the Caribbean. These are oblique convergence and forearc subsidence. They can be expected to have an important influence on the development of accretionary wedges and forearc basins, but no definitive studies of their effects are available. With appropriate site surveys these studies could be made in the Caribbean region.

Most convergent plate margins are arcuate features. In a rigid plate model this means that parts of these margins are obliquely convergent. Yet no study of oblique convergence has been undertaken in the context of the Ocean Drilling Program to date.

Accretionary tectonics at an obliquely convergent margin results in distinct structures that reflect material flow nonperpendicular to the boundaries of accretionary wedges. These are:

a) enechelon fold belts,

b) flower structures with local or regional deformation partitioning (dip-slip on thrusts, strike slip along steep shear zones),

c) along-strike variations of sedimentary facies in front of an obliquely convergent margin can be used to establish direction and rate of oblique thrusting within the accretionary wedge.

Principal stress orientations and their relation to slope direction and plate motion direction, can be used to determine the relative contributions of gravity effects and bulldozing in accretionary wedge building. Structures and their geometry can in part be documented by detailed offshore geophysical investigations (reflection seismics, sidescan sonar and swath mapping), but the study of fault and shear zone kinematics requires direct observation by drilling. Principal stress orientations can only be determined in boreholes by observation of breakouts. Here the use of new logging technologies (e.g. borehole televiewer, four-arm caliper log, formation microscanner) available to the Ocean Drilling Program is crucial. The Caribbean is probably the best area in the world to study oblique convergence due to its abundance of arcuate and/or transpressive plate margins (Fig. V-1) (e.g. northern Lesser Antilles forearc, south Caribbean deformed belt, Panama deformed belt).

One full ODP drilling leg would be needed to analyze kinematics and dynamics of oblique convergence in a well chosen and well site-surveyed area, preferably at the northern termination of the Lesser Antilles forearc, or along the South Caribbean deformed belt.

Forearc Subsidence: Much research has been concentrated on the upward and outward growth of accretionary complexes by subduction accretion and underplating. However, it is clear that in some forearc regions, subsidence of the forearc region has occurred (Japan, Peru-Chile trench). Typically, such forearc subsidence has been attributed to tectonic erosion of the underlying plate. Rates of subsidence are on the order of 100's m/my.

Forearc subsidence has been studied by drilling only in the two areas above. The Caribbean also contains documented but undrilled examples of forearc subsidence; particularly the Puerto Rico forearc and the inner Barbados Ridge complex. Both of these may provide superior sites for study of forearc subsidence, due to high potential for well resolved dating and abundant existing data.

The Caribbean wall of the Puerto Rico Trench has subsided about 3.5 to 5 km in the last 7 ma, giving the spectacular average rate of 0.5 to 1 km/ma. This is based on the existence of dredge hauls of neritic carbonate of Miocene-Pliocene age from depths of 3.5 km (Schneiderman et al., 1972; Perfit et al., 1980) and the continuity of seismic reflectors from the dredge sites to onland exposures in Puerto Rico (Meyerhoff et al., 1983; Moussa et al., 1987). Possible causes of subsidence and further description are in section VII-10. The actual subsidence rates and duration and the seismic properties of the reflectors are vital for progress in understanding the causes of the Puerto Rico forearc subsidence.

Seismic studies of arcward tracts of the Barbados Ridge complex indicate widespread shoaling in late Miocene time, followed by subsidence of the inner wedge and the outer forearc basin of up to 2.5 km (Speed et al, 1988; Torrini and Speed, 1988). The subsidence continues heterogeneously today.

The panel advocates ODP drilling of Caribbean forearc sites to improve our understanding of the bathymetry - time relations of forearc subsidence.

Fluids in Accretionary Wedges

As sediment is deformed in accretionary wedges large volumes of water and other fluids are expelled, mandating an active hydrologic system. These fluids influence overthrusting (Hubbert & Rubey, 1959) and wedge geometry (Davis et al., 1983), control temperature regimes (Reck, 1987), carry material as solutes, dissolved gases, and muddy slurries (Westbrook & Smith, 1983; Brown &

Westbrook, 1987), impact small-scale structural evolution, diagenesis, and metamorphism (Schoonmaker, 1986), and even spawn biological oases on the deep sea floor (Kulm et al., 1986; Le Pichon et al., 1987). In the accretionary wedge environment a potential linkage exists between earthquakes, sediment deformation, and fluid flow. Documented expulsion of deep-source fluids in subduction zones (Moore, Mascle, Taylor et al., 1987; Le Pichon et al., 1987) suggest potential models for long distance lateral transport of hydrocarbons.

Hydrogeological regimes of accretionary wedges are subdivisible into those dominated by coarser grained sediments of localized conduits of high primary permeability and those characterized by fine-grained, inherently impermeable muds where fluid is expelled principally along fault-controlled fractures. Existing drilling, submersible, and marine seismic reflection studies have provided some results on the geometry, source depths, and effects of fluid flow in both hydrogeological regimes of accretionary prisms. Complete understanding of the consequences of fluids in these environments requires information on rates and periodicity of flow in addition to more data on conduits, sources, and effects.

The Barbados Ridge is one of the best natural laboratories for the analysis of fluid expulsion from accretionary wedges. Here a north-south transition from fine to relatively coarse grained sediment types encompasses both hydrogeologic end members of accretionary prisms. Drilling in the Barbados accretionary prism has and should continue to be successful because of excellent biostratigraphic resolution, relatively shallow water depths, and excellent site surveys.

A comprehensive hydrogeological program should assess the overall fluid budget of the accretionary prism, including determination of fluid sources, expulsion paths, flow rates, and geophysical and geological effects. Transects across both the northern and southern extents of the Barbados Ridge, which differ markedly (Fig V-6), will evaluate both low and high permeability hydrogeologic regimes along a single subduction zone with little variation in the age and rate of incoming oceanic lithosphere. Along these transects, holes should be located: 1) near the outer and inner deformation fronts, spanning the decollement where accessible, as well as other faults and permeable stratigraphic conduits (Fig. V-

2, sites e and f; Figs. V-3A,5,6), 2) across the interior of the accretionary prism focusing on out-of-sequence thrusts or mud volcanoes/diapirs and 3) outboard of the inner and outer deformation fronts for the reference state of incoming fluids and to ascertain fluid expulsion along permeable sedimentary layers, incipient faults, and mud extrusion structures. Scientific investigations should include analyses of porewater chemistry, and structural and diagenetic alteration of sediments. A complete suite of logs should be run including the borehole televiewer and a microresistivity tool. Downhole instruments should be utilized to measure temperature, pore pressure, and permeability. Long-term monitoring of selected sites should be instituted to assess the relationship between deformational cycles and fluid flow. Tools being developed for Western Pacific drilling can potentially provide many of the necessary measurements. However, a continuing technological development effort will be necessary to modify and improve these prototype devices.

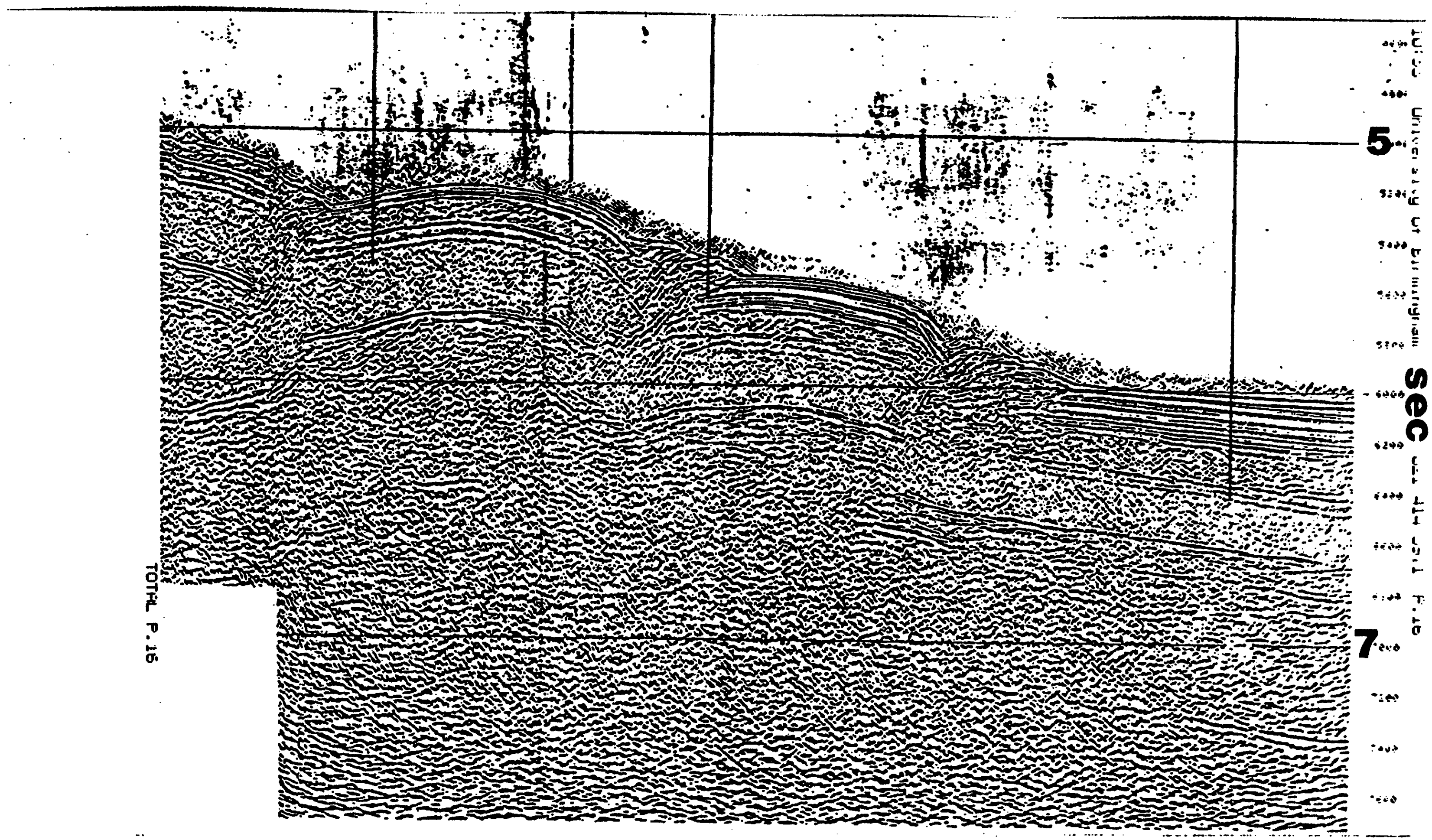


Figure V-5: Seismic section across outer deformation front at 12°12'N (Fig. V-2, sites F) with thick, probably relatively permeable incoming sediments; horizontal length about 10 km.

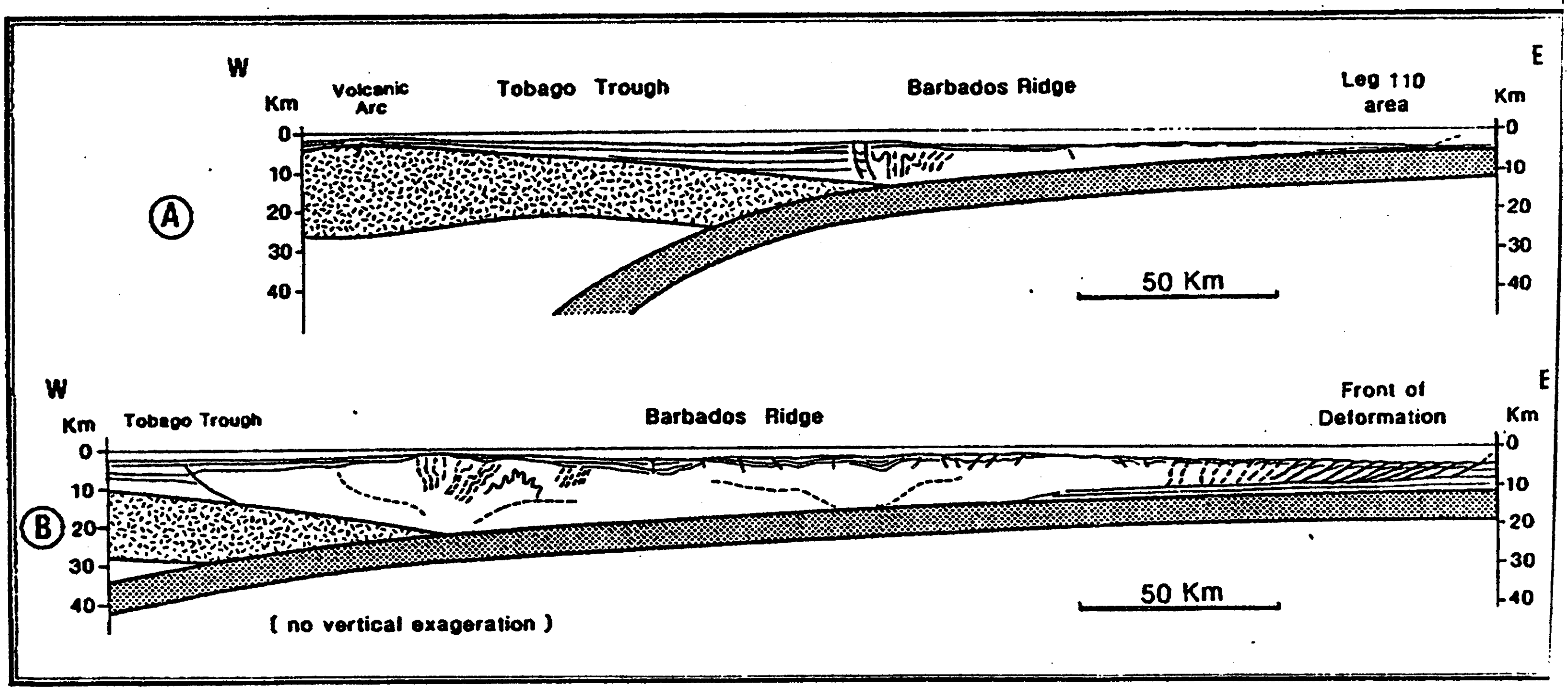


Figure V-6: Generalized cross sections across the Lesser Antilles forearc and Barbados Ridge at northern (15°30'N) (A) and southern (12°30'N) (B) transects.

VI. MAGMATIC PROCESSES PANEL REPORT

Chair: H. Sigurdsson

Panelists: Bouysse, Donnelly, Jackson, Klaver, Meschede, Perfit, Waggoner, White

Summary

The Cayman Trough is a prototype example of a pullapart basin in which formation of oceanic lithosphere has occurred. The obliquity of slip in the Cayman Trough is probably the world's greatest, such that the Trough may provide the prime test of the cold-edge effect on lithosphere formation. It will also provide a test of petrologic models which indicate magma types evolve in pullaparts from early alkalic through transitional to late tholeiitic types during progressive opening.

The Colombian and Venezuelan Basins of the Caribbean region contain widespread oceanic basaltic plateaus of Late Cretaceous age, together with minor tracts of normal oceanic crusts of unknown age. The oceanic plateaus differ from normal crust formed by MOR processes by greater thickness, extent of flows, and magma chemistry and are distinct chemically from the long-lived and more localized hotspot emissions as in Hawaii. Studies of the Caribbean plateaus can provide strides in understanding of the following: 1) magmatic evolution of oceanic plateaus; 2) kinematics during plateau formation; 3) role of nonsubductible plateaus in development of allochthonous terranes at continental margins; 4) tectonic environment of plateau formation, either during North America-South America drifting or as a phase of an intra-Pacific event; and 5) Cretaceous magmatic-tectonic history of the Pacific Farallon plate if the Caribbean plate is derived from the Pacific.

The Neogene Lesser Antilles arc magmas contain chemical and isotopic compositions that suggest sediment- or slab-derived fluids are involved in their petrogenesis. An important implication of this is that major geochemical heterogeneities may arise in the mantle because of sediment subduction and that sediment subduction must be included in whole-earth geochemical models. Further understanding requires drilling adjacent to the arc to investigate the geochemistry of older arc magmatic products and

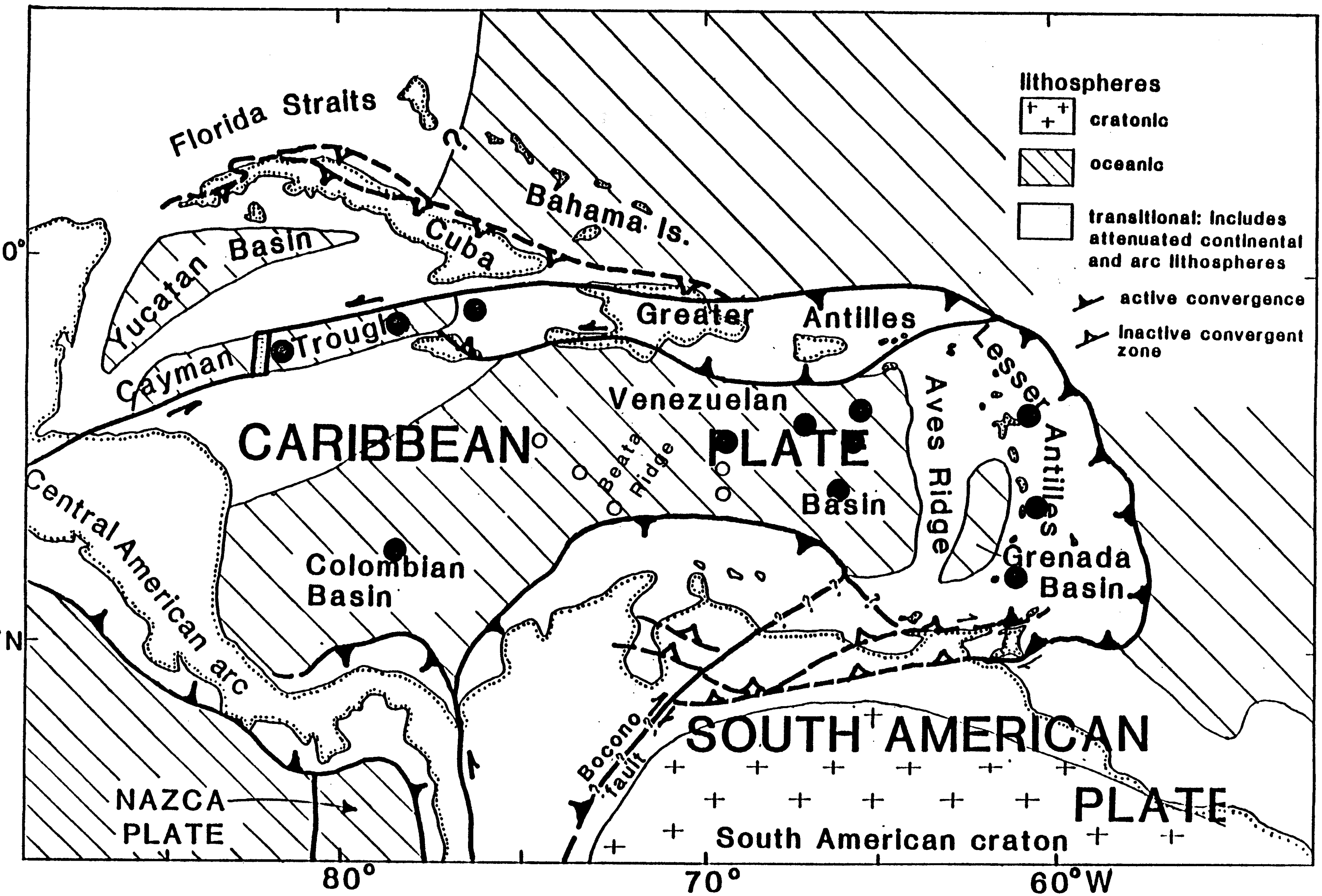


Figure VI-1: ODP targets in the Caribbean region recommended by the Magmatic Processes Panel; open circles are DSDP sites where plateau basalt was sampled.

volcanic history of the arc.

Introduction

The Magmatic Processes Panel addressed topical and regional problems of the generation, migration, and emplacement of magmas in the development of Caribbean lithosphere. Their scope included processes of oceanic and arc magmatism, the roles of fluid and sediment in magma generation, and the relationships of obducted Caribbean ophiolites to basinal lithospheres. The panel recommended that three broad problems be addressed with vigor by future ODP drilling (Fig. VI-1):

1) crustal formation in a transform plate boundary: Cayman Trough

2) Caribbean oceanic plateaus

3) sediment subduction and mantle heterogeneities: the Lesser Antilles arc

Crustal Formation in a Transform Plate Boundary: Cayman Trough

Introduction: The Cayman Trough is a 1600 km long and 120 km wide submarine depression that is a segment of the North American-Caribbean plate boundary. A short north-south trending spreading center, in the central portion of the Trough, connects long transform faults on the northeast and southwest (Fig. VI-2). The Trough is bounded by two arc-like submarine ridges, the Cayman Rise on the north and the Nicaraguan Rise on the south. The geology and geophysics of the Trough are discussed by Holcombe et al. (1973); Perfit and Heezen (1978); Stroup and Fox (1981); Rosencrantz and Sclater (1986); and Rosencrantz et al. (1988).

The Cayman Trough, also discussed in section III, is an important and unique geologic feature for a number of reasons. First, it has been a highly oblique transtensional plate boundary between the North American and Caribbean plates since at least mid-Tertiary time and contains the best recorded history of such plate motion. More precise data regarding the geologic history of the Trough can provide important constraints on the evolution of the Caribbean plate and the complex development of the

NA-Ca boundary zone in the Greater Antilles.

Second, the Trough is prototype example of a pull-apart basin, where oceanic crust has been created and accretion has been localized. Petrologic models suggest an evolution of basaltic magma types from early alkalic through transitional to tholeiitic during the development of such basins. Indeed, early rifting along the eastward extension of the Cayman Trough in Jamaica and Hispaniola is associated with the eruption of alkalic basalts (Wadge and Wooden, 1982; Mann et al., 1984).

Third, the juxtaposition of a short, slowly spreading (<2 cm/yr) ridge and two long transform faults provides the opportunity to study an end-member example of the "cold-edge effect" or "transform fault effect" (Langmuir and Bender, 1984) on magma genesis. Models predict a thermal effect on the petrology and geochemistry of mantle-derived magmas and the structure and development of oceanic lithosphere (Fox and Gallo, 1984; Stroup and Fox, 1981; Langmuir and Bender, 1984; Elthon, 1985). Testing of such models is important to understand mantle melting processes, magmatic evolution at accreting plate boundaries, and mechanisms driving the plates. The Cayman Trough is an ideal site to test and more fully develop many of our current hypotheses and models.

Current Knowledge: The Cayman Trough is a deep feature, with average depth of about 5,000 meters (Fig. VI-2). It appears to have an oceanic crustal structure throughout and thin crust relative to normal oceanic crusts, but this is based on limited seismic refraction data. (Ewing et al., 1960). Single-channel seismic transects and GLORIA coverage show the Trough to have extremely rugged north-south trending ridges with relief up to 2000 m (Holcombe et al., 1973; Rosencrantz and Sclater, 1986; Edgar, 1987 pers. comm.). The GLORIA data suggest the Mid-Cayman spreading center is tectonically complex and quite distinct from normal spreading centers at mid-ocean ridges. Its complexity may be due to frequent rift jumps, small transform offsets, and diapiric rise of serpentinite along fracture zones. Geophysical coverage in the Trough has been significantly improved by a French cruise in December 1987.

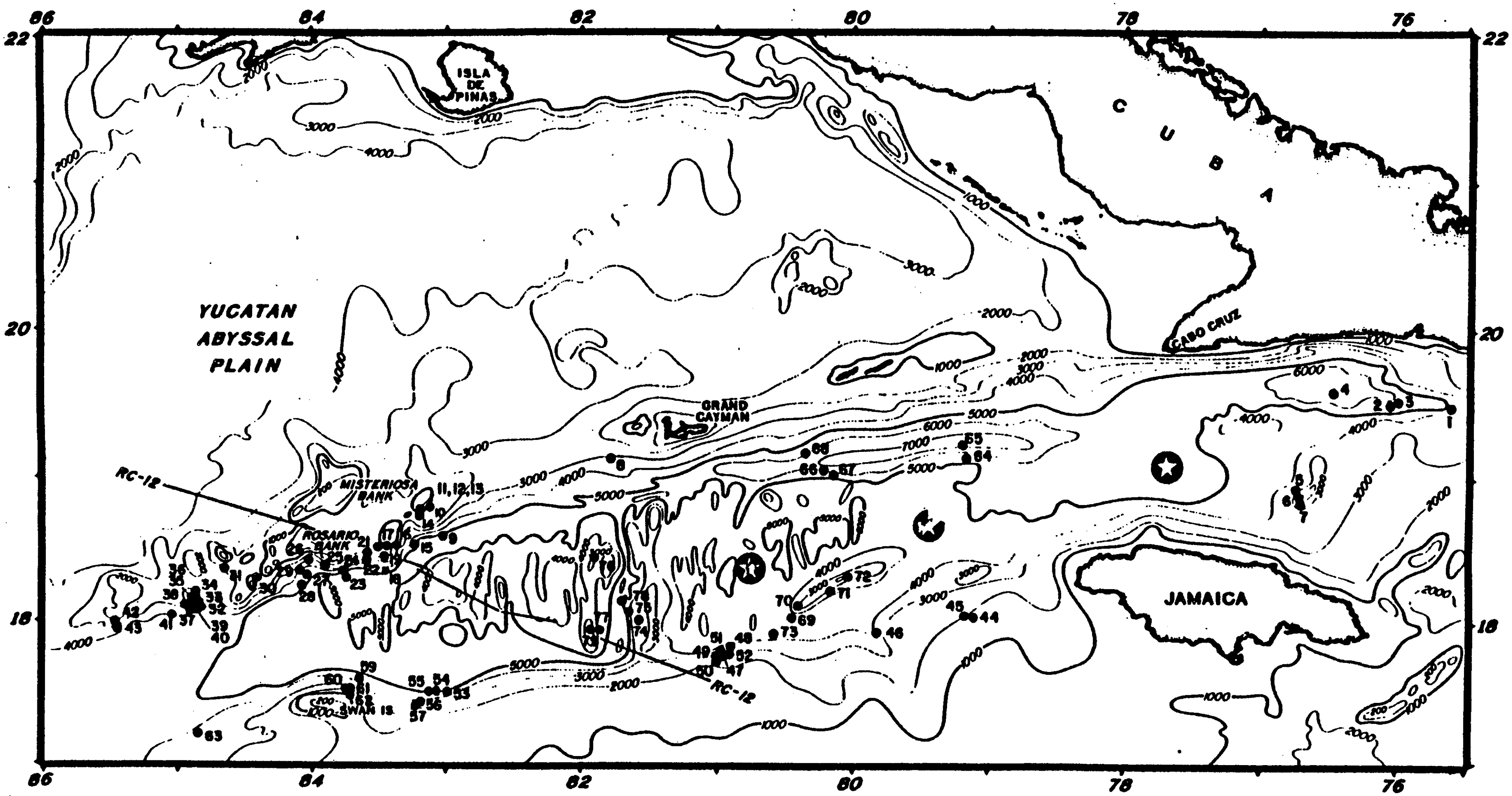


Figure VI-2: Cayman Trough: bathymetry in M; numbers are dredges (Perfit and Heezen, 1978); stars are ODP targets recommended by magmatic Processes Panel.

Interpretations of magnetic lineations in the Trough, discussed in section III, are somewhat controversial, and the first opening of the Trough is thought to be as old as mid-Eocene by Rosencrantz and Sclater (1986) and as young as Late Miocene by MacDonald and Holcombe (1978). Rates of spreading calculated on the basis of magnetic anomaly identification vary from 20 to 40 mm/yr, whereas rates estimated from crustal subsidence, geologic evidence and plate circuits are less than 20 mm/yr (Perfit, 1977; Rosencrantz and Sclater, 1986; Stein et al., 1988). Thick sediment cover and poor magnetic signals at both ends of the Trough have hampered attempts to decipher the early spreading/rifting history.

Dredging and ALVIN dives have recovered basalts, diabases, gabbros and serpentinized peridotites from the ridge crest and adjacent transforms (Perfit, 1977; Perfit and Heezen, 1978; CAYTROUGH, 1979; Stroup and Fox, 1981). An unusually high percentage of the samples are gabbroic rocks, many with complex metamorphic textures. Stroup and Fox (1981) suggest anomalously thin oceanic crust in the Trough as a consequence of the "cold edge effect" resulting in decreased melting in the asthenosphere. Slow spreading rates, low heat flow, and crustal depths support this hypothesis. A lack of hydrothermal activity and the absence of mineralization also suggest small magma production.

The basaltic rocks have affinities with normal and E-type MORB and have depleted LIL and REE patterns and Sr and Nd isotopic characteristics of MORB from the North Atlantic (Fig. VI-3a) (Perfit, 1977; Perfit and Waggoner, 1980; Thompson et al., 1980, Waggoner, 1988 unpubl). In particular, they have higher concentrations of TiO_2, Na_2O, P_2O_5, Sr, Zr and Y than N-type MORB and unusual "humped" LREE patterns yielding high Ce/Yb values (Fig. VI-3a,b,c). These trace element characteristics are very similar to those of basalts from other spreading centers associated with rifted arcs and "leaky" transform domains (e.g. Ayu Trough, Perfit and Fornari, 1982; Woodlark Basin, Perfit et al., 1987). Klein and Langmuir (1987) suggest the unusual compositions are directly related to the ridge depths and caused by low extent of melting of shallow asthenosphere.

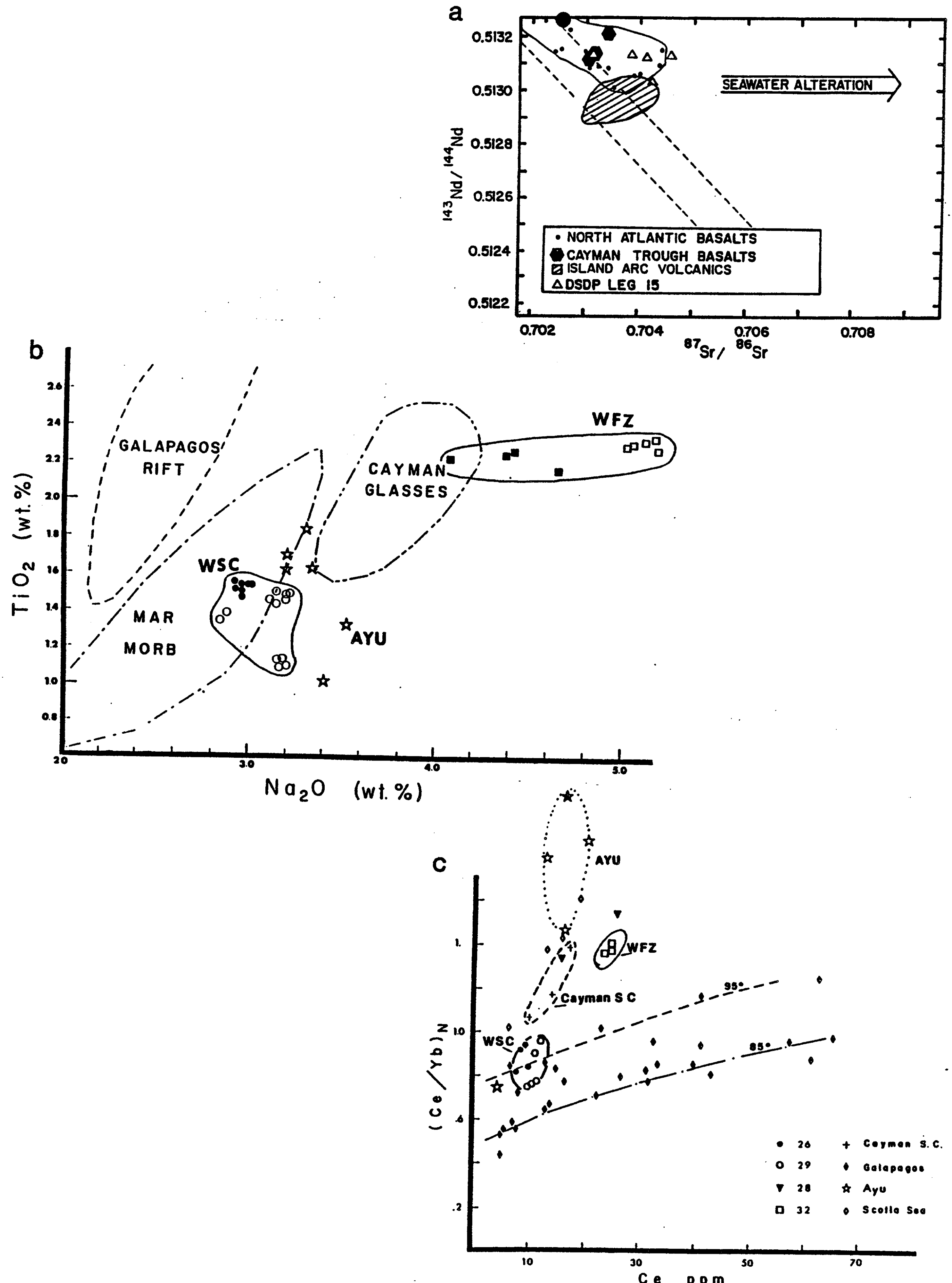


Figure VI-3: Basaltic rocks dredged from the Cayman Trough: a) Nd vs Sr isotopic compositions; b) TiO_2 vs Na_2O; c) Ce/Yb vs Ce.

Present limited isotope data suggest that basalts presently erupting along the mid-Cayman Rise are highly depleted (Figs. IV-4,5), but we have no knowledge of geochemical characteristics of magmas erupted in early stages of opening of the Trough.

Objectives of Cayman Trough Drilling: Drilling in the Cayman Trough would provide the first detailed study of the development of an active leaky transform plate margin and elucidate the magmatic evolution of a small oceanic rift and accretionary plate boundary. The lithospheres cut by the Trough are of uncertain origin but are possibly ancient arc terranes (Nicaraguan Rise and Cayman Ridge). Spatial-temporal chemical and petrologic changes should be anticipated, and current petrologic models predict one or more of the following possibilities: a) early rift-related alkalic volcanism, with oceanic island basalt or arc-alkalic trace element and isotope characteristics; b) early rift volcanism with geochemistry similar to East African continental rifts or analogous to arc pull-apart basins, such as the Eocene-Miocene Low Layton formation in Jamaica, Paleocene-Eocene bimodal volcanism in Jamaica, and Pliocene to recent rifts in Hispaniola (Jackson, 1987; Mann et al., 1984); c) later spreading center volcanism showing affinities with "leaky" oceanic transforms, generating E-type MORB.

This ridge-transform system has the smallest known ridge to transform length ratio, and should consequently show the greatest "cold edge effect" on the composition of melts. Transform fault effects on geochemistry of magmas are hard to evaluate, but there is some chemical indication of an unusually small degree of melting in the generation of Cayman basalts (high Na_2O, TiO_2, La/Sm, very low CaO/Al_2O_3). The origin of thin oceanic crust in the Cayman Trough could be related to slow spreading rates and low degrees of melting and may reflect low magmatic budgets. Periodically replenished magma chambers, characteristic of many normal spreading centers, may be absent from the Mid-Cayman spreading center, and consequently rapid freezing of the magma at shallow levels may occur.

Plate driving forces in the opening of the Cayman Trough are somewhat unusual, in that mantle upwelling is passive and due solely to the pulling apart of the plates. There is no thermal anomaly to drive a convective system. The Cayman Rise thus provides an opportunity to study one of the

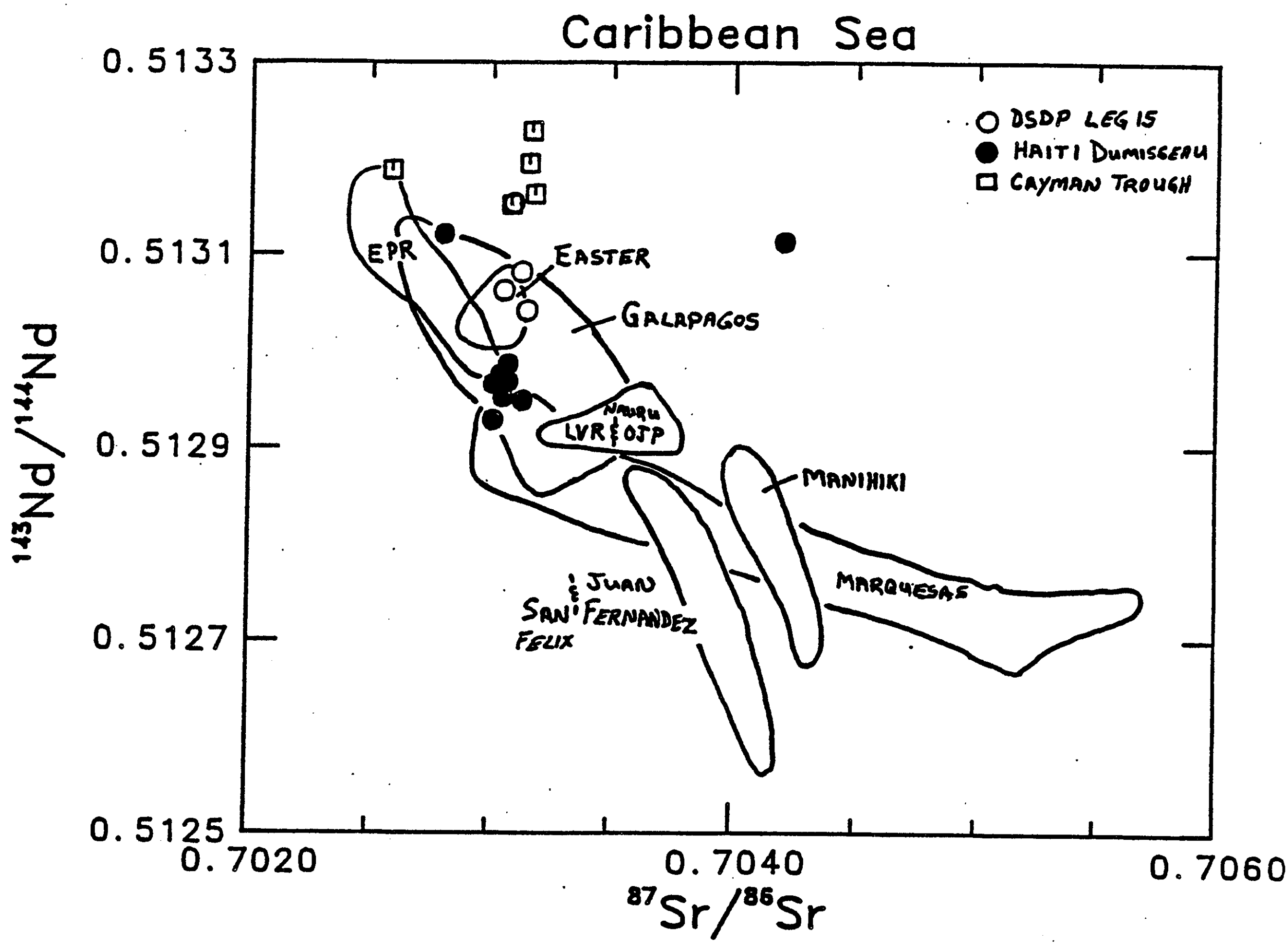


Figure VI-4: Nd vs Sr isotopic compositions of Caribbean oceanic plateau basalt from Leg 15 and Haiti and Cayman Trough basalt (G. Waggoner, unpubl., 1988).

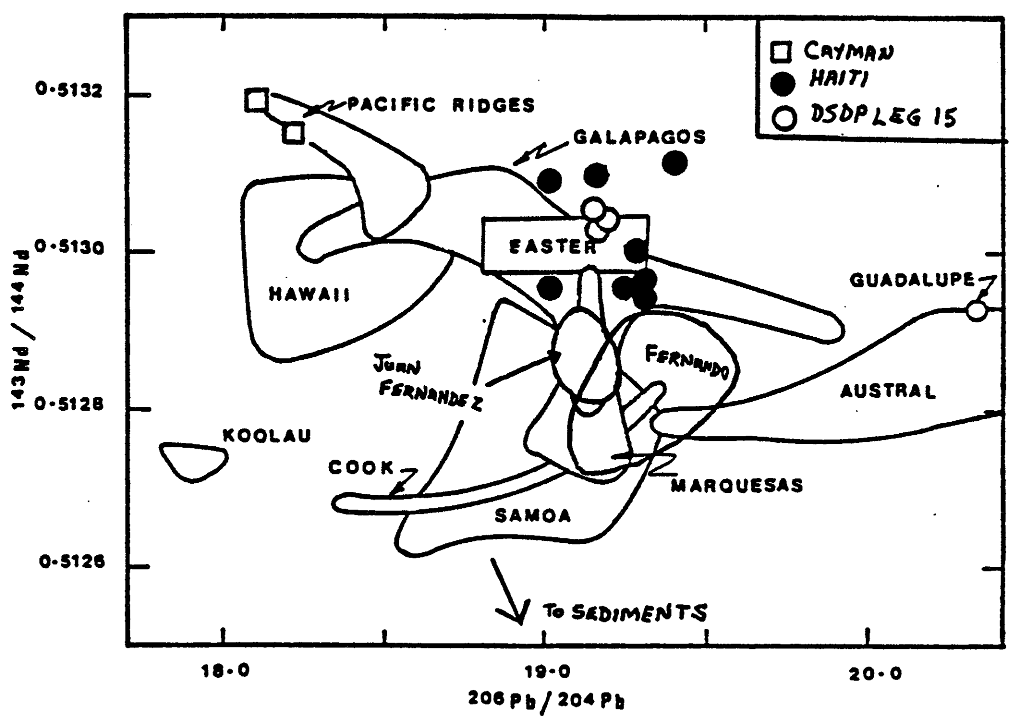


Figure VI-5: Nd vs Pb isotopic compositions of Caribbean oceanic plateau basalt from Leg 15 and Haiti and Cayman Trough basalt (G. Waggoner, unpubl., 1988).

theoretical end-members of plate driving mechanisms. Moreover, chemical and isotopic compositions of Cayman Trough basalts (the most depleted end-member) will serve as a baseline for comparable studies in the Caribbean.

Cayman Trough drilling could provide a window for investigating incorporation of lithospheric mantle in rift magmas. Because rifting may have occurred in a former island arc terrane, early rift volcanism may have incorporated arc or continental isotopic signatures. If present, such isotopic signature could indicate continental/arc lithospheric mantle delamination.

The results of studies of Cayman Trough magma genesis and tectonic evolution can serve as a model for other intra-oceanic rifts and transforms, such as the relatively little studied transforms in Pacific (e.g., Siqueiros, Batiza et al., 1977; Natland and Melson, 1980).

Because of the relatively thin layer 2 in the Cayman Trough, it is feasible here to drill through layer 2 into layer 3 to study the physical and chemical relationships of the layered oceanic crust. The Cayman Trough may indeed be the best place in the oceans to carry out such a study.

Finally, sampling the sedimentary cover along a transect of the Trough will provide much needed temporal constraints on the opening of the Trough and its subsequent development. Because the history of relative motion between the North American and Caribbean plates is recorded by the Cayman Trough, it is a very important objective to determine the timing and duration of events along the Trough.

Proposed Cayman Trough Drilling: The Magmatic Processes Panel proposes three single-bit drilling sites in order to meet the objectives stated above (Fig. IV-1). All three sites would be in the eastern part of the Cayman Trough and located so as to obtain the temporal variation in basalt geochemistry and magmatic processes during opening and evolution of the Trough. The first site should be in the easternmost part of the Trough, southeast of Cuba (19°06'N; 77°30'W), to recover volcanic rocks (alkalic basalts or transitional arc lavas?) from the initial opening phase. The hole would penetrate over 0.5 km of sediment before encountering volcanic basement. A minimum of 100 m deep sampling of layer 2 is proposed. The second site should be about midway between the active Mid-Cayman Rise and the eastern end of the Trough (18°42'N; 79°27'W). At this site, drilling should proceed until the gabbroic section of the oceanic crust is encountered, approximately 500 m below the top of oceanic crust. Reentry of this hole may be required. The third site should be located 170 km east of the Mid-Cayman spreading center (18°24'N; 80°45'W), for sampling of younger oceanic crust to sub-bottom depth of about 200 m.

Caribbean Oceanic Plateaus

Introduction: In 1970 drilling from the Glomar Challenger in the Venezuelan and Colombian Basins during Leg 15 of the Deep Sea Drilling Project encountered basalt and diabase at five sites (Fig. II-1, sites 146/149, 150, 151, 152, 153), with total recovery of only about 15 m of volcanic/hypabyssal rocks (Edgar, Saunders et al., 1973). This discovery led to the recognition of a Coniacian to early Campanian flood basalt event within the Caribbean and showed that the top of such basalt is the widespread smooth B" seismic reflector. Such basalts also cause the relatively high thickness and shallowness of the Caribbean crust, compared to normal oceanic crust (Donnelly et al., 1973). The Caribbean crust is 1.5 to 2.5 km shallower than predicted from the depth versus age relation for normal oceanic crust (Sclater et al., 1977) and conforms to the depth relation for aseismic ridges (Detrick et al., 1977).

The creation of large oceanic basaltic plateaus represents one major and distinct process of formation of oceanic crust, characterized by large outpouring of magma over a relatively short time span (Winterer, 1976; Thiede, Vallier et al., 1981; Larson and Schlanger, 1981; Batiza et al., 1981; Mahoney, 1988). Oceanic plateaus differ from oceanic crust formed by steady-state accretion in several respects, especially in crustal thickness, extent of flows and geochemistry. They are also geochemically distinct from the long-lived, but comparatively smaller and localized intraplate hotspot activity, exemplified by the Hawaiian islands. Perhaps the closest currently active analogue to the Cretaceous oceanic plateaus is the Iceland plateau, although the latter may be longer lived (20 m.y.).

A major, perhaps global magmatic event in the Cretaceous (100 to 85 Ma) led to formation of numerous oceanic plateaus in the western Pacific. The Caribbean plate may represent a very well preserved example of this type of plateau (Larson and Schlanger, 1981). The plateaus extend throughout most of the Colombian and Venezuelan Basins, and crust of normal thickness and depth occurs mainly in small scattered patches (Fig. III-6) (Diebold et al., 1981; Bowland and Rosencrantz, 1988). Obducted Caribbean crust around the margin of the Caribbean plate may expose oceanic plateau lava (Burke et al., 1984).

The Caribbean oceanic plateaus may have partly controlled the eastward motion of a possible early (pre-Cayman) Caribbean plate between the North and South American plates, because of the buoyancy and nonsubductibility of the thickened Caribbean crust. To summarize, study of the Caribbean oceanic plateaus is of particular importance to understand:

1. origin and magmatic evolution of oceanic plateaus,
2. role of buoyant oceanic plateaus in formation of allochthonous terranes and their accretion to continents (Nur and Ben-Avraham, 1982),
3. influence of the oceanic plateau on the tectonic evolution of the circum-Caribbean region.

Structure: The Caribbean plate containing oceanic plateaus has crustal thickness on the order of 5 km greater than "normal" oceanic crust and has an areal extent of 6×10^5 km^2. Together, the plateaus have similar dimensions to the greater Iceland plateau (including the Kolbeinsey platform) with an area of 4×10^5 km^2.

Volcanological features of note are an abundance of hyaloclastite layers in the Caribbean plateau (Edgar, Saunders et al., 1973), similar to the western Pacific plateaus (Larson, Schlanger et al., 1981). The abundant hyaloclastites are probably related to rapid outpourings of lavas and may be thus a function of high mass eruption rates, unlike extrusion at mid-ocean ridges. The smooth B" feature may also be an indication of extensive magmatic events, long-range outflow, and shallow injection of sills.

Seismic studies in the southeastern Venezuela Basin (Fig. III-6) do not prove whether the oceanic plateaus (capped by the smooth B" reflector) formed by eruption above older normal oceanic crust (characterized by a rough B" reflector in the terminology of Diebold et al., 1981) or were primary crustal products. Thus, we do not yet have conclusive evidence for a two-layered crust in areas of oceanic plateaus, although layering below the plateaus is suggested (Stoffa et al., 1981). The geochemical and petrologic character and age of the rough B" reflector are unknown, as discussed in section III, but due to its more normal depth to Moho and seismic reflection characteristics it has been suggested to be oceanic crust produced at a spreading center (Diebold et al., 1981). It may therefore represent either crust formed during the opening between North and South American plates, or crust formed at a spreading center in the Pacific.

Possible Subaerially Exposed Equivalents: Possible equivalents of the Caribbean oceanic plateau basalts may occur in lava successions exposed in the Greater Antilles, Netherlands Antilles, and in ophiolites in Central America. The best preserved of these are in Haiti (Sen et al., 1987; Dumisseau formation) and in Curacao (Klaver, 1987; Beets et al., 1984). Dating of the subaerially exposed sequences shows that volcanism began about 110 Ma and terminated around 80 Ma. Thicknesses of the lavas vary from about 1500 m in Haiti to more than 5000 m in the Netherlands Antilles. The thickness of the Curacao formation is comparable with estimates for the entire Caribbean plateau basalt sequence. The presence of lapilli tuffs, well sorted conglomerates and a paleosol of weathered basalts in Aruba indicates that some of the Caribbean flood basalt volcanism may have been subaerial (Beets et al., 1984).

Trace element characteristics of the Curacao and Haiti basalts indicate a range from N-type MORB to E-type MORB, which is in agreement with the range of Leg 15 basalts (Klaver, 1987; Beets et al., 1984; Sen et al., 1988). Based on the limited sampling to date, it appears that slightly enriched N-type MORB occurs in the Venezuelan Basin whereas the E-type MORB occurs on the Beata Ridge (Waggoner, unpubl. data). Ophiolitic complexes exposed on the Pacific coast of Costa Rica (Nicoya, Santa Elena, Quepos and Osa) may include lavas of the B" Caribbean event, but age determinations and correlations with crusts of the Colombian and Venezuelan Basins are very difficult due to their absence of sedimentary material. They include ultramafics, MORB, and alkalic basalts. Some of these basalts extruded in shallow water as indicated by a high content of vesicles (Meschede et al., unpubl. data; Schmidt-Effing et al., 1980).

Geochemical Characteristics: To date, the geochemical characteristics of the Caribbean oceanic plateau volcanism have been assessed from only five shallow-drill Leg 15 DSDP sites and the Dumisseau formation on Haiti (probably an uplifted portion of the Beata Ridge section of the Caribbean basaltic crust). The Curacao and Aruba lava formations may also represent crust of this origin (Beets et al., 1984; Klaver, 1987). Leg 15 basalts have solidified from relatively evolved magmas in which olivine is absent. The oceanic plateau basalts, as sampled at DSDP Leg 15 sites and in the Dumisseau formation in southern Haiti, are of two general types: more common low-potassium and LREE-depleted basalts, and rare higher-potassium, high-titania, and LREE-enriched basalts (Donnelly et al., 1973; Bence et al., 1975), and show a dual nature in terms of trace element and isotope characteristics at some sites with trace elements indicating N-MORB affinity and isotopes indicating an E-MORB affinity (Figs. VI-4,5). The trace element abundances in basalts from sites 146, 150, 152 and 153 are generally low and similar to MORB, with depleted LREE abundance patterns, high La/Ta and low Zr/Y typical of N-MORB. Curacao and Aruba basalts resemble slightly depleted MORB and are similar to basalts from sites 146, 150, 152 and 153. Basalts from site 151 and the Dumisseau formation in Haiti have higher trace element abundances, enriched LREE patterns, low La/Ta (~10) and high Zr/Y, typical of hotspot, E- or T-Type basalts.

The relatively low LILE concentrations, high CaO/Al_2O_3 (0.84) and FeO (10.3%), low Na_2O (1.8%) and $[Sm/Yb]_N$ (0.85) suggest an origin of the basalts by large degrees of melting. Parental magmas may have been picritic, if the coeval Curacao submarine basalts (Klaver, 1987; CaO/Al_2O_3 ~0.86%, Na_2O ~1.6%, FeO ~9.5%) are representative of the Caribbean oceanic plateaus. This large-scale melting has not, however, obscured isotopic and trace element ratio affinities with hotspot magmas, such as the low (~10) La/Ta ratios in site 151, in Dumisseau basalts, and in Curacao-Aruba basalts. It must be stressed, however, that a range exists from normal type to enriched type MORB in the scanty sample and data base available. The origin of this large-scale melting event could be related to a global mantle convection-related thermal event, or to uprise of a mantle megalith, such as derived from old subducted lithosphere (Ringwood, 1982).

The Haiti Dumisseau basalts show a total range in isotopes that is equivalent to the range in the Leg 15 basalts (Figs. VI-4,5). How typical the Dumisseau basalts are of the Caribbean oceanic plateaus is an important problem awaiting resolution, particularly since drilling has so far only scratched the uppermost surface of the Caribbean basalt formation. Nd and Sr isotopes (Waggoner, unpubl. data; Fig. VI-4) indicate that these basalts, with the exception of the upper flow at site 146 and two basalts from the upper part of the Dumisseau formation in Haiti, have oceanic island affinities, with radiogenic isotope characteristics similar to the Easter and Galapagos Islands hotspots. The three exceptions to the above have N-MORB-like characteristics, with possible minor seawater alteration effects on Sr isotope ratios. Pb isotopes (Fig. VI-5) indicate oceanic island affinities for these basalts. Combined Pb and Nd isotope characteristics indicate that the source of the oceanic plateau volcanism is most similar to the hotspot sources that produced the Easter and Galapagos volcanism.

The geochemical evidence thus requires both a MORB and hotspot type of mantle source feeding the Caribbean oceanic plateaus in the Cretaceous. The Cayman Rise magmas erupting today show that the modern sub-Caribbean mantle is clearly depleted, similar to suboceanic mantle feeding other midocean ridges (Perfit, 1977; Thompson et al., 1980). Thus, either the hotspot source shut off in Campanian time or the plate has experienced major motion since its passage over a Pacific hotspot (Duncan and Hargraves, 1984).

The Venezuelan and Colombian Basin crusts show many similarities with the structure of western Pacific oceanic plateaus created during the episode of Late Cretaceous global volcanism (Winterer, 1976; Thiede, Vallier et al., 1981; Larson and Schlanger, 1981). Basalts from Pacific plateaus often exhibit a dual nature of depleted trace element levels and hotspot type isotopic ratios (Mahoney, 1988). Based on Sr and Nd isotopes, the Nauru basin volcanism is similar to the volcanism of Caribbean oceanic plateaus. The Caribbean oceanic plateaus show a higher degree of isotopic and trace element variation than Pacific oceanic plateaus. This may be related to either an inherently more heterogeneous source, differences in source melting processes, or the relatively better sampling in the Caribbean than Pacific plateaus. Recently completed drilling and future drilling of Pacific oceanic plateaus will provide more information on their variability, but the Caribbean will still remain an important testing ground for understanding the origin of plateau volcanism and accretion processes.

Unsolved problems of the Caribbean oceanic plateaus include the following:

1. What is the age of initiation of Caribbean plateau volcanism, and what are their spatial age distributions? Is the age distribution symmetric about a central axis or paleoridge, as predicted from normal spreading processes, or is it diffuse, as expected from eruption from multiple sources? The latter is the case in the Iceland oceanic plateau, where frequent rift jumps and diffuse volcanism characterize the build-up.

2. Is there a regional/spatial distribution in geochemical/petrologic types of basalts?

3. What is the thickness of the formation and the eruption rate?

4. What signal can be found in ocean sedimentation in response to the plateau eruption event?

5. What is the petrologic variation with age in the erupted basalts, as revealed by deep drilling? The Curacao formation suggests a sequence from early picritic lavas, followed by normal tholeiitic to more evolved lavas (Klaver, 1987).

6. Basalts of the Caribbean plateau are evolved ($Mg/Mg+Fe^{2+}$ 0.52 to 0.65; Bence et al., 1975) and were not derived directly from the Earth's mantle. They must have been staged in reservoirs at some level within the crust to evolve before eruption. There is thus a requirement for high-level

magma reservoirs to store and evolve large volumes of magmas. Are the 200 to 800 m high circular surface features on the oceanic plateaus central volcanoes, which overlie former magmatic reservoirs? (see Fig. 4 in Edgar et al., 1973).

7. The hypothesis that Caribbean plateau basalts are either far-travelled flows or large sills requires high mass flow rates and thus shallow crustal reservoirs. Are these Galapagos-type or Iceland-type reservoirs that develop caldera collapse upon eruption? Klaver (1987) has proposed high-level magma reservoirs for the Curacao and Aruba lava formations.

8. The lack of evidence for axial features or bilateral symmetry in structure or magnetics of the Caribbean plate may be related to diffuse rift zones and frequent rift-jumping, as characteristic of the Iceland oceanic plateau.

9. Are the abundant hyaloclastites an indication of far-travelled flows and high mass eruption rate? Analogy with far-travelled subglacially erupted Icelandic flows supports this concept.

Proposed Drilling: Many unsolved problems regarding the origin of oceanic plateaus and evolution of the Caribbean plate can be addressed with sampling and information gained from drilling at the following sites (Fig. VI-1).

1. Four shallow, single-bit holes with 200 m penetration into the plateau basaltic crust. These holes would address the problem of spatial age relations and geochemical variations within the plateau. It is estimated that these four sites would require one drilling leg. Proposed sites are: a) northeast Venezuelan Basin hole, in about 1 km of sediment (16.6°N; 65.5°W); b) southwest Colombian Basin hole, through about 0.5 km sediment, near the area of Bowland and Rosencrantz's (1988) paired reflectors (13°N; 78.5°W); c) south of Puerto Rico, in about 500 m sediment (16.3°N; 67°W); d) south of the Dominican Republic, to study volcanic edifices in central part of plateau, which may represent last stages of Caribbean plateau volcanism (16.3°N; 69.1°W).

2. Single deep hole through the plateau top, either on the Beata Ridge or in the eastern part of Venezuelan Basin (16°N; 65.7°W), for recovery of a detailed record of variation in geochemistry of Caribbean plateau volcanism with time (Fig. IV-1). We anticipate drilling through about 1 km sediment and about 0.8 to 2 km of basaltic crust. This single deep hole would require one drilling leg.

3. Single hole in region of normal crustal thickness in the southeastern Venezuela Basin, through 1 km of sediment and penetrating about 200 m into oceanic crust (Fig. IV-1; 14.7°N; 66.2°W). This hole would reveal the age and petrology of the unknown basement which could represent either normal oceanic crust created during the opening between North and South America, or at a spreading center in the Pacific. This hole would be valuable for investigating the paleoceanographic/ sedimentological response to the plateau-forming volcanic event. This single hole would require half a drilling leg.

Sediment Subduction in the Lesser Antilles Magmatic Arc

Introduction: Geochemical features of volcanic arc magmas indicate that a sediment-derived component or slab-derived fluids exist in petrogenesis of magmas in the subduction zone setting. An important implication of this observation is that major geochemical heterogeneities may arise in the Earth's mantle because of sediment subduction and that this process must be included in whole-earth geochemical models. The process of sediment subduction, the nature of the fluids, and their effects on the magma-producing asthenospheric mantle wedge are now areas of intense research, but very little direct observational data exist, and most of what exists is from the Lesser Antilles arc.

The process of subduction is associated with the release of fluids from sediments and altered oceanic crust, ranging from dewatering of sediments in the accretionary wedge to dehydration reactions in the subduction zone at high pressures and temperatures. Direct evidence of the former process comes from DSDP Site 541 in the Barbados Ridge accretionary complex, about 300 km east of the Lesser Antilles volcanic arc (Biju-Duval, Moore et al., 1984). The 450 m deep hole showed unusually high fluid pressures and high temperatures, indicative of geothermal gradient of 10°C/100 m. Heat transfer is most likely by upward movement of warm water, and fluid chemistry is affected by reaction with volcanic ash deposits interbedded in the hemipelagic sedimentary pile. A further study of the generation and discharge of fluids from the Lesser Antilles accretionary wedge is a major target of proposed ODP drilling.

The fate of fluids deeper in the subduction zone is unknown, but most models of generation of volcanic arc magmas require the involvement of slab-derived fluids during melting of the asthenosphere wedge. Such fluids, released during dehydration reactions of minerals in subducted sediments and oceanic crust at depths of 100 to 150 km, are believed to be enriched in incompatible elements and radiogenic isotopes. The upward movement of such fluids by hydrofracturing or infiltration could lead to metasomatism of the overlying mantle wedge and partial melting. The resulting magmas would thus exhibit the distinctive isotopic and trace element signatures of volcanic arcs.

Geochemical studies of Recent Lesser Antilles arc magmas show that radiogenic isotope characteristics require the involvement of substantial quantities of sediment in the source region of these magmas (White et al., 1985; White and Dupre, 1986). The isotopic evidence of sediment subduction in the Lesser Antilles is particularly strong, because of the cratonic provenance of much of the sediments being deposited in front of the southern part of the arc today (Figs. VI-6 and VI-7). Further study of sediment subduction and its role in magma evolution requires drilling adjacent to the arc. In order to study geochemistry of older arc magmatic products and volcanic history of the arc, we propose drilling in the forearc region just east of the arc edifice (Fig. IV-1), where a well-developed sequence of tephra layers and other volcaniclastic deposits should be recovered, judging from known distribution of Quaternary volcaniclastics around the arc (Sigurdsson et al., 1980). Drilling at these sites will serve both the objectives of study of the structural development of the forearc, the volcanic history of the arc, and for geochemical studies of the role of sediment subduction in arc magma petrogenesis.

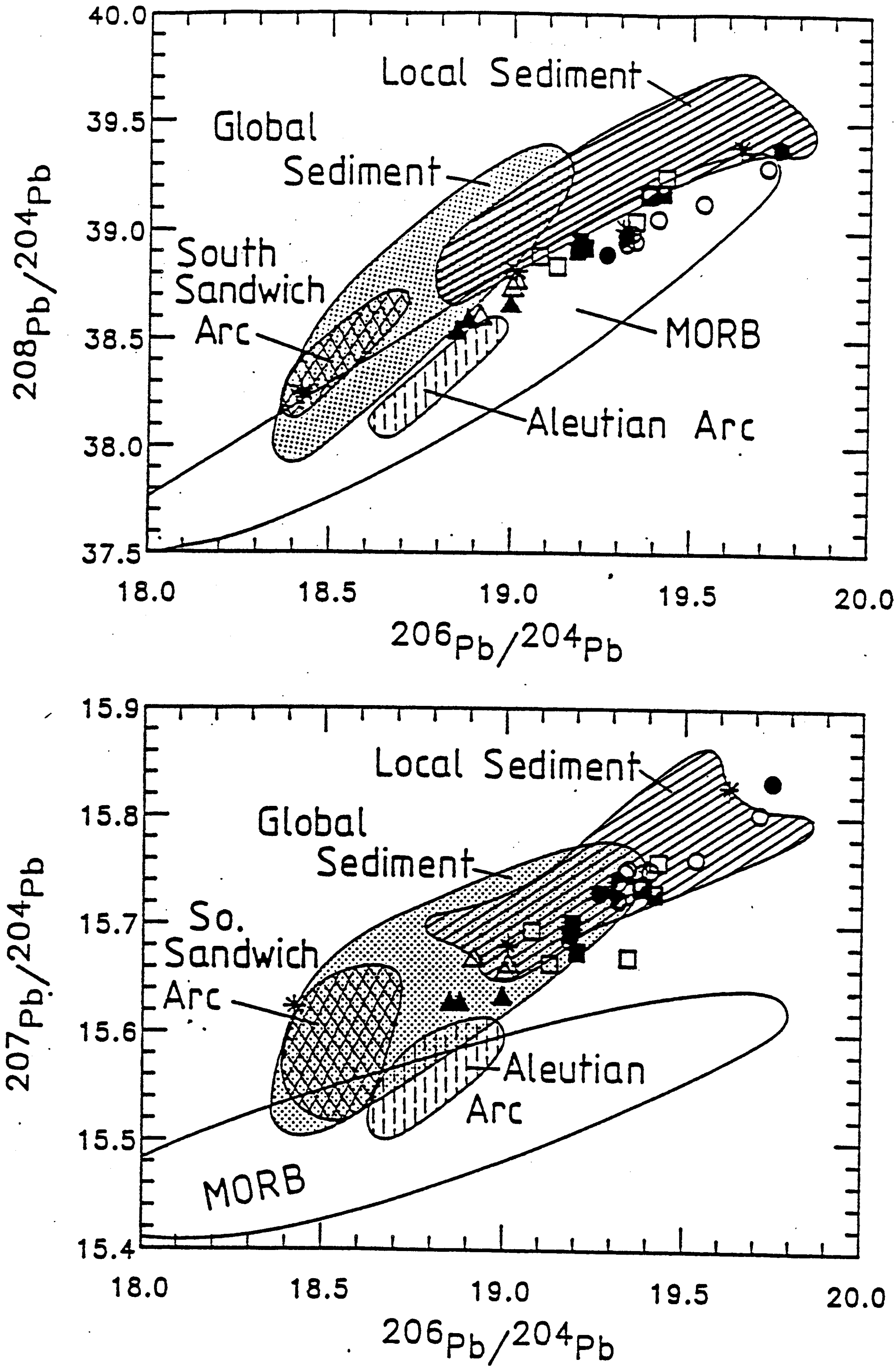


Figure VI-6: Pb isotopic ratios of Lesser Antilles volcanics and local sediment, from White and Dupre (1985).

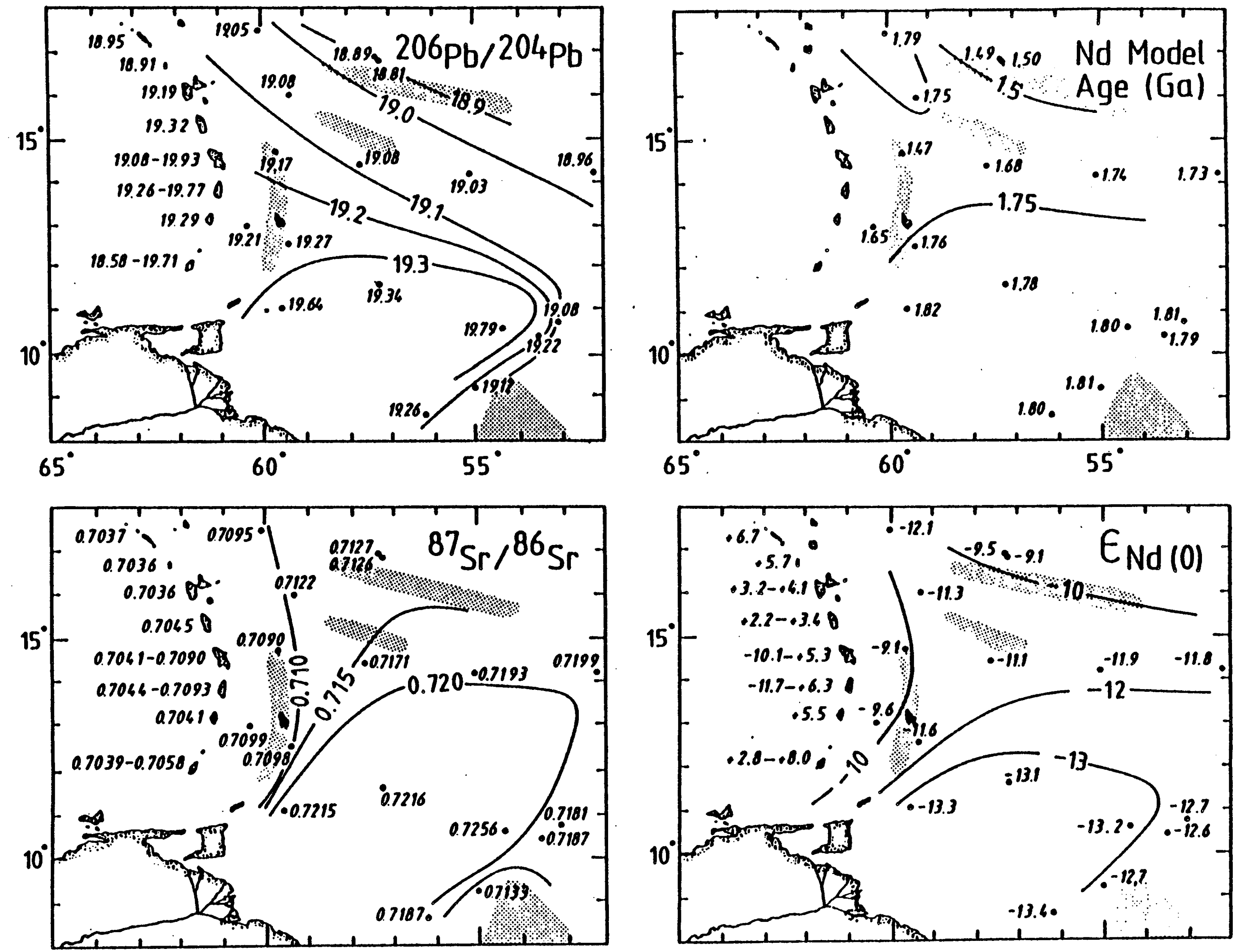


Figure VI-7: Geography of isotopic compositions and Nd model ages of Lesser Antilles sediments; ranges of arc magmas are shown; from White et al., 1985.

Structure: The Lesser Antilles is one of the best studied volcanic arcs on Earth (e.g. Brown et al., 1977; Sigurdsson et al., 1986; Bouysse, 1988). This arc shows remarkable petrological and geochemical diversity (Brown et al., 1977). The geochemistry of the craton-derived sediment being subducted results in the sedimentary signature being comparatively easily identified in the arc lavas. The nature and geochemistry of the sediment potentially being subducted have been much more thoroughly studied here than in other arcs (White et al., 1985). As a result, drilling is likely to yield more scientific information here than in other arcs. The rate of subduction is probably low, and there is an abundant supply of terrigenous sediment. The oceanic crust which is being subducted under the arc is pre-84 Ma, judging from magnetic anomalies.

The crust beneath the arc is about 30 km thick, composed of an upper crustal layer of 6.2 and a lower layer of 6.9 km/sec. The upper layer is the product of arc magmatism, whereas the lower layer may be original oceanic crust on which the arc was built, with additions of plutons during arc evolution.

The forearc region of the Lesser Antilles is a complex structure, which ranges from 150 km width in the north to 450 km in the south. In the north is the southeastern continuation of the Puerto Rico trench, over 8 km in depth, which shallows southwards and disappears under the well-developed Barbados accretionary prism, as first shown by Chase and Bunce (1969). The accretionary prism has a thickness of over 20 km (Westbrook, 1975) where it culminates under Barbados.

Because of the high influx of sediment, the seaward boundary of the forearc is not marked by the typical oceanic trench, but rather by a deformation front, characterized by thrusting and folding. The structural boundary is characterized by a sediment wedge, which overlies acoustic layered sequence and in turn oceanic crust. The sediment wedge is derived from offscraping of the subducting oceanic plate. This abyssal sediment on top of the Atlantic crust ranges in thickness from over 6 km in the south to 700 m in the north, and ranges from Late Cretaceous to Recent. The accretionary prism has formed mainly by accretion and imbricate-thrust development of the prism. The drilling results show

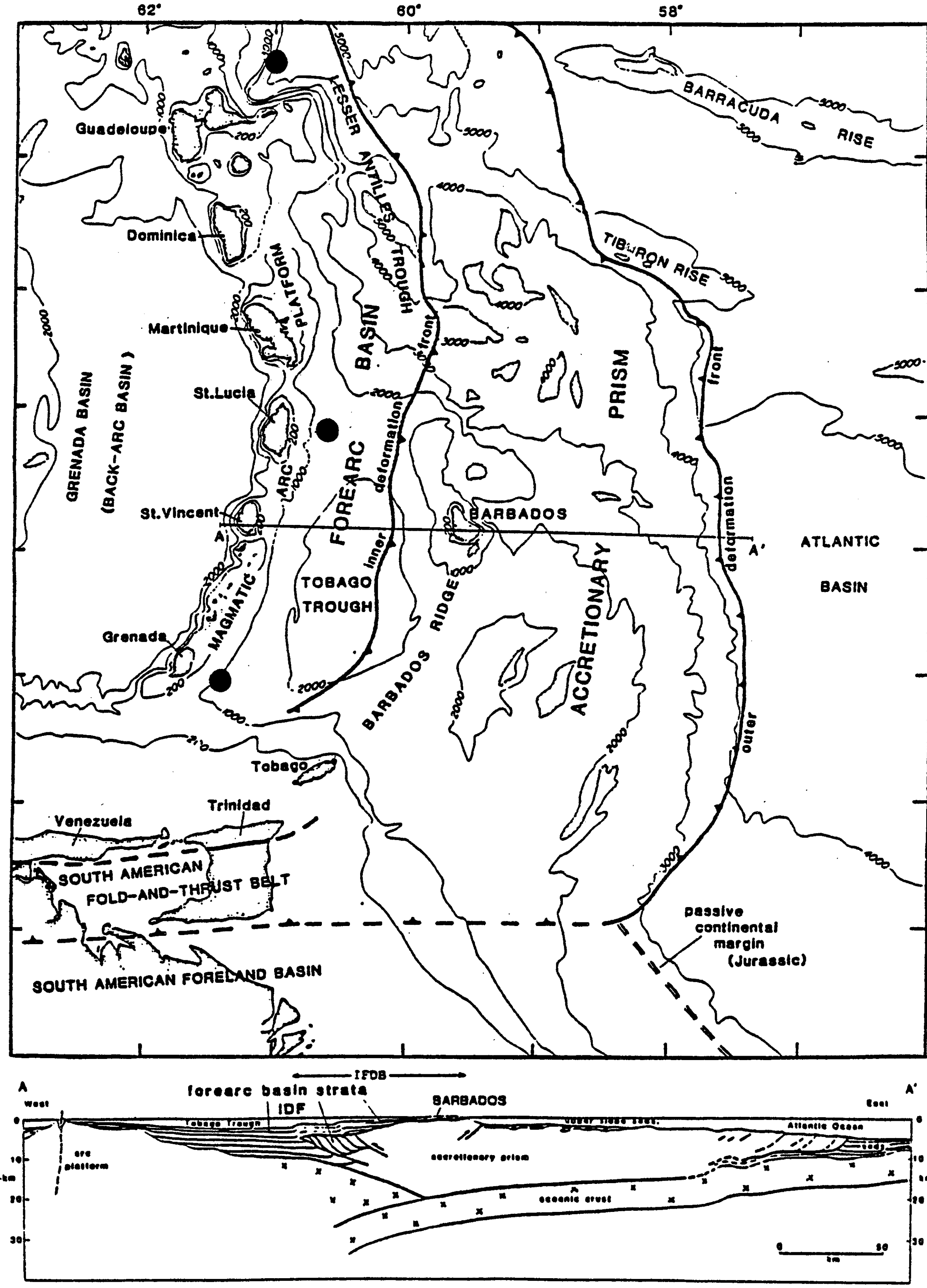


Figure VI-8: Lesser Antilles magmatic arc platform and forearc basins; dots are proposed sites for drilling Quaternary and Neogene tephra successions.

that the upper quarter to third of sediment on the incoming oceanic plate are offscraped at the deformation front, and that the underlying sediment being underthrust at least tens of kilometers below the prism. The prism complex is separated from the active arc by the Tobago Trough, a major forearc basin which contains more than 10 km of sediment fill. The sediment basin is underlain by a segment of oceanic crust, about 100 km wide.

Isotope evidence of sediment subduction: The isotopic character of Quaternary volcanics in the Lesser Antilles arc has been studied extensively (White et al., 1985; White and Dupre, 1986; Davidson, 1983). A large range in Pb isotopic ratios is observed; $^{206}Pb/^{204}Pb$ ranges from 18.85 to 19.9; higher than in any other oceanic arc studied to date (Fig. VI-6). The Sr and Nd isotope ratios in Lesser Antilles arc magmas are similar to those of oceanic island basalts, but with little or no overlap with the MORB field.

Assessment of the role of sediment subduction in the geochemistry of arc magmas requires a knowledge of the characteristics of the sediment involved. The forearc region of the Lesser Antilles and the adjacent Atlantic ocean floor receive sediment from a number of sources. In the south the sediment is dominantly terrigenous, whereas the origin of sediment in the north is largely hemipelagic. Four components of sediment can be recognized: 1) volcanic ash from the arc; 2) biogenic component with Sr and Nd isotopic composition equal to that of sea water ($^{87}Sr/^{86}Sr$ 0.70916). 3) pelagic clays; 4) terrigenous material.

A major source of the terrigenous sediments is influx of continent-derived material from the Precambrian Guiana Shield, largely brought to the basin by the Orinoco River. Because of its great age, the cratonal sediment would therefore be expected to show an unusually radiogenic Pb character, compared to other marine sediments.

White et al. (1986) have studied the isotopic and trace element character of these sediments by analysis of surface sediments from piston cores and evaluated their role in the geochemical evolution of Lesser Antilles arc magmas (Fig. VI-7). They found that the Pb is remarkably radiogenic, with

$^{206}Pb/^{204}Pb > 18.8$ for all samples and as high as 19.8 (Fig. VI-7). Sr/Nd isotopic composition are less unusual, and fall within the range of other sediments from the ocean basins. Sr and Pb isotope ratios increase and Nd ratios decrease towards the South American continent, indicating that the radiogenic Pb is most likely in the terrigenous component. The radiogenic Sr and Pb and the unradiogenic Nd of the sediments suggest an old continental source. Gneisses of the Guiana Shield include some as old as 3.5 Ga or older, and are drained by the Orinoco River. The Shield has $^{206}Pb/^{204}Pb = 16.92$, and $^{208}Pb/^{204}Pb = 42.31$.

There is strong similarity in Pb isotope character of sediments and the arc magmas. Both are more radiogenic than arc volcanics and sediments in other regions. This is unlikely to be coincidental, and is probably good evidence of sediment subduction and incorporation in arc magmas. The amount of sediment required to account for the Pb in the arc magmas ranges from 0.5 to 3.5%, averaging around 1%. Extremely radiogenic Pb and Sr in lavas from Martinique and St. Lucia probably experiences high-level contamination. There is an irregular stepwise northward decrease in Pb and Sr isotope ratios in the arc volcanics, which matches the northward change in the sediment isotope character.

Drilling Objectives: The question of sediment subduction is intimately related to questions of evolution of continents and chemical evolution of the mantle. The role of sediment subduction in island arc magmatism can be addressed by drilling near the Lesser Antilles arc (Fig. IV-1). Specific questions are:

1. Is sediment subduction a necessary condition for magma genesis?
2. What is the relationship between island arc volcanism, sediment subduction, and the topography of the subducting plate?
3. Is there a petrologic evolution, or succession of island arc volcanic compositions, and does this relate to topography of the subducting plate and any changes in sedimentation?
4. How do changes in the geochemistry of subducting sediment affect the geochemistry of the arc magmas?

A final goal is assessment of sedimentary sequences in the arc. Extending the arc history would allow a more complete picture of the role of sediment subduction to be developed.

Specific Drilling Targets: Drilling in the forearc basins, 50 to 100 km east of the active arc (Fig. IV-8), will sample a continuous record of arc volcanism as tephra layers and other volcaniclastic sediments from the arc, interbedded with pelagic sediments. Studies of tephra dispersal from the arc during the Quaternary show that important eruptions deposit substantial tephra fall layers at this distance, which form suitable volcanic material for petrologic and geochemical studies. Drilling in these basins is proposed separately for the study of forearc evolution, and the same sites will thus serve the objectives of both forearc study and a geochemical study of the volcanic arc products. It will be necessary to drill at least three forearc sites along the arc in order to obtain an overall view of the process, and to detect geochemical/petrologic gradients in magma types along the arc.

VII. INDIVIDUAL INVESTIGATOR PROPOSALS FOR OCEAN DRILLING SITES AND OTHER STUDIES IN THE CARIBBEAN REGION

Introduction

This section contains proposals by individual workshop participants for ocean drilling at particular sites in the Caribbean region, together with recommendations for further seismic reflection and field surveys before ODP drilling commences. Table VII-1 lists the proposals by author and number. Table VII-2 codes proposed sites relative to a site map, Figure VII-1.

These proposals for drilling sites were generated before the workshop with the goal of providing an explicit platform for panel deliberations. They are included here to expand on specific problems of regional and thematic scope and to provide future ODP proposers with specific background material and the views of informed scientists.

Table VII-1
Individual Drilling Site and Other Study Proposals

Proposers	Proposal Number
Bouysse, Westercamp and Andreieff	1
Buffler, Austin, Rosencrantz, Mann, Sclater and Salvador	2
Buffler, Austin, Mann, Rosencrantz, Salvador and Sawyer	2
Burkart	3
Donnelly	4
Draper	5
Edgar	6
Gose	7
Hall	8
Kellogg, Breen and Ladd	9
Larue	10
MacDonald	11
Mascle	12
Moore and Mascle	13
Nagle	14
Pindell	15
Rosencrantz, Sclater, Salvador and Mann	16
Saunders	17
Schlanger	18
Schubert	19
Smith	20
Speed	21
Waggoner	22
White	23
Klitgord	24
Jackson and Hendry	25
Mauffret	27
Meschede and Frisch	28
Perfit	29
Guque-Caro	30
Barker and Payne	31
Behrmann	32
Salvador and Rosencrantz	33
Droxler	34
Keller	35
Tectonics Panel	36

Table VII-2
Individual Drilling Sites Coded for Position on Figure IX-1

Proposed site no.	(First) Author
1-1, 1-2, 1-3, 1-4	Bouysse
2-7, 2-7F, 2-SE-1A, 2-SE-2A, 2-SE-2B	Buffler
3-1	Burkart
4-a, 4-20, 4-21, 4-b	Donnelly
5-1, 5-2, 5-3	Draper
6-1, 6-2, 6-3, 6-4A, 6-4B	Edgar
7-1	Gose
8-A, 8-B	Hall
9-1, 9-2	Kellogg
10	Larue
11-1, 11-2a, 11-2b, 11-2c, 11-3	MacDonald
12-1-1, 12-2-1, 12-2-2, 12-3-1, 12-3-2	Mascle
13-NBR1, 13-NBR2, 13-NBR3, 13-NBR4	Moore
14-1, 14-2	Nagle
15-1, 15-2	Pindell
16-A, 16-B, 16-C, 16-D, 16-E, 16-F	Rosencrantz
17-1-1, 17-1-2, 17-3-1, 17-5-1	Saunders
18-1	Schlanger
19-1	Schubert
20-1, 20-2, 20-3, 20-4, 20-5	Smith
21-1, 21-2, 21-3, 21-4, 21-5	Speed
22-ESP3, 22-146/149, 22-ESP1	Waggoner
23-1, 23-2	White
24-1, 24-2, 24-3, 24-4, 24-5, 24-6, 24-7	Klitgord
25-1, 25-2	Jackson
26-1	Peterson
27-1, 27-2, 27-3	Mauffret
28-1, 28-2	Meschede
29	Perfit
30-1	Duque-Caro
31-1	Barker
32-1, 32-2, 32-3	Behrmann
34-1	Droxler
35-1, 35-2, 35-3, 25-4	Keller
36-1	Tectonics Panel

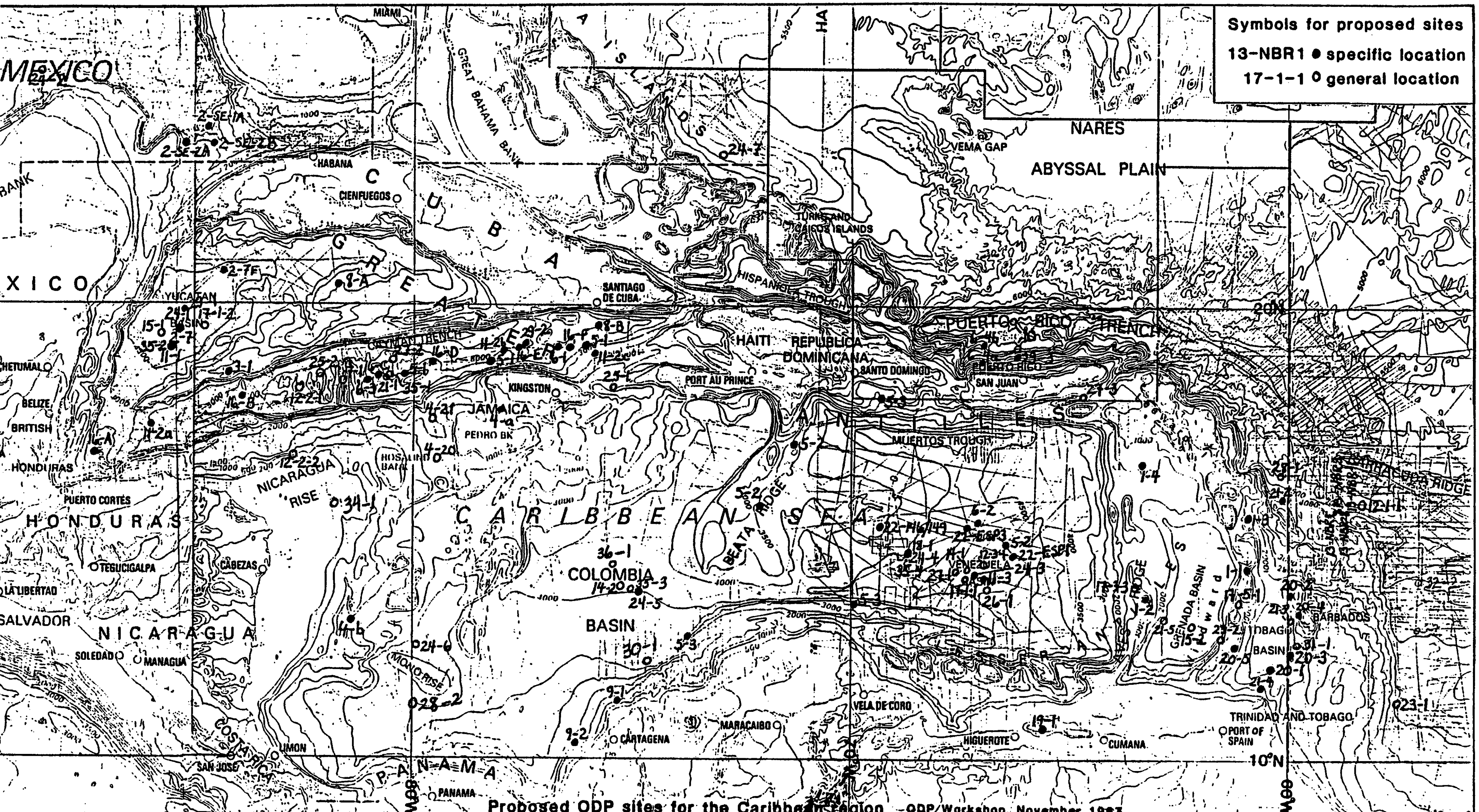


Figure VII-1: Proposed drilling sites from individual proposals.

1-1 *DRILLING IN ST LUCIA PASSAGE (LESSER ANTILLES)*

Philippe BOUYSSE and Denis WESTERCAMP

Location : Between Martinique and St Lucia ; minimum water depth : 800 - 1000 m.

Purpose : Study of the evolution of an island arc : Mesozoic substratum, back-arc basin spreading, major volcanic gaps, interaction of subducted ridges.

Comments :

This site is located on the southern half of the Lesser Antilles Ridge, just when the Outer (Older : early Eocene to mid-Oligocene) and Inner (Recent : early Miocene to Present) volcanic arcs coalesce ; also in an area where, up to now, no Mesozoic arc volcanic rocks crop out, in contrast to the northern half of the Lesser Antilles (north of Dominica). The proposed site is situated in an inter-island channel which seems to have been relatively little volcanically productive during the cycle of the Recent arc. It is also close to the oldest outcrops of Martinique (upper Oligocene) and of St Lucia (upper lower Miocene).

The main objectives are :

1 - Reach, if possible, the Mesozoic (to lower Paleocene ?) arc basement the occurrence of which would definitely demonstrate the formation of the Grenada Basin by back-arc spreading, sundering of the Eastern Caribbean proto-arc into a remnant arc (Aves Swell) and an active island arc (Lesser Antilles), according to the classical scheme of Karig. In the Eastern Caribbean, this back-arc opening seems to have occurred only once (during an interval of some 120 Ma of arc activity), which is quite unusual for an island arc.

2 - Check the age and the duration of this opening, which is thought to have occurred during the Paleocene, and to have lasted some 8 m.y. This contention is supported by the hypothesis that suggest non-concurrence of arc volcanism and intra-arc oceanic crust accretion. Therefore, it is worth to obtain age constraints for the latest volcanism of the Mesozoic proto-arc, and the earliest volcanism of the subsequent arc cycle (Older arc).

3 - Obtain a better understanding of the evolution of the Older arc which is only very incompletely known in the north and in the south of the Lesser Antilles.

4 - Constrain the second major volcanic gap in the Cenozoic history of the Lesser Antilles, which occurred between the Older arc and the Recent arc. This gap whose duration may have been of some 8 m.y., is thought to have been induced by the interaction of a buoyant Atlantic oceanic ridge with the Eastern Caribbean subduction.

5 - Prove the interaction of a subducted non-buoyant ridge with an arc volcanic front. We suppose that the subduction of this kind of ridge generates, amongst other effects, a centrifugal migration of the eruptive centers on either side of the arc segment located above the ridge. Site n° 1 is located above the inferred extension of the St Lucia Ridge, presently detected by G. Westbrook, in front of the Barbados accretionary prism. If this reasoning is proven to be true, the youngest volcanic formations, on this site, should not be older than late Miocene.

1-2 *DRILLING ON AVES SWELL*

Philippe BOUYSSE

Location : Aves Swell ; water depth between 1400 and 300 m.

Purpose : Study of the subsidence of a remnant arc.

Comments :

The Aves Swell is now widely considered as an inactive island arc. It is completely submerged, except at the minute Aves islet. Aves Swell was active during the Cretaceous and it is assumed that the definitive cessation of its volcanic activity happened by the onset of the Cenozoic, in relation with the opening of the Grenada Basin (cf. site n° 1).

Therefore, a borehole (or a series of boreholes) on the axis of this ridge (taken as a representative example of remnant arc), might calibrate its subsidence curve.

We favor the Pelicano seamount site, culminating at -315 m. Previous dredge hauls give the (incomplete) succession (cf. Bouysse et al., Documents du B.R.G.M., n° 92, 1985) :

- pelagic limestones : Pleistocene.
- pelagic deposition : upper Miocene to lower Pliocene.
- neritic deposits : Oligocene to lower Miocene.
- neritic limestones : middle Eocene.

A "by-product" of this site may be the assessment of the latest volcanic activity (before the opening of Grenada Basin) of Aves Swell, by drilling down to the magmatic basement (cf. site n° 2).

It will be useful, also, to check the validity of the heat-flow profile made by Clark et al. (1978) which shows anomalously high values, contradictory with a remnant arc inactive since some 60 m.y.

1-3 *DRILLING OFF EASTERN DOMINICA (LESSER ANTILLES)*

Denis WESTERCAMP

Location : East of Dominica, water depth between 1000 and 2500 m.

Purpose : Fore-arc volcanism, related to early dehydration of sediments on the subducted slab.

Comments :

The dehydration of the upper part of the subducting slab (sediments and crust) is the argument the most commonly used to explain the orogenic magma genesis, by partial fusion of the asthenospheric wedge.

But it has to be kept in mind that this dehydratation occurs for pressures < 30 kb, i.e. that it is completed before the slab reaches the 80 km depth.

In the Lesser Antilles arc, the volcanic front is located, as for other island arcs, above a mucher deeper Benioff slab. In the Lesser Antilles, according to Wadge and Shepherd data (1984), this depth ranges from 120 to 180 km (160 to 180 km beneath Dominica).

Therefore, two explanations are possible :

1) the hydrated mantle is dragged by convection before to undergo fusion at the proper depth ;
2) the dehydration does not play a significant role in the normal arc magmatic production, which, then, is triggered by the fusion of the sediments.

Considering the second alternative, we suggest that if the dehydration is important, it should generate fore-arc magmas of boninite type.

In order to test this somewhat speculative hypothesis following conditions are required :

- location above the part of the slab 40-80 km deep ;
- location in an area of high recent magmatic production.

These conditions are realized off, and to the east of southern Dominica, known for a very high rate of magmatic production (cf. the Roseau ignimbritic event, producing some 60 km³ of tephra, ca. 30000 years B.P.). This area should be first surveyed with seismic reflection in order to detect concealed intrusive structures.

I-4 *DRILLING IN THE GRENADA BASIN*

Patrick ANDREIEFF

Location : Aloi Flat, northern Grenada Basin ; water depth : ca. 1200 m.

Purpose : Miocene/Pliocene boundary in the Caribbean.

Comments :

All the previous drilling sites in the Caribbean (legs 4, 15, 78A, 110) failed to obtain a continuous section, with undissolved calcareous microfossils around the Miocene/Pliocene boundary. Onshore, this boundary is generally marked by a sharp contrast in the deposition conditions due to a shallowing of the water depth, and the chronological hiatus is of at least 1 m.y.

Therefore, there is a need of obtaining a continuous oceanic section under less than 3000 m of water depth, in order to characterize the Miocene/Pliocene boundary, in the Caribbean, in terms of planktonic biostratigraphy (foraminifers and nannofossils) with the help of magnetostratigraphy, and oxygen and carbon isotopes calibration.

The Aloi flat, some 100 km south of Saba Bank, appears to be a suitable area, with a very smooth morphology, protected from slumping or pyroclastic flows coming from the Aves Swell and Lesser Antilles Ridge.

2 Tectonic Significance and Objectives for Drillholes in the Straits of Florida and Yucatan Basin

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TECTONIC SIGNIFICANCE

We propose drilling sites in the area of the SE Gulf of Mexico and the Yucatan Basin. These sites are proposed to better understand the tectonic processes of synchronous extension (formation of Yucatan Basin) and compression (formation of Cuban foreland basin) in the Caribbean "plate buffer zone".

Perhaps the most complex geology and tectonic processes are found in "plate buffer zones" or areas (often oceanic) which are found between two larger plates. Examples include the Caribbean, Scotia Sea, Southwestern Pacific, and the Mediterranean. Because buffer zones have probably been important sites of complex tectonics through geologic time, investigation of tectonic processes in these zones and their plate tectonic controls is critical.

Priority questions for research in these areas include:

1. How well do theoretical models based on observations from the large ocean basins describe subsidence in small basins found in "plate buffer zones" like the Caribbean and the Mediterranean?

2. What are the driving forces for the tectonic processes of "plate buffer zones"? Does the movement of larger plates control ocean opening and closure within buffer zones, or are these processes controlled locally by mantle convection related to subduction, slab pull, slab dip changes, etc.?

Recent Progress in the Mediterranean - Significant progress towards answering the above questions is being made in the Mediterranean. Work there by Malinverno and Ryan (1986), Channell (1986) and Horvath and others (1981) has addressed problems of extension and compression and tectonic driving forces in small, mostly Neogene, extensional basins like the Tyrrhenian Sea, the Pannonian Basin and the Aegean Sea.

Each of these areas consists of a "back-arc" or internal basin situtated on the concave side of a thrust belt with high curvature (an "orocline"). In each deformed arc the internal zones are thrust onto the external zones, an event that is usually interpreted as the result of a continent-continent or arc-continent collision. Drilling in internal basins of the Pannonian (Royden and others, 1983) and Tyrrhenian areas (ODP Leg 107, 1987) has shown that these basins were depocenters for marine deposits at times coincident with nappe emplacement in the peripheral orogenic belts. A significant amount of crustal shortening can be inferred from the stratigraphic and structural record of the thrust belts while a significant thinning can be inferred from the subsidence history of the basin. These amounts (where known) are shown on Table 1.

Based on these Mediterranean observations, three models have been proposed to explain the mechanism of extension/compression and tectonic driving mechanism:

1) Arc migration model - In Italy, Malinverno and Ryan (1986) have suggested that outward trench migration of the external zone results from the sinking of the underthrusting plate into the asthenosphere which produces back-arc extension. Localization of basin areas results from "pinning" of the arc by promontories with continued subduction, oroclinal bending, and back-arc extension.

2) Slab movement - In the Pannonian Basin, Royden and others (1982) suggested that lithospheric thinning that initiated Pannonian extension, was due to asthenospheric flow induced by a steepening of the dip of the subducted slab as a result of the cessation of

subduction. In a later paper Royden and others (1983) abandoned this model and adopted the arc migration model.

3) Delamination of mantle lithosphere - Channell (1986) has favored this process which is thought to occur if the lithosphere has been thickened rapidly during compression. Once delamination is achieved, the region transforms rapidly from one of compression to extension.

4) Gravitational instability - Horvath and others (1981) have proposed that the arc-foredeep boundary of the external zone is gravitationally unstable and back-arc basin formation may be considered as a gravity runaway of particular segment of the orogenic belt. Malinverno and Ryan (1986) have noted that it does not seem convincing that gravity alone can lead to the formation of an internal basin where seafloor is deeper and whose crust is thinner than that of the foreland.

In all four models, local subduction zone and mantle effects are suggested as the primary control on the observed extension-compression phenomenon. These local tectonic controls are consistent with the formation of tightly curved orogenic belts which are difficult to explain through the motion of the larger plates bordering the buffer zone. The main differences between the models involve relative timing of compression and extension. Models 1 and 2 predict backarc extension accompanying arc migration prior to terminal collision. Model 3 predicts backarc and episutural extension following terminal collision. Model 4 predicts backarc and episutural extension prior to and following terminal collision.

BACKGROUND INFORMATION FOR DRILLING IN THE YUCATAN BASIN/STRAITS OF FLORIDA

The northern Caribbean provides an easily accessible and well understood area to further explore problems of subsidence and plate driving forces in a plate buffer zone. Two general advantages offered by the northern Caribbean area include:

1. The area of the Yucatan Basin, western and central Cuba, and the Bahamas has been situated on the stable North American plate since the medial Eocene and therefore, is not overprinted with complex, post-Eocene strike-slip tectonics.

2. The Yucatan Basin and Straits of Florida have been the site of recent work (much of it here at UTIG) on seismic stratigraphy, heat flow, depth to basement, correlation to onshore Cuban stratigraphy, and subsidence modeling. These studies provide an observational and theoretical basin for drilling.

Tectonic Setting - A recent tectonic synthesis by Pindell and others (in press) suggest that the Yucatan Basin formed as a backarc basin through northeastward migration of a Paleocene - early Eocene Cuban arc and subduction zone. Collision and obduction of the Cuban arc onto the Bahamas Platform in the early-medial Eocene resulted in the formation of a Cuban foreland or "foredeep basin". This collisional event welded the Yucatan Basin and Cuban arc onto the stable North American plate, and post-medial Eocene interplate movement shifted southwards to the Cayman Trough strike-slip system.

Character of the Straits of Florida - Angstadt and others (1985) used MCS profiling and drilling results from ODP Leg 77 to Late Cretaceous to Holocene geologic history of the Straits of Florida. This work provided preliminary correlation between offshore units and exposed Jurassic - Eocene sediments on Cuba (Schlager, and others, 1983). An important conclusion of both studies is the identification of the "Cuban foredeep" as a foreland collisional basin developed during the Paleocene-Eocene collision of the Cuban island arc with the Bahamas Platform (Fig. 1). The Cuban foredeep contains over 3 km of gravity flow deposits that accumulated in an elongate corridor along the base of the modern Cuban slope. Drilling at Site 540 provided a long-range age correlation for the seismic sequences identified by Angstadt and others (1985). The ages and interpreted seismic facies correspond well to sediments exposed in the uplifted Cuban orogenic belt (Schlager and others, 1983).

Character of the Yucatan Basin - Rosencrantz, and others (in press) describe the Yucatan Basin as follows:

"The Yucatan Basin, in its present form, is at least Medial Eocene in age, as indicated by sediment fill and faulting of basement (Fig. 2). Crust underlying the basin to the south along the western edge of the Cayman Ridge includes granodiorites which show Late Cretaceous K-Ar cooling ages. The Yucatan Margin Complex, along the western side of the basin, includes rocks which range in age from Cretaceous to Paleozoic, and which show lithological affinities with rocks now found in the overthrust belts of Cuba. Seismic profiles show that the central part of the basin is underlain by a NNE-SSW trending rectangular, flat-floored deep 330 km long by 120-180 km wide. Seismic reflection, seismic refraction and gravity information all indicate that this deep is underlain by oceanic crust. The subsidence age of this crust, as determined by the relation between depth and age for small enclosed basins of finite age (3D model) developed by Boerner and Sclater (1987) lies between 50 and 60 Ma. Its heat flow age, as determined by the Boerner and Sclater model, lies between 42 and 53 Ma. The agreement of these ages, and their overlap, indicate clearly that the deep is Paleogene in age, probably early middle Eocene".

Character of the Cuban Orogenic Belt - The Cuban orogenic belt consists of medial Cretaceous to Paleocene island arc and ophiolite sequence that overthrust a medial Jurassic to Paleocene passive margin sequence in late-Paleocene - early Eocene time (Pardo, 1975; Pardo and others, in prep.). Paleogene thrusting in Cuba is, therefore, largely coeval with early to medial Eocene extension in the Yucatan Basin and Paleogene subsidence in the Cuban foredeep. High quality geologic maps of the Cuban thrust belt were produced in the 1950's by oil company geologists and are currently being reinterpreted in a plate tectonic framework here at UTIG (Pardo and others in prep.) (Fig. 3).

PROPOSED DRILLING SITES AND OBJECTIVES

We propose to drill the foredeep and back-arc basin of the Cuban orogenic belt in order to explore the linked, tectonic interactions between extension and compression in a plate buffer zone similar to those currently under study in the Mediterranean.

In the Straits of Florida, the general area of the drill site will be situated about 40 km from the NW coast of Cuba and 50 km SE of DSDP Site 540 (Fig. 1). This site will sample sedimentary units related to the major tectonic and depositional events of the area:

1) The pre-"Mid-Cretaceous Unconformity" or "MCU" section of mostly Jurassic to early Cenomanian carbonates that accumulated in a passive margin setting,

2) The "MCU" itself, which records a time of late Cretaceous sea level fluctuation and stress on nearby carbonate platforms,

3) A late Paleocene to medial Eocene section of mainly terrigenous clastic rocks that accumulated in the collision-related Cuban foredeep, and

4) A medial Eocene to Holocene, mixed clastic-carbonate section that records the establishment of major currents through the Straits of Florida.

Straits of Florida Drilling Objectives

Objectives include:

1) Verification of proposed ages, seismic sequences and facies types in the Cuban foredeep.

2) Improved stratigraphic correlation of sediments of the Cuban foredeep to exposed rocks of Cuban orogenic belt.

3) Subsidence history of a foreland-type basin on thinned continental crust and correspondence to known thrust history of Cuba; relation of foredeep subsidence to thrusting in Cuba.

4) Variation in hydrographic regime during closure of the Cuba - Bahamas Passage. Particular emphasis will be placed on identifying the age and character of the numerous erosional unconfirmities in the post-Eocene section and comparing

these to the development of paleo-circulation through the Straits of Florida.
5) Obtain near continuous Cretaceous-Cenozoic sedimentary sequence to serve as a type section for thrusted sediments in Cuba.

In the Yucatan Basin, two general areas of drilling are proposed in the deeper, western sub-basin (Fig. 2). The more southern site (Site 7 on Fig. 2) is located near a basement high in the area of oceanic crust. The site to the north (Site 7F) is located on the northern edge of the oceanic crust. Both sites have been described in detail by Rosencrantz (1984). Site 7 is intended to establish the age of oceanic basement of the deeper area of the western Yucatan Basin. Site 7 is intended to establish the age and history of rifting near the boundary between oceanic and the stretched continental/arc lithosphere of Cuba.

<u>Yucatan Basin Objectives</u>

Objectives at both sites include:
1) Verification of proposed age of the Yucatan Basin, ocean floor and its rift margins
2) Check on accuracy of depth to basement and heat flow predictions in a back-arc setting (Rosencrantz and others, 1987),
3) Correlation of Yucatan Basin subsidence to collision-related uplift of Cuba and subsidence of Cuban foredeep, and
4) Variation in hydrographic regime during opening of the Yucatan Basin.

Table 1: Comparison of Data From Cenozoic Caribbean and Mediterranean Basins
(modified from Horvath and others, 1981)

	Average water depth	Sedimentary thickness/km	Moho depth/km (crustal velocities/(km/s))	Thickness of the lithosphere/km	Heat flow mW/m^2	Intermediate and deep seismicity	Amount of extension	Amount of shortening in thrust belt
Pannonian	0	4* 2**	26-30 (5.7-6.9)	56	40-60* 90-110**	localized (Vrancea) 70-150 km	100 ± 50	120 ± 60
Aegean	0.5*-1.0**	1-2*,0.5**	20-30 (6.0-6.8)	thin	50-80* 90**	poorly defined Benioff zone, 0-180 km		
Alboran	1.0	2.0	16 (6.0-6.3)	70-90	60-80	localized (Granada) 600 km		
Tyrrhenian	1*-3**	3-8*,2**	12**	30	110**	discontinuous Benioff zone, 200-300 km	350 km	250-320 km
Yucatan	4	1*, 2**	13		48.0-74.8	none reported		

* Peripheral part

**Central part

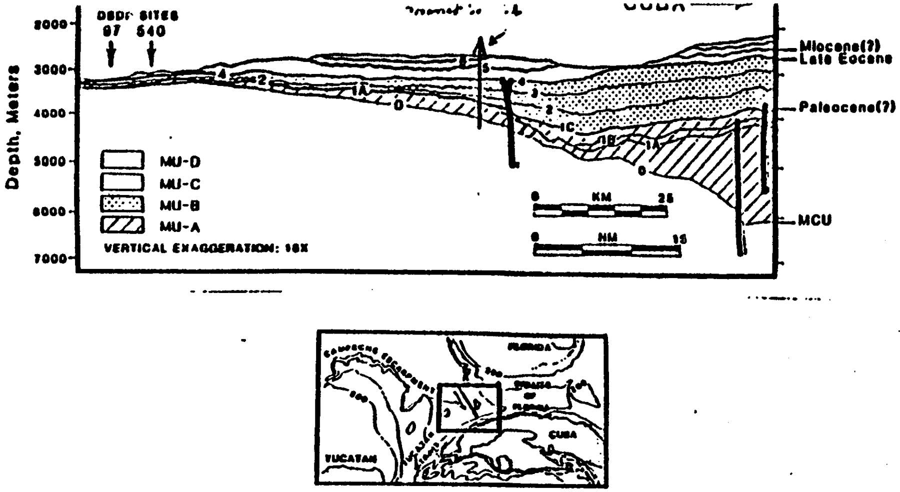

Figure 1: A generalized cross section of the post-mid-Cenomanian section in southeastern Gulf of Mexico based on depth-converted multifold profiles SF-8B and GT2-10C (from Angstadt and others, 1985). Seismic sequences (S.1, S.2, etc), their bounding unconformities (1A, IB, etc.), map units (MU-A, B. C. D), and DSDP Holes 97 and 540 are all indicated. Note particularly thickening of MU-A and MU-B toward Cuban margin. This thickening defines the "Cuban foredeep" formed during collision of the Cuban arc with the Bahamas platform. Inset shows location of line. Drilling will penetrate a more complete section of the Cuban foredeep than that sampled by Leg 77.

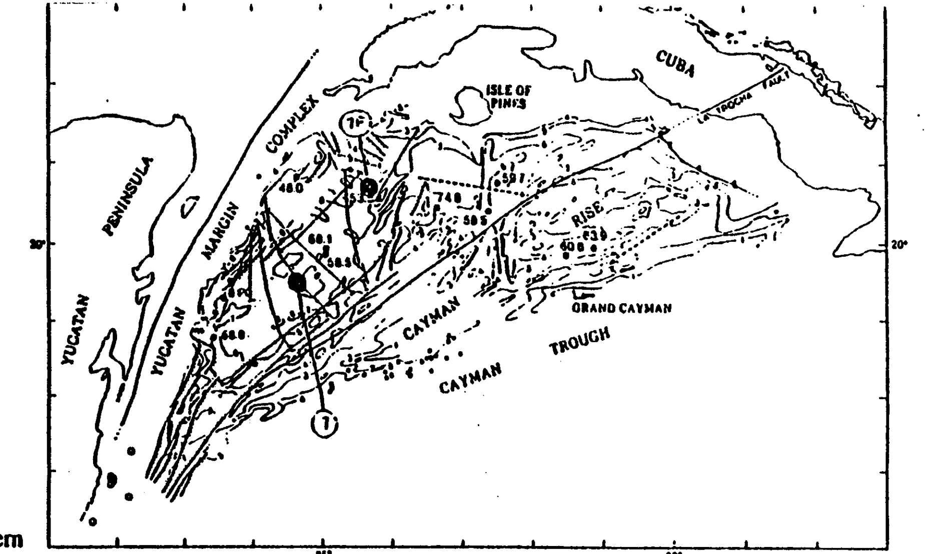

Figure 2: Simplified structural map of the Yucatan Basin (after Rosencrantz, in preparation). Contours describe present, loaded depths to basement in kilometers. The patterned area outlines that portion of the basin underlain by oceanic crust. Traces of the two major transform faults are drawn as heavy solid lines, and the thrust fault beneath the Cuban margin is marked by a heavy line with sawteeth on the upper plate. Traces of lesser basement faults are shown as hatchured lines, with tics on the downthrown side of the fault. The tracks of seismic reflection profiles along which depths to basement are measured are shown as light solid lines, and the locations of published seismic refraction profiles as heavy dashed lines. Dots mark the positions of published heat flow stations; filled squares the positions of published rock dredges; and open circles well locations. Heat flow values are in mWm^{-2}. Large block dots indicate the approximate positions of proposed drill sites 7 and 7F.

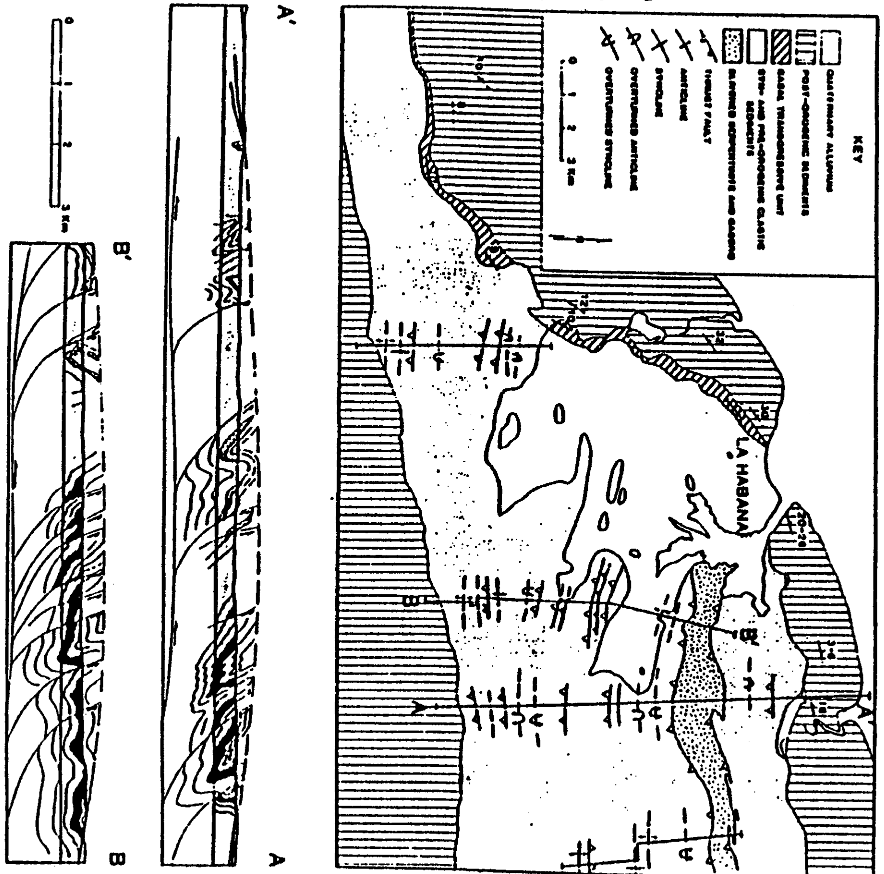

Figure 3: Geologic sketch map and sections of the western Cuban thrust belt near Habana (modified from Bronnimann and Rigassi, 1963). Intensely thrusting rocks exposed within the center of the dome range in age from Turonian to early Eocene. Tilted, basal transgressive unit is early to medial Eocene in age and marks the end of thrusting in this part of Cuba. Overlying sediments are medial-late Eocene to Oligocene in age. Major angular unconformity would correlate to Horizon 4 in the Cuban foredeep (Fig. 4).

2 Jurassic History and ODP Drilling Objectives, Southeast Gulf of Mexico

by

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INTRODUCTION

We propose a set of ODP sites in the deep southeastern Gulf of Mexico to sample a thick Jurassic section inferred by seismic data to lie beneath the deep water Lower Cretaceous rocks drilled during DSDP Leg 77. When integrated with regional seismic studies and correlated to equivalent age rocks on Cuba, it will provide key data for documenting the early paleogeographic and tectonic evolution of the Gulf/Caribbean region during the initial breakup of Pangea when South America/Yucatan moved southward away from North America.

SETTING

The study area is located in the deep part of the southeastern Gulf of Mexico between Yucatan and South Florida and just north of western Cuba (Fig. 1). Tectonically, the area comprises a relatively narrow band of rifted and subsided continental crust (thin transitional crust - Fig. 1A) formed along the southern margin of North America during the early evolution of the Gulf/Caribbean region. It is a key area for better understanding the reconstructions and paleogeography of Pangea during its initial breakup when South America/Africa began moving away from North America (Figs. 2A & 3A).

The southeastern Gulf also is critical for helping to distinguish between the two major groups of models of the early evolution of the Gulf of Mexico and proto-Caribbean. In one group, opening of the Gulf is achieved by treating Yucatan as a block independent of the opening of the North Atlantic, moving it out of the northern Gulf by either a counter-clockwise rotation, a clockwise rotation, or by translation to the south without rotation (White, 1980; Hall et al 1982; Pindell and Dewey, 1982; Shepherd, 1983; Buffler and Sawyer, 1985; Pindell, 1985; Salvador, 1987). These models imply various amounts and directions of displacement along major transforms between Yucatan and North America (southern Florida). For example, the model by Pindell (1985) invokes a counter-clockwise rotation of Yucatan, a complex triple-junction associated with two spreading centers in the Gulf, a southeast movement of an independent Florida Straits block along Atlantic fracture zones, and a zone of transpression in the study area.

A second group of models attaches Yucatan to the South America/Africa plate, with the opening of the Gulf intimately related to a contemporaneous phase of sea-floor spreading in the central North Atlantic (van der Voo et al, 1976; Pilger, 1978; Buffler et al, 1980; Klitgord et al, 1984; Klitgord and Schouten, 1986). In this scenario, the Gulf and proto-Caribbean open along flow lines parallel to those in the central North Atlantic; spreading centers in the two oceans are linked by a broad transform boundary

This model further implies major displacement between Yucatan/South America and North America across the study area

Seismic stratigraphic studies in the deep southeastern Gulf suggest the presence of a thick pre-middle Cretaceous sedimentary section overlying transitional crust (Schlager et al, 1984). This section apparently represents a long and complex early Mesozoic history involving the transition from a nonmarine setting to a deep marine setting during rifting and subsidence. DSDP Leg 77 sampled only a part of this history, including: 1) tilted fault blocks of early Paleozoic metamorphic basement injected with Early Jurassic mafic dikes, an example of transitional crust (Sites 537 and 538); 2) an almost complete deep water Early Cretaceous section (Sites 535 and 540); 3) the prominent mid-Cretaceous unconformity (MCU), here a Late Cretaceous starved interval with debris flows; and 4) a pelagic Tertiary section (Buffler, Schlager et al, 1984). Location of the sites are shown on Fig. 1C, while a schematic cross-section summarizes the geologic and tectonic setting (Fig. 2).

Lying below the Early Cretaceous rocks is a thick section of sedimentary rocks of presumed Jurassic and older age, which have been tentatively subdivided into three major sequences (Fig. 2) (Schlager et al, 1984). The oldest sequence is contained in a tilted and truncated rift basin of possible Late Triassic - Early Jurassic (?) age (TJ) (Figs. 2 and 3), based on analogy with similar sequences along the U.S. east coast. This is unconformably overlain by a widespread Middle Jurassic (?) unit (J1), that may represent a broad carbonate platform in the southwest (Figs. 2, 3 and 4), but also could be part of nonmarine synrift sequences to the north (Figs. 2 and 3). A third unit (J2) onlaps and fills the deformed J1 unit, both along a major NW-SE trending graben system (Fig. 4) and in the rift basins to the north. It is inferred to be Late Jurassic (?) in age, based on superposition below the Early Cretaceous rocks drilled at Sites 535 and 540 (Figs. 2 and 5). A marine origin is inferred based on the similarity of seismic facies with the overlying Early Cretaceous rocks (Figs. 4 and 5).

None of these Jurassic units were penetrated during Leg 77 with one possible exception; an unfossiliferous dolomite sampled at the bottom of Hole 536 may represent the top of Unit J1, suggesting that J1 may be a carbonate platform in this area (Figs. 2 and 3). This interpretation is further supported by seismic data along the eastern platform margin where a possible flexure in J1 and change of seismic facies could represent a carbonate margin (Fig. 4). This margin is faulted, however, and forms the west flank of a large NW-SE trending graben system through the area. Alternatively, this flexed and faulted margin could represent 1) a downdropped block of J1, or 2) a transform boundary juxtaposing completely different rocks, which also would explain the different seismic facies on either side of the structure. In the latter case, the fault zone could represent be a flower-structure such as forms along a transform fault, and thus, unit J1 would be different on either side of the fault zone (Fig. 4). A major transform boundary could be expected in this area as indicated by the models discussed above.

Jurassic rocks also outcrop throughout western Cuba just to the south of the study area. They should be equivalent to the Jurassic rocks in the study area, as this entire area probably formed the southern rifted margin of North America during the initial separation of South and North America. We are now learning much more about the Mesozoic rocks of Cuba based on: 1) literature coming from eastern European geologists working in Cuba, (e.g., Pszczolksowski, 1978) and 2) an extensive data set on Cuban geology (rock samples, maps, etc.) provided to UTIG by Chevron (Gulf) Oil Company for further study and compilation. These new data document an upward transition from a nonmarine setting to a deep deep marine setting during the Jurassic, a sequence similar to that inferred from seismic in the deep southeastern Gulf.

The Jurassic sedimentary section in the study area also can be traced seismically to the north across the eastern Gulf and up onto the northeastern Gulf shelf, where the Jurassic has been drilled. Jurassic sedimentary rocks, however, appear to be mainly absent on the flanks of the study area over the eastern Yucatan basement to the west and the Sarasota Arch area to the east (Salvador, 1987). Extensive Jurassic volcanic rocks, however, have been encountered in the bottom of many wells in the south Florida region (Smith, 1982; Klitgord et al, 1984). Thus, a comparison of Jurassic rocks in the southeastern Gulf with rocks on Cuba and in the circum-Gulf region would be important for reconstructing the early tectonic setting and paleogeography of the southern margin of North America prior to, during, and following the breakup of Pangea.

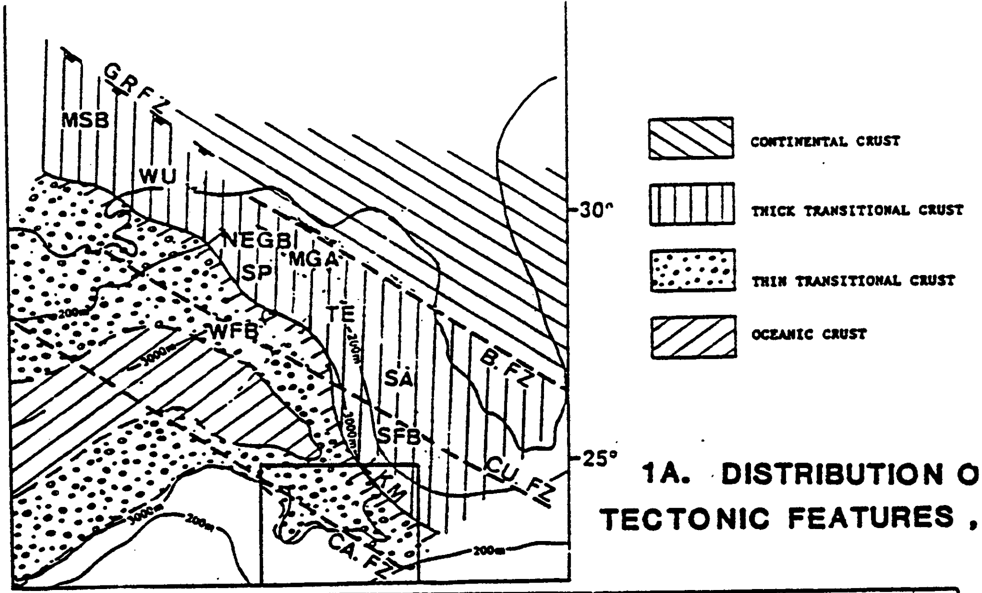
DRILLING OBJECTIVES

We propose a minimum of two sites to sample the Jurassic and possible older rocks on either side of the NW-SE trending fault zone that forms the western flank of the NW-SE graben and eastern flank of the inferred carbonate platform (Figs. 1-5). This is critical for evaluating the age, depositional setting and tectonic setting of the Jurassic rocks in the study area. The eastern site (SE-1) would be located just west of Site 535, where the Jurassic subcrops nearer the base of an erosional channel (Fig. 5). A reentry hole approximately 1500 m deep would penetrate all of J1 and into the top of J2, possibly sampling the overall transition from shallow to deep marine. A western site (SE-2A) would be located near Site 536, where there is a relatively thin Cretaceous - Tertiary section. Here a 1500 m hole would penetrate the updip part of the J1 platform and also part of the old TJ rift sequence (Figs. 2 and 3). Alternatively, a site nearer the platform margin (SE-2B) would penetrate the entire platform section and possibly the underlying basement (Fig. 4) (A site further north with less Cretaceous overburden can be located to provide approximately 1500 m penetration to basement).

KEY PROBLEMS TO BE ADDRESSED

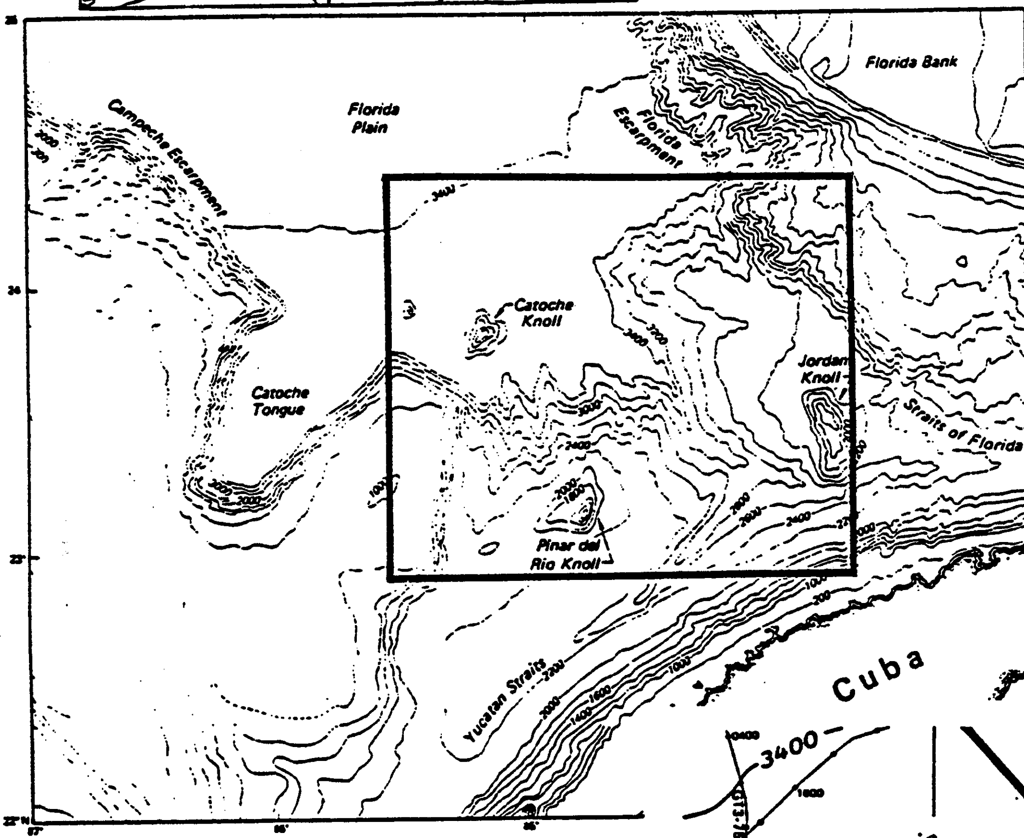
The set of sites proposed here to sample the Jurassic and possibly older section in the southeastern Gulf of Mexico, when integrated with the seismic studies of the area and the new outcrop data from Cuba, will provide information to help solve many problems. Most importantly, the Jurassic rocks hold the key for understanding the early Mesozoic sedimentary history along the southern margin of North America, thus providing clues for better understanding the reconstruction of Pangea and the paleogeography during its breakup. More particularly, the rocks will document the nature and timing of the evolution from a nonmarine setting to a deep marine setting, as the area rifted to form transitional crust and subsided. This involves the opening of a relatively narrow but important seaway between the early Gulf of Mexico and a proto-Caribbean Sea. This seaway has important implications for the changing Jurassic paleoceanographic conditions in the region, as the major plates moved apart and connections between the North Atlantic and Pacific Ocean evolved.

Secondly, Jurassic data from the southeastern Gulf/ area could provide information indirectly about the tectonic evolution of the region. Rifting, sedimentation and subsidence in the study area probably are related to a broad transform boundary, as implied from the various tectonic models. Thus, the data could provide clues as to the timing and opening direction of the Gulf basin. For example, drilling Jurassic Unit J1 on either side of the NW trending fault zone should help determine the nature of the zone (i.e., normal faulting vs. strike-slip), which, in turn, will help in evaluating the nature and orientation of any transform boundary through the area. On a broader scale, the data could provide important insights to help model the rifting mechanisms and subsidence history of a unique end-member of passive margin evolution, i.e., a major transform boundary connecting two oceanic spreading centers along which major rifting and subsidence of continental crust took place but no oceanic crust was emplaced.



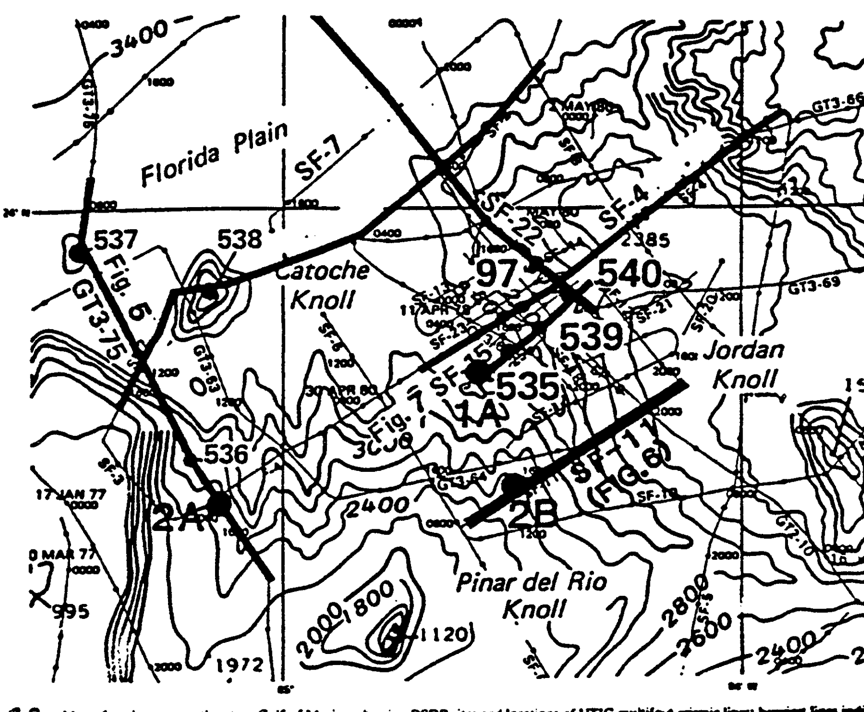
GRFZ	Gulf Rim Fracture Zone
BFZ	Bahama Fracture Zone
MSB	Mississippi Salt Basin
WU	Wiggins Uplift
NEGB	Northeast Gulf Basin
MGA	Middle Ground Arch
SP	South Platform
TE	Tampa Embayment
WFB	West Florida Basin
SA	Sarasota Arch
SFB	South Florida Basin
CUFZ	Cuba Fracture Zone
CAFZ	Campeche Fracture Zone

1A. DISTRIBUTION OF CRUST AND MAJOR TECTONIC FEATURES, EASTERN GULF OF MEXICO



1B Map of southeastern Gulf of Mexico showing major topographic features. Water depths in meter

FIG. 1 TECTONIC SETTING AND LOCATION OF STUDY AREA, SOUTHEAST GULF OF MEXICO



1C Map of study area, southeastern Gulf of Mexico, showing DSDP sites and locations of UTIG multifold seismic lines; heaviest lines indicate portions of seismic lines illustrated in this chapter. Water depths in meters. (from Schlager et al.

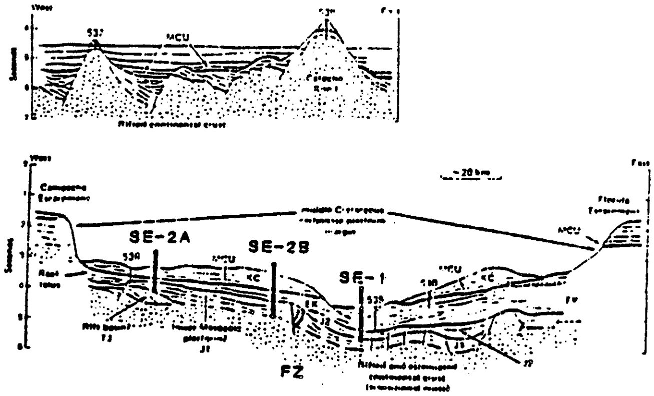


Figure 2. Schematic sections across study area, showing location of DSDP Leg 77 sites. MCU = mid-Cretaceous unconformity; TJ, J1, J2, are seismic units described in text. Location of proposed ODP sites SE - 1, 2A - 2B (modified from Schlager et al, 1984).

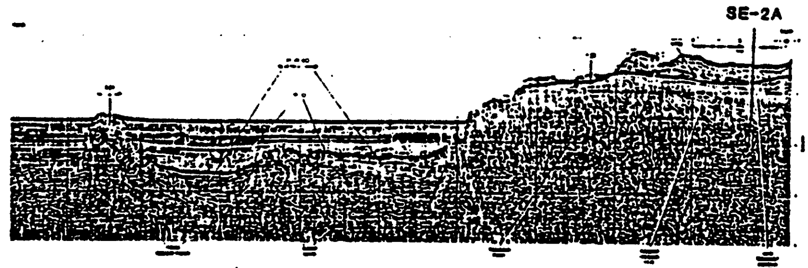


Figure 3 Portions of seismic line GT3-75 near the base of the Campeche Escarpment, showing the regional setting of Sites 536 and 537. Site 536 is on a large high-standing basement block. Just to the south is a rift basin truncated and onlapped by the J1 unit. To the north is a lower area of fault blocks. Older sedimentary sequences have been tilted and younger basins filled with synrift sediments. Site 537 is on the top of one of the tilted blocks. Drilling there recovered 500(±)-Ma-old phyllite. Location of proposed ODP drill site SE-2A. (From Schlager et al., 1984).

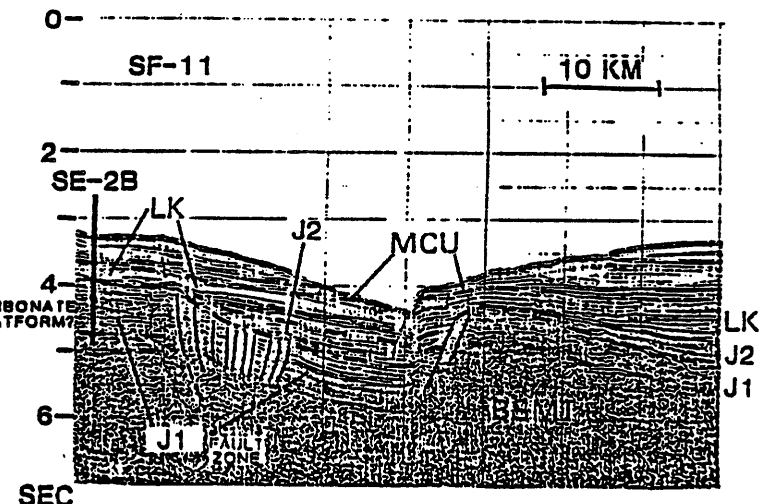


Figure 4. Seismic line SF-11 showing prominent NW-SE trending graben system and faulted margin of inferred Jurassic carbonate platform. See text for alternate interpretations of fault zone. Location of proposed ODP site SE - 2B.

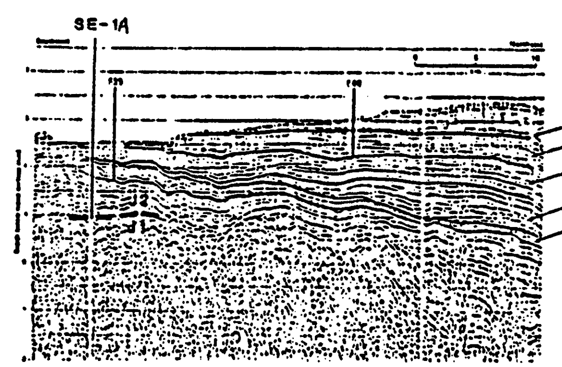


Figure 5. Depth section of seismic Line SF-15, showing Early Cretaceous seismic units EK 1-4, J1, and J2 near Holes 535 and 540 and proposed ODP site SE-1. Modified from Schlager et al, 1984.

3 Cayman Ridge SW of Rosario Bank at about lat 18° 15'N, long 84° 25'W at a water depth of about 2000 m. Estimated total depth of well 1000-1500 m. (3-1)

Burke Burkart

<u>Justification for Drillsite Location</u>

The proposed drillsite is selected to penetrate Rosario Reefs and older carbonates of the Cayman Ridge and, possibly, the igneous and metamorphic basement.

Much of the evolutionary history of the NOAM-CARIB plate boundary will be recorded in the stratigraphic sequences of the Cayman Ridge. Perfit and Heezen (1978) gathered data from dredge samples from which stratigraphic sequences could be pieced together. These sections, by the very nature of the type of sampling, are sketchy, yet they served as a basis for their model of evolution of the plate boundary, many aspects of which are still viable. These sections are also helpful in identifying drillsites along the northern boundary of the Caribbean plate.

The drillsite suggested here can test the composite stratigraphic section of Perfit and Heezen (1978). A well drilled here also has the potential of testing the basement, which probably consists of Paleozoic metamorphics and Late Cretaceous granodiorites.

Testing the basement and older sedimentary rocks is important in reaching back to the time of earliest movements across the NOAM-CARIB plate boundary. Recent identification of a belt of Late Cretaceous plutons in Chiapas (Mexico) and Guatemala (Burkart et al. 1987) revives interest in the proposed island arc of that age of Perfit and Heezen (1978). Granitoid rocks of the Soconusco intrusives of Chiapas are offset left laterally 130 km across the Polochic fault from petrologically similar rocks of the same age in the Santa Maria Batholith in Guatemala. The Late Cretaceous-Paleocene island arc these plutons probably represent must have continued southeastwardly across what is now the Motagua fault zone across which, according to various models, up to 1400 km of sinistral offset has taken place. The granodiorites of the Cayman Ridge and the potentially correlative granodiorites of Jamaica and Hispaniola may be offset segments of the Central American arc of Laramide age. The present-day, wide distribution of granitoids (along the present plate boundary a distance of 2500 km) may represent the original arc distributions, with only a modest rearrangement in the Neogene by transform faulting (Perfit and Heezen, 1978). As yet there has been no positive correlation of rocks in the Caribbean basin with those of the Maya block in northern Central America. An opportunity may exist to establish a firm stratigraphic connection in support of those models wherein sinistral offset of great magnitude is postulated across the NOAM-CARIB plate boundary.

Stratigraphically above the Cayman Ridge granodiorites are Late Cretaceous-Paleocene shallow water limestones, interbedded with volcanic detritus and overlain by thick sequences of volcanic, metavolcanic, fine and coarse clastics (Perfit and Heezen, 1978). A veneer of Eocene through Recent carbonates rises to above sea level on Grand Cayman Island. Cores from this site will elucidate the depositional history of the northern plate margin about which there has been speculation and controversy. Age of initial strike-slip activity across this region may be revealed in this core as can the history of deepening of the trough.

4 PROPOSAL FOR CARIBBEAN SCIENTIFIC DRILLING

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NICARAGUAN RISE

One of the outstanding problems of Caribbean tectonic history is the history of the Nicaraguan Rise. As shown by seismic refraction surveys (Ewing et al, 1960, Edgar et al 1971), this area is underlain by a considerable thickness of materials with velocities not typical of oceanic crust. These thicknesses and velocities are summarized below.

Cruise	VEMA 8	VEMA 8	VEMA 8	VEMA 8	VEMA 8	VEMA 12
line	21	20	19	18	35	85
latitude	17.55- 17.52	16.23- 17.02	14.72- 15.02	12.75- 13.75	18.28- 17.27	16.68- 17.60
longitude	79.08- 80.07	79.25- 79.60	78.23- 78.48	77.52- 77.67	75.23- 74.33	74.00- 74.62
end	E W	S N	S N	S N	W E	S N
water	.86- 1.92	1.39- 1.39	1.95- 2.22	.94- 4.02	2.56- 2.56	4.02- 1.83
uncon. sed.	.59- .76	1.0- 1.0	.77- .69	1.6- 1.3	.70- .70	.26- .32
1st layer	2.3- 1.7	3.2- .93	1.8- 3.2	1.3- 1.4	3.5- 3.1	.14- .39
vel.	3.9	4.8	4.4	(4.6)	2.8	3.19
						1.22- .98
						3.78
2nd layer	3.3- 2.1	4.5- 2.6		2.3- 2.5	5.3- 3.8	1.39-4.22
vel.	5.2	5.5	6.3	5.8	(4.4)	5.10
3rd layer	12- 14			12- 14		15.56- 16.42
vel.	6.2	6.7		7.0	6.4	6.73
mantle vel.	7.6			(8.1)		7.86

I regard the Nicaraguan rise as probable continental crust which is a part of the Chortis block. I believe that it thinned during the Cenozoic and that this thinning represents some of the displacement shown by the Cayman Trough fracture zone. Such thinning of the Chortis block suggests that the Cayman Trough fracture zone is somewhat decoupled from the Chortis block. On land we see abundant evidence of thinning of the Chortis block in the form of north- south and north northeast- south southwest grabens, many of which are flanked by very young alkalic volcanic centers.

DRILLING OBJECTIVES

1) Age of thinning. This could be ascertained through stratigraphic inference. Deepening would be inferred by passage upwards from shallow water sediments to pelagic facies, such as was seen on the Ninety-East Ridge. The nature of shallow water facies would be of value for a reconstruction of the pre-thinning environment of the Nicaraguan rise.

2) Nature of the "continental" materials underlying the Nicaraguan rise. This objective is probably not attainable. Very likely any Chortis basement is buried beneath a great thickness of Cretaceous and earliest Tertiary shallow- water sediments. The seismic refraction surveys suggest that the thicknesses of these materials are too great for oceanic drilling. They may be inferred in the forms of clastic debris if coarse sands are encountered, but these sands would also probably terminate drilling.

3) Paleooceanography of the Nicaraguan rise. The subsidence of the Nicaraguan rise would remove a barrier to the circulation of water masses of various depths between the Yucatan Basin and Colombian Basin. A goal of Nicaraguan rise drilling would be to sample carbonate-rich sections of various depths so that, by Oxygen isotope and faunal analysis the disappearance of provinciality might be deduced.

4) Igneous history. The Chortis block and Nicaraguan rise is the site of late Cenozoic alkalic volcanism, seen on land in Costa Rica, Nicaragua, Isla Providencia, Jamaica, Honduras, Utila, and also Hispaniola. Most of the dates are Plio- Pleistocene, but the Jamaican material is dated as late Miocene. A goal of drilling on the Nicaraguan rise would be to find, thorough the appearance of biotite- rich ash, the stratigraphic appearance of this event.

A further igneous event which might be dated by drilling here is the ignimbrite of the Chortis block. Radiometric dates suggest two major episodes, roughly early and middle Miocene. The Nicaraguan rise lies downwind (for high-altitude winds) and is well placed to receive the ash from this event. Leg 67 found some ash (including possibly the Matagalpa event), but this leg was upwind and found only limited ash. The contrast between sites 154 (Caribbean) and 158 (Pacific) shows that virtually all of the ash from explosive volcanism travels east, and the record is far more complete in the Caribbean.

DRILLING STRATEGY

The most productive drilling will be single- bit holes with HPC or equivalent in the upper layers (critical for igneous stratigraphy and paleooceanography). Probably the shallowest water should be avoided; not only is the water too shallow for positioning of the ship, but the is a probability of encountering reefal materials which might be difficult to drill.

I recommend holes in moderate to deep water on both the north and south side of the Nicaraguan Rise. The map shows some suggested localities.

a: deep between Jamaica and Pedro Bank; subsidence history of deep, possible volcanic stratigraphy of young alkaline volcanics.

20: deep between Pedro and Rosalind Banks; subsidence history of deep. Profile of Edgar et al (1971, fig. 18) suggests 800 m pelagic sediment.

21: deeper water on north side; paleooceanography; subsidence history; above- mentioned profile also shows about 800 m sediment.

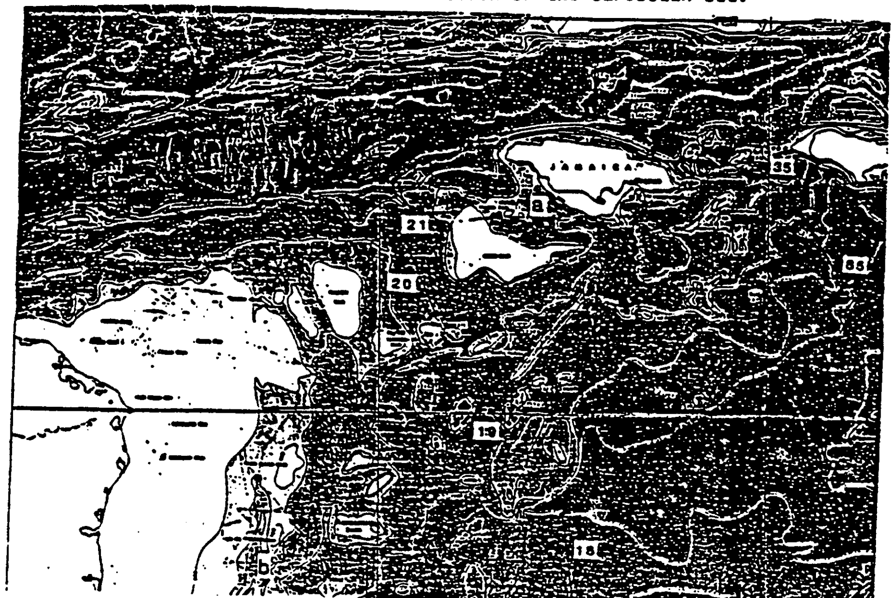
b: Spur south of Isla Providencia (Colombian territorial waters?); volcanic history; possible Paleogene; tephrachronology of Chortis ignimbrites and volcanic front eruption.

21: Deeper water south of Pedro Bank; paleooceanography, subsidence history; possible Paleogene This might have the most complete Tertiary section of any of the five sites suggested. Profile of Edgar et al (1971, fig. 18) suggests more than 1000 m. sediment.

References:

Ewing, J.I., Antoine, J., and Ewing, M. (1960) Geophysical measurements in the western Caribbean and Gulf of Mexico. J.G.R., 65, p. 4087- 4126.

Edgar, N.T., Ewing, J.I., and Hennion, J. (1971) Seismic refraction and reflection in the Caribbean Sea. A.A.P.G. Bull., v. 55, p. 833- 870.



5

From: Gren Draper
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Site group 1: Cayman Trough

Compared to the length of its bounding transforms, the Cayman Trough spreading center is the shortest speading segment in the world. There must, therefore, be a great deal of lateral heat loss which would mean that for a given age the depth of the sea floor must be lower in the Cayman Trough compared to normal ocean floor. Rosencrantz et al (1986) have calculated the theoretical depth-age relations for the Cayman Trough and used it to develop a model for the opening history of the Cayman Trough. As the Cayman Trough is the only divergent margin in the northern Caribbean. it has great regional significance as it could provide the only way to document the extent and history of strike slip movement on the Northern Caribbean plate boundary zone.

Suggested drilling and data collection: three or more sites in the Cayman Trough (see map); geochronological, magnetic, geochemical data.

Benefits: Rigorous check of Rosencrantz et al depth-age calculation (how much lateral heat loss); insights into tectonics of spreading at a slow speading center with lateral heat loss; tighter controls on models of spreading history of the Cayman Trough and hence on Tertiary strike slip movement of northern Caribbean Plate Boundary.

Site Group 2: Central Caribbean Crust

The interior of the Caribbean is composed of the anomolously thick crust of the Venezuela and Colombia Basins which are in turn divided by the Beata Ridge . The major basement reflector, B", was sampled on DSDP leg 15 and found to be composed of diabase of generally oceanic affinities. Later speculation has suggested that it (a) represents a widespread sill or flood basalt event, (b) is an oceanic plateau derived from the pacific, (c) resulted when the Caribbean passed over the Galapagos hot spot (d) is a back arc basin. Recent work at Florida International University has indicated that the rocks of the Venezuela basin and the lower part of the sequence in southern Haiti are N-type MORB, but that the Beata Ridge and the upper Haitian sequence are enriched by a "hot spot" basalt componenent (? indicating they are sea mount structures). Compilations for D-NAG have indicated the presence of B" type magmas around the Caribbean.

The basic tectonic problems are: what exactly is the central Caribbean crust, how did it get to its present position and how does it realte to on-land occurrences of similar B" rocks. Available samples from DSDP are small in number and geographically restricted.

Suggested drilling and data collection: more holes in the Venezuelan and Colombia Basins and especially the Beata Ridge(see map) tobe drilled as deep as possible (can we penetrate B"?); detailed magnetic, geochronologic and geochemical studies (including lead and neodymium isotopes)

Benefits: clearer picture of actual nature of Central Caribbean which can lead to improved understanding of regions thickened oceanic crust, and their later role in collisional processes.

Site Group 3: Accretionary complexes associated with amagamatic underthrusting

Seismic studies have shown that accretionary structures are found on the both the southern and northern boundaries of the Caribbean, offshore Colombia/Venezuela and eastern Hispaniola (Muertos Trough) respectively. Much has been learned concerning sedimentary and tectonic processes in accretionary complexes arcs where underthrusting is rapid enough, and sufficiently long lived, to produce arc magmatism, but little is known about structures such as those which border the Caribbean, which might be considered intermediate between subduction complexes and foreland thrust belts.

Suggested Drilling and data collection: holes to be drilled at various sites on the prisms (see map), but especially at the toe to compare fluid activity with comparible sites on the Barbados ridge.

6

Terry Edgar

1. Cayman Trough
latitude: 19°03'N
longitude: 75°35'W
water depth: 3075 m
penetration: 0.7 sec two-way time (630 m @ 1.8 km/s)
data source: USGS Farnella '85 5D302,0200; Fig. 1

<u>Background</u>: The initial stages or crustal rifting and subsequent formation of ocean crust are characterized by stretching, thinning and subsidence of the continental crust, such appears also to be the case in the extreme eastern and western ends of the trough. The transition between the subsided continental crust and oceanic crust can be readily identified by both seismic reflection and refraction techniques.

<u>Problem</u>:

1. To establish the age of initial subsidence of the continental crust which would mark with imprecedented accuracy the time of initial opening of the trough. This would be a marker for a major change in plate motion that affected practically every tectonic region in the Circum-Caribbean region.
2. To establish the subsidence history at the time of initial stages on the crust to its final deposition.
3. to establish a deep water paleontological section in quiet intermediate-depth water to compare with that of the deep and shallow water deposits on Jamaica.

<u>Program</u>: Only one hole in intermediate depth water needs to be drilled to achieve the goals. The accoustically transparent sediments contain no strong reflectors from the surface to acoustic basement, which should provide ideal coring conditions for the paleontological goal as well as for reaching acoustic basement.

2. Venezuela Basin
latitude: 14°20'N
longitude: 67°00'W
water depth: 4990 m
penetration: 1.5 sec (225 om @ 3.0 km/s)
data source: Diebold et al., 1981, JGR, V.82, p7901 (Fig. III-6)

<u>Background</u>: Smooth basement horizon B" in the venezuela basin was penetrated at three locations (sites 146/149, 150, and 153) during the DSDP drilling on Leg 15. Horizon B" appears to be composed of diabase sills and basalt flows. The sills and flows may be penecontemporaneous with the formation of the crust or post date it by a significant interval of time. In the southeastern part of the Venezuela basin horizon B" is absent and the basement topography assumes the roughness that is characteristic of that in the main ocean basins. Tentatively identified magnetic anomaly lineations and DSDP ages indicate that the age of the crust increases towards the area of rough basements and it has been shown that the contact between the two basement types is a fault contact in some areas and in others a change in acoustic facies that appears to be the terminous of the flows and sills.

<u>Problem</u>: Other areas of the ocean basins are also characterized by a smooth basement layer similar to that of the Venezuela basin, but this location is the only known area where the transition from smooth to rough basement can be clearly identified without structural complications. Here is the opportunity to compare the ages and lithologies of the basements and establish whether smooth basements of the world oceans could be the result of spreading ridge activity (penecontemporaneous formation) or off-axis volcanic activity.

<u>Program</u>: The sediment thickness throughout the area of rough basement is at least 1.5 seconds reflection time, based on published seismic data. The site proposed has a minimum of 1.5 sec reflection time, but it is not at the deepest basement location where the oldest

3. Cayman Trough

latitude: 18° 38'N
longitude: 80° 21'W
water depth: 5100 m
penetration: 0.3 sec two-way time (300 m @ 2 km/s)
data source: USGS Farnella JD301-1050 hr-85 ; Fig. 2

Background: Attempts to justify the cooling curve with other age dating techniques across the spreading center in the Cayman Trough have required rather contrived explanations that are not very satisfying. The Cayman Trough is a deep rift or pull-apart basin underlain by thin oceanic crust created by slow east-west seafloor spreading. The topography fails to match the standard cooling, being too deep. Part of the problem may be that the spreading center has developed in a narrow rift between two blocks of continental rocks which may have affected the cooling history. With uncertain age and spreading rate it is difficult to definitely explain the depth of the ridge.

Problem: To establish an age of the crust at a selected place in the trough to establish an age. With one age point the cooling curve can be used to model the thermal history of the trough. These results will have a profound influence on the thermal parameters used to model the drifting of continents and the formation of new ocean crust.

Program: Only one hole is needed to establish an age to model the thermal history. The site selected is over a small pond of sediment, probably filled in by sediments remobilized from local topography, although presently below the depth of calcium carbonate compensation, it surely reviewed an initial cover of carbonate sediment at much shallows depths, assuring a good paleontological date.

ODP Caribbean Conference
Site Proposal
Terry Edgar

4. Puerto Rico Trench

	A		B
latitude:	19°00'N	latitude:	19°25'N
longitude:	67°00'W	longitude:	67°00'W
water depth:	300cm	water depth:	6200 m
penetration:	0.75 sec	penetration:	0.6sec

Fig. 3

Background: According to dredge samples and seismic profiles, the south wall of the Puerto Rico trench subsided about 3000 m since late Miocene - early Plioiene time. Currently the trench and its gravity abnormally is maintained by a small component of subduction in what is otherwise an area of dominantly strike-slip motion. Consequently, it has been proposed that the trench formed since late Miocene time. It has also been proposed that the south wall of the trench was formerly attached to the Bahamas but broke away when it docked against the Greater Antilles.

Problem: The subsidence of 3000m since late Miocene-early Pliocene time (subsidence rate; 0.6 mm/yr.) is fairly rapid, and a continuous core would provide evidence of the subsidence history up on which subsidence models could be developed. In addition, a suitably placed hole could recover early Tertiary or Mesozoic rocks for comparison with those of the Bahamas in the hope of substantiating on refuting the docking concept. This is particularly important because of the profound effect such insight would have on the understanding of the regional tectonics.

Program: Two holes are proposed in this area; one for recovery of the late Tertary sediments to document the subsidence and one to recover the earliest sediments overlying basement. The first site is located in the deepest water (3000 m) where it appears that a complete late Tertiary section exists. The second is located near the northern-most limit of the sedimentary section adjacent to the steep north wall from which only igneous and metamorphic rocks have been dredged. The younger sediments are not present at this location and only about 0.15 sec of sediment overlies what appears to be basement.

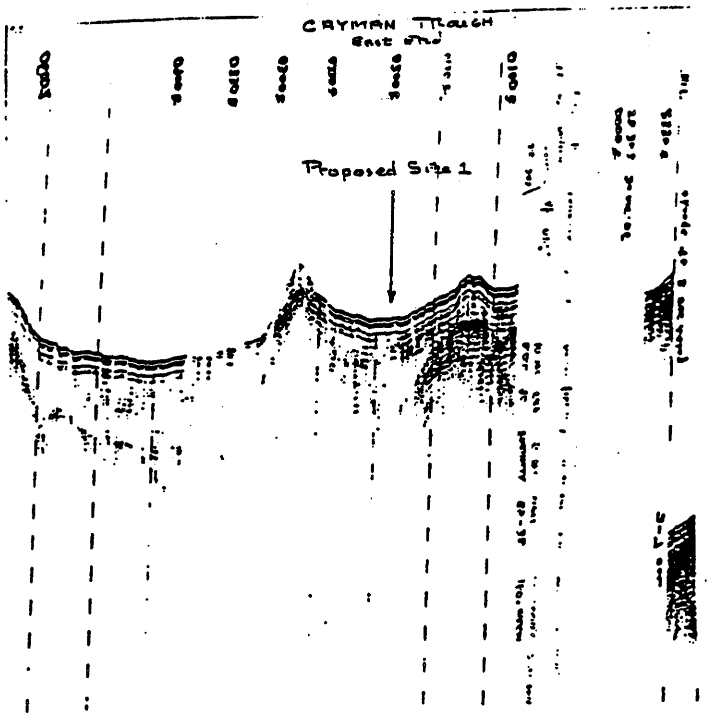


Fig. 1 Edgar: Site 1, Cayman Trough

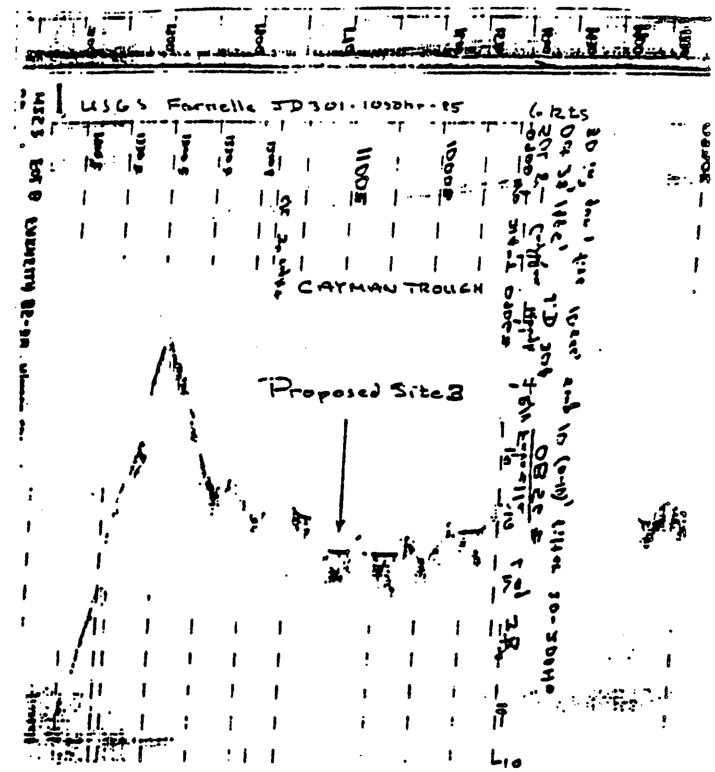
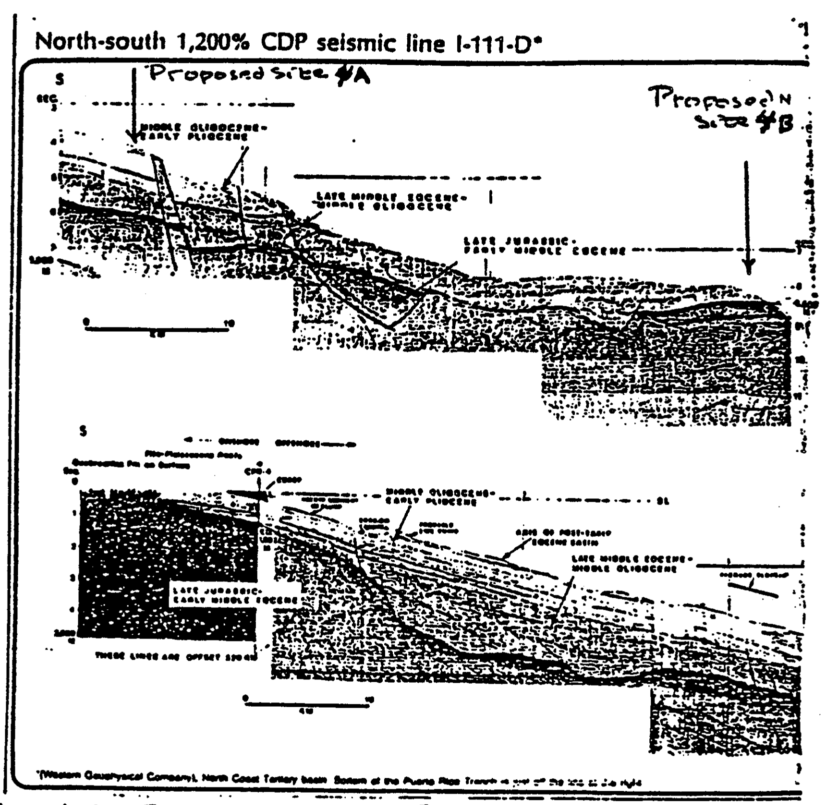


Fig. 2 Edgar: Site 3, Cayman Trough



Meyerhoff et al., 1983, Oil & Gas Journal

Fig. 3 Edgar: Site 3, Puerto Rico Trench

7 Deep sea drilling in the Caribbean

Wulf A. Gose, University of Texas at Austin

There are numerous problems related to the evolution of the Caribbean Plate which can only be resolved through drilling or where drilling could provide significant information; e.g.

1. What is the age and nature of the crust below B"?
2. What is the nature of the areas in the Venezuelan Basin characterized by smooth versus rough acoustic basement?
3. Is the Bonnaire Block a far travelled terrane?
4. Where is the eastern limit of the Chortis Block?

These questions, while important for the tectonic history of the Caribbean, address, however, only specific Caribbean problems and would yield little information of interest to the general community. In addition, the lack of comprehensive geophysical surveys precludes an intelligent choice of specific drill sites.

Much of our knowledge of the plate tectonic history of the Caribbean has been derived from studies of the Cayman Trough and it is in this area that drilling can make important contributions to both specific Caribbean as well as general problems.

1. A reevaluation of the sea floor magnetic anomalies associated with the (7-1) Cayman spreading center implies that the spreading rate is only about half as fast as previously thought. Drilling into several magnetic anomalies would firmly establish their age, the initiation of spreading, and the spreading rates. The same slow rate has also been arrived at from an analysis of paleomagnetic data in terms of the McKenzie and Jackson model which relates paleomagnetically observed rotations in plate boundary zones to the total displacement across the zone. Knowledge of the spreading history makes it possible to test the McKenzie and Jackson and similar models of strike-slip induced rotations.

2. Among spreading centers, the Cayman spreading center seems to represent an end member in that it is characterized by a short ridge and very long transform faults, as well as very slow spreading. The thermal evolution of oceanic crust generated under these conditions will be different from "typical" oceanic crust. In order to explain the thermal subsidence it is necessary to take lateral heat loss into account . Does this faster aging of the crust have any effect on the chemistry, mineralogy, physical properties? Only by direct sampling and by measuring the heat flow can these effects be assessed.

Stuart A. Hall

Potential ODP Drilling Sites in the Caribbean

One of the major obstacles to understanding the tectonic evolution of the Caribbean region is the lack of knowledge of the age and nature of the basement underlying much of the present Caribbean Sea. The primary objective of any further drilling in the Caribbean region, therefore, should be to determine the age and nature of the basement in the three major basins (Colombian, Venezuelan and Yucatan Basins). Unfortunately in the case of the Colombian and Venezuelan Basins, available evidence, predominantly seismic refraction and reflection data, suggests that where there is a close to normal oceanic thickness for the crust, the water depth (3-4 km) and sediment thickness (3-4 km) are such that penetration to the basement by present ocean drilling capabilities appears unlikely.Locations in these basins where "normal" oceanic crust is believed to be present are shown in figure 1. Such sites should be considered priority sites when enhanced drilling capabilities are available. In the meantime since thickened crust in these basins has been sampled by previous holes, there appears to be little benefit in drilling further holes into this buoyant material.

In the case of the Yucatan Basin, the opportunities for penetrating basement at reasonable depths are more widespread. To date there have been no deep sea holes in the Yucatan Basin and consequently the age of much of the lower sedimentary section as well as the nature, depth and age of the basement are unknown. A reasonable amount of multichannel seismic reflection data is available but in order to capitalize upon its potential, it is essential that a deep hole, preferably to basement, be drilled in the central portion of the basin. Maps of the depth to basement, based upon these seismic data, have been prepared by the Institute for Geophysics of the University of Texas at Austin. These indicate that basement may be encountered at depths of 3 to 4 km(Fig. III-7). A hole drilled at this site would provide an opportunity to determine among other things:

(a) the age and nature of the basement
(b) the depositional history of much of the basin
(c) the subsidence history of the deep basin

In addition to a hole in the Yucatan Basin, I believe the second priority should be a hole in the Cayman Trough region. This hole should be located (Fig. III-8). in part of the crust that is considered to have been created soon after the initiation of spreading of the mid-Cayman Rise. Information from such a hole together with available geologic and geophysical data would enable the history of movement along the Cayman Trough to be established and provide a much needed tectonic framework for the region. In particular, by placing time constraints upon the motions in the area, it will be possible to correlate the geologic events in Central America with those in the Greater Antilles.

Integration of the results from holes A and B with available data will enable the Late Mesozoic and Cenozoic geological history of the northwestern Caribbean to be obtained and its relationship to the Gulf of Mexico system to the north clarified.

9 Potential Drill Sites in the Southwest Carribean Deformed Belt

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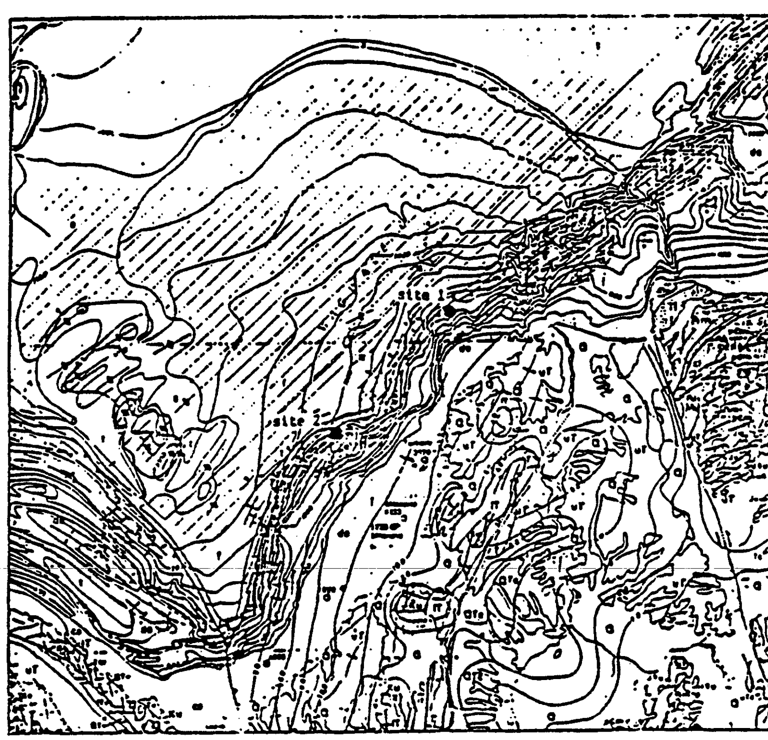
Many ancient turbidite systems have been interpreted as originating in an active convergent margin setting. How turbidites are preserved in the geologic record controls the structures we observe in them, and if deformation occured during deposition, it may also partially control the stratigraphic relationships. The Magdalena fan, located on the continental margin off the mouth of the Magdalena River in northern Colombia, is an example of a fan being deposited on the inner trench slope at an active convergent margin. Because the growth of the accretionary wedge depends on the maintenance of a critical surface slope, the fan deposition will perturb the pattern of deformation at the convergent margin.

Drilling sites in the Magdalena fan (Site 1) and in the fold belt (Site 2) would demonstrate the temporal relationships between turbidite deposition and folding and thrusting. In addition, the thickness and pressure of Miocene shales and muds and their role in the deformation could be determined. Data to be collected would include age data, structural fabrics, and pore fluid pressures. At Site 2 drilling should continue through the toe of the accretionary wedge into the decollement. The two sites should require about half of a drill leg.

Considerable data is available for the proposed area including multichannel seismic profiles, Chevron and Ecopetrol have dense gravity surveys, and there are four drill holes upslope on the continental shelf. Breen and others will propose a sidescan survey of the area to the next NSF Panel. Kellogg and others will be using precise Global Positioning System (GPS) geodetic measurements to determine the rate of convergence across the margin beginning in January 1988.

Figure 1.



TIMING AND MECHANISM OF FOLDING AND THRUST FAULTING IN THE NORTH PANAMA THRUST BELT

by Nancy A. Breen

INTRODUCTION

The northwestern part of the north Panama thrust belt has a distinctive structural style characterized by a low wedge taper, landward verging thrust faults, regularly spaced, symmetric parallel folds, and mud volcanoes located on the anticlinal ridges (Tagudin, et al., 1986; Reed et al., 1986; Breen et al., in press).

Breen et al., (in press) argue that this area of the north Panama thrust belt is mechanically similar to salt-based fold-and-thrust belts. Instead of weak salt, however, overpressured muds are acting as the weak layer. Folding precedes faulting as the weak mud migrates to fill the anticlinal core. Mud volcanism occurs on the anticlinal ridges, dewatering the overpressured source regions in the anticlinal cores.

This hypothesis has consequences that may be tested by drilling. The mud volcanoes should all originate from the same stratigraphic layer. Folds should grow significantly before faulting occurs. Faults may also vent overpressured fluids. We propose to investigate the origin of the mud volcanism as well as the timing of the structural development through drilling.

SPECIFIC QUESTIONS AND DRILLING TARGETS

1) How fast does the toe of the accretionary wedge migrate forward? This question could be answered by determining the age of initiation of each of the anticlines. The SeaMARC II side-scan image shows that the anticlinal ridges have lower reflectivity than the surrounding basins. This change is probably a result of a change in depositional environment as the anticlines rise out of the basin. Drilling the first few anticlinal ridges would provide dates for the onset of the change in sedimentation type on each fold. This would give us the age of the initiation of each fold, and therefore the rate of the forward growth of the deformation front. These holes would need to be no more than 50m deep.

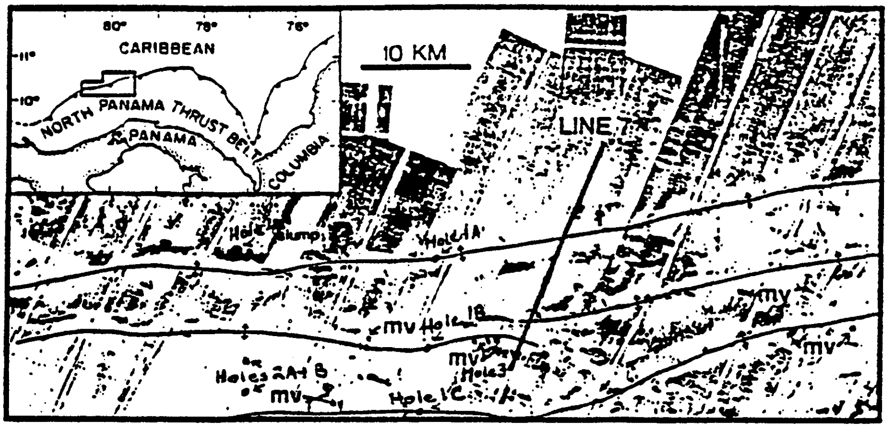
2) How fast do folds grow, and what is the relationship between the timing of faulting and folding? These questions could be answered by stratigraphic analysis of holes drilled in the synclinal basins. The rate of depostion in the basin gives an lower bound on the upward rate of growth of the surrounding folds. The seimic profiles indicate that unfaulted folds are associated with symmetric synclinal basins, but that the basins are tilted as the seaward fold is faulted and thrust forward. Therefore, two holes, drilled fore and aft of the axis of the syncline should show similar rates of deposition until a thrust fault becomes active in the seaward fold, when the locus of sedimentation should shift toward the landward side of the basin. The timing of the faulting can then be compared to the timing of the folding as determined from the holes on the anticlines.

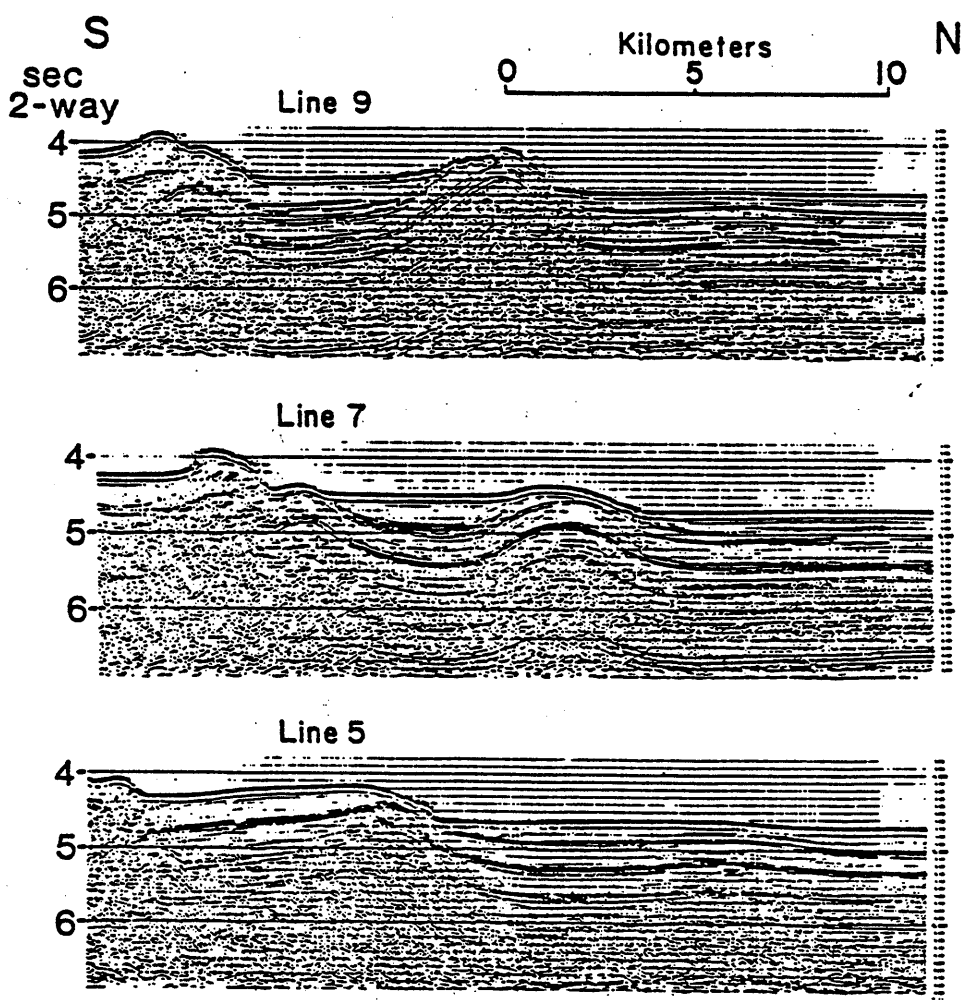
3) What is the history and origin of the mud volcanoes? Mud diapirs along the northern Colombian coast are known to originate in an overpressured Miocene mud. Are the north Panama mud volcanoes also from this layer? Are the mud volcanoes composed of mud flows, flows with entrained blocks, or are they built out of material that has settled out of water seeping from a central vent? How quickly do these mud volcanoes grow? These questions can be answered by drilling through the flanks of one of the mud volcanoes into the anticline below. This will determine the original stratigraphic level of the material, the structure of the mud volcanoes, and constrain the age of the mud volcanism. Mud volcanoes in the north Panama thrust belt generally are about 100m high, so a shallow holes is all that is necessary here. Drilling slightly deeper, into the underlying anticline, will allow us to determine the structural and depositional setting in which the mud volcano originated.

4) Are fluids and mud also extruded along faults? The SeaMARC II side-scan mosaic show high intensity reflections along traces, similar in character to the reflections from the mud volcanoes. Are these slumps, fault scarps, or composed of extruded material related to the mud volcanism? A shallow hole in one of these high reflectivity areas would distinguish between these possibilitites. Drilling (as opposed to dredging, for instance) at this site would allow us to determine the structure of the deposit, age of initiation, and the structural and depositional setting.

These seven holes, five of them quite shallow, would probably take only half a drilling leg.

Sites of proposed holes





10

Proposal To Study the Puerto Rico Trench: D. K. Larue, Dept of Geology, University of Puerto Rico, Mayaguez, P.R. 00708

There are two fundamental reasons for initiating studies of the Puerto Rico trench. First, the PR trench represents one of the type areas in the world for oblique subduction. Much more emphasis has been placed in the past by the ODP on areas of more normal accretion. However, it is clear that the geologic record contains considerable evidence that continental truncations and growth may be related to areas of oblique convergence (for example, the Mesozoic/Cenozoic tectonic history of the western North America). Although such fossil zones of oblique convergence are relatively common in the geologic record, there are few well-studied, active, oblique -convergence analogues to compare sedimentation, deformation, metamorphism (including diagenesis), and so forth.

Preliminary data on the PR trench suggest that an ODP investigation would be important for another reason. Several workers have proposed that the inner wall of the PR trench underwent massive subsidence in the post-Pliocene, possibly resulting from tectonic erosion. Therefore, the PR trench has additional "global significance" in that it is not only a poorly -studied zone of oblique subduction, but its inner wall also underwent massive tectonic subsidence relatively recently (about 4 km in 4 m.y.).

The PR trench is also a site of considerable regional Caribbean controversy. One of the major points of conflict about the trench is its age. Some workers have argued that the PR trench is a post-collisional feature, perhaps Eocene to Oligocene in age, whilst others argue the trench may be as young as Pliocene, and that the Greater Antilles were sutured to and part of the North American plate during the middle Tertiary. Ascribing whether the Greater Antilles was part of the North American or Caribbean plate during the middle Tertiary has considerable implications for reconstructions of the plate evolution of the Caribbean.

In the above I have attempted to show why the PR trench is important in global and regional perspectives. Now I would like to point out some of the interesting features about the trench area that are still poorly understood. First of all, the actual plate boundary between the Caribbean and North America in the PR trench is poorly defined. There are several potential areas where the deformation front of the PR trench could be placed. Furthermore, tectono-lithologic and geomorphic elements of the PR trench are not particularly well assigned. For example, some workers have attributed the Main Ridge of the inner wall of the PR trench to be an accreted fragment of the once continuous Barracuda Ridge, that may extend beneath the Lesser Antilles subduction zone, below the Caribbean plate, and "daylight" on the North American plate northwest of the island of Puerto Rico. hat is, large features of the inner wall of the PR trench are of unknown significance, are poorly ated, and cannot be tied with a unique or well-constrained tectonic model. Similarly, active eformation features of the PR trench are poorly studied, and the affect of oblique subduction on he orientation of structural elements and deformation processes has not been addressed. Moreover, he ages of sediments in ponds in the trench area are also poorly constrained in age.

In summary, the Puerto Rico trench represents an ideal location to study the geology of a subduction zone characterized by oblique underthrusting accompanied by tectonic subsidence. The PR trench is also unusual in a more geopolitical sense in that there is an abundance of seismic reflection data onland and offshore of Puerto Rico, and plans are being made for a 10,000 ft hole to be drilled and cored onland Puerto Rico that will cut through the entire middle Tertiary to Holocene section. That is, ODP drilling would be augmented by studies currently being undertaken onland Puerto Rico.

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11 RECOMMENDATIONS FOR CARIBBEAN DEEP-SEA DRILLING OBJECTIVES/SITES

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Three areas are recommended, with different rationales.

Area 1: Yucatan abyssal plain. Although fan-like magnetic anomalies are known in this area, and have been interpreted in terms of age, in reality there is no hard age evidence for this basin. Several entirely different tectonic hypotheses have been presented for its origin. These include 1) back-arc spreading 2) 'Bay of Biscay'-type rifting 3) fragmentation from the main Caribbean plate. Drilling here should avoid the ENE Cayman structural ridges which extend into mid-basin. The optimum location for drilling site 1 is near 20N, 085W. Objectives at this site, in addition to establishing the age and thereby restricting the speculation on the tectonic evolution, should include determining the latitude of origin paleomagnetically. An associated seismic survey should attempt to determine the anisotropy of Vp of the uppermost mantle here, to allow comparisons with other regions of fanning or radiating magnetic anomaly patterns as in the Cocos plate, the Bay of Biscay, and the central west Pacific; all are areas with which this target has similarities.

Area 2: Cayman trough. As this is possibly the world's shortest ocean basin, and probably also the one with the highest breadth to length ratio, it merits study for its similarities and uniqueness in relation to other areas of oceanic crust of similar age. Unfortunately, its age is poorly controlled. Symmetric magnetic anomalies about the mid-Cayman spreading ridge extend for only a few m.y. across the middle quarter of the basin. Much speculation attends its age of formation, which can be best settled by drilling into the oldest crust, which presumably lies at either end of the trough. The west end is evidently structurally more simple, but has a thick sedimentary cover. Providing that this cover can be penetrated a site 2a should be drilled near 17.3N, 086W. Otherwise, a site 2b should be drilled near the east end of the trough in a structurally less complex but probably younger crust, or a site 2c could be risked in possibly older but also structurally more complex setting (site 2b 19N, 078W; site 2c 19N, 076W).

Area 3: Southeast Venezuelan basin. This area of the abyssal plain is most like other oceanic crust, and therefore unusual in the Caribbean main basin. It has relatively thin crust, with rough 'basement' relief, and great depth. It appears to be old, more or less normal, oceanic crust. Evidently it is not covered by the Caribbean 'flood basalt' of Late Cretaceous age which characterizes so much of the Venezuelan, and Colombian basins. Is this crust a window of older crust which was not covered by the 'flood basalt', or is it a region of older or younger crust attached to the main Caribbean crust after the 'flood' event? Site 3 near 14N, 067W could possibly reveal much about early Caribbean crustal history. Relating this to global processes, except perhaps for a better understanding of the 'flood' basalt event, is more a challenge than is the case for other Caribbean sites.

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12 New deepsea drilling in the Caribbean.

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The Caribbean has been an area of oceanic seafloor accretion , active margin processes , and mountain building since probably late or middle Jurassic times . Parts of this geological history are now exposed in the deformed belt and island arcs fringing the Caribbean seas . They have been studied for several years by Caribbean , North American and European scientists. Part of the answers to fundamental questions still remains below the sea which explains why extensive geophysical surveys (seismic reflection mainly , and more recently Seabeam mapping and heat flow measurements) have been carried out for about 15 years.

The Caribbean is also a place where present major tectonic , volcanic , and sedimentary processes are taking place ; they include fore arc accretion and magmatic activity along island arcs and active continental margins , crustal extension and rifting with related rapid basin subsidence and oceanic floor accretion in predominantly strike-slip regimes , intensive sedimentary supply from major deltas such as the Orinoco and the Magdalena rivers.

The Caribbean thus appears as a place where major geological processes have been or are still taking place . If some of them can be studied with conventional field or marine surveys , others need deep seimic drilling for direct basement or sediment sampling as well as downhole measurments. We propose 3 topics for new deepsea drilling. They are not only relevant to Caribbean geology , but they also deal with problems of worldwide interest which are especially well documented in the Caribbean.

FOREARC ACCRETION , RELATED SEDIMENT DEWATERING AND FLUID MIGRATIONS : THE NORTHERN BARBADOS TRANSECT.

DSDP Leg 78-A and ODP Leg 110 on the northern Barbados transect have brought a large amount of new data about tectonic and hydrogeological processes occurring at the front of an accretionary prism. The Barbados Ridge thus appear as one of the best documented forearcs ever drilled and is now considered as a reference . The section investigated by drillings however is just 25 km long and can be compared with the width of the accretionary complex which is about 150 km here. Moreover the deepest hole did not exceed 700 m when the prism rapidly thickens to several thousand meters a few 10 km west of the front. Obviously new drilling is necessary for a complete understanding of the tectonic development of the prism. A second major objective of drilling would be to make in-situ permeabiliy, fluid flow and temperature measurements in order to improve the hydrological models developped during ODP Leg 110.

(12-1-1) The northern Barbados transect is particularly well located for new drilling since : 1/ The water-depth is not to great which allows good to moderatly good preservation of microfauna ; 2/ The fine-grained sedimentary facies (mainly mudstones and claystones) lead to excellent core recovery . These two points are essential to any structural interpretation of the cores. The whole Barbados Ridge is furthermore well covered by multi-channel seismic surveys (including deep seimic profiles), Seabeam and Gloria sea-bottom mapping , and superficial heat flow measurments.

THE EARLY STAGES OF TRANSFORM MARGIN DEVELOPMENT : THE CAYMAN TROUGH .

Whereas several legs of the DSDP and ODP programs have been devoted to passive and active continental margins studies , very little attention has been paid to continental margins which develop in a predominantly transcurrent regime. Such margins are well known in the equatorial Atlantic . They are, however, in a late stage of passive subsidence since they were formed in Cretaceous times . An siutable understanding of the initial tectonic and thermal processes controlling the (rapid) subsidence of such margins required investigating a young oceanic basin whose margins are undoubtedly controlled by transcurrent faults . One of the best exemples in the World is perhaps the Cayman Trough which is floored by oceanic crust of (poorly dated) Oligocene to recent age . This deep basin is more than 1000 km long for with width not exceeding 150 km. Its average water-depth is about 5000 meters with a maximun of almost 7000 meters at the foot of one of the boundary faults. Present displacement along these faults (the Oriente and Swan faults mainly) is attested to by their seismic activity.

Deepsea drilling is necessary to date the oceanic floor of the basin; this in turn will reveal the rate of oceanic accretion as well as the rate of tectonic and/or thermic subsidence of the margins. Additional objectives would be : 1/ in situ measurment of heat flows in different part of the basin ; 2/ the presence or (12-2-1) not of hydrothermal activity close to the main boundary faults ; 3/ the distribution of sedimentary facies in the basin ; 4/ the (12-2-2) age of block faulting and tilting on its southern edge (Nicaraguan Rise).

JURASSIC AND EARLY CRETACEOUS PALEOGEOGRAPHY.

The kinematic of plate motion is relatively well known in the Atlantic area since about middle cretaceous time . In the Caribbean , the oldest sediments so far drilled are of Turonian age . Little is known however about the paleogeography of the Pacific and the Tethys in Jurassic and early Cretaceous times . In the western Alps rifting occurred in early to middle Jurassic times and led to oceanic accretion in the late Jurassic . In the Pacific , a Jurassic oceanic crust is presumed to be present below the thick lava flows of Cretaceous age in the Nauru basin . One or several links could have occurred between the Pacific and Tethian Oceans through the Caribbean and the Gulf of Mexico .Two deep drilling sites are proposed in the Caribbean to document these early stage of plate motions .

The first location would be in the Venezuelan Basin with the purpose of drilling below reflector B" (lava flows of late (12-3-1) Cretaceous age) where discontinuous and subhorizontal reflectors could represent volcanic flows similar (and related ?) to the Cretaceous lavas in the Nauru Basin .

The second location would be northeast of the Demerara Rise (Guyana Margin) where Upper Jurassic and/or early Cretaceous (12-3-2) oceanic crust and related continental margin deposits are believed to occur .

13 STRUCTURAL AND HYDROGEOLOGIC STUDIES OF THE NORTHERN BARBADOS RIDGE

By J. Casey Moore and Alan Mascle

Topical Perspective

Studies of the structural, geophysical, geochemical, diagenetic, and biological phenomena have recently provided startling insights into processes of fluid flow in accretionary prisms. These investigations show that fluids are instrumental in controlling overthrusting and wedge geometry, in establishing the temperature regimes, and in controlling the movement of material, both as solutes as muddy slurries. Submersible studies indicate that shallow cementation radically alters the physical properties (including permeability) of the prism while deeply sourced fluids support biological oases that have fundamental implications for paleoecological interpretation.

Hydrogeological regimes of accretionary prisms can be subdivided into at least two end-members: 1) those dominated by fine-grained inherently impermeable sediments, usually in relatively sediment-starved environments, and 2) those characterized by thicker turbidite sequences with localized layers of higher primary permeability. Both need to be investigated to evaluate the hydrogeologic complexity of accretionary prisms. The Barbados Ridge provides an appealing natural laboratory for the analysis of these contrasting environments. This proposal addresses continuing structural and hydrogeologic study of the Northern Barbados Ridge; hopefully, it will be complemented by a similar proposal across the Southern Barbados Ridge. Investigation of the structural and hydrogeologic evolution of the Barbados Ridge follows the one of the highest topical recommendations of the second Conference On Scientific Ocean Drilling (COSOD II).

Regional Background

Penetrations near the deformation front of the Northern Barbados Ridge have comprised some of the most successful scientific drilling at any convergent margin. Significant accomplishments include: 1) characterization of the decollement zone and underlying sediments, 2) definition of fluid flow paths through and below the accretionary prism, and 3) documentation of up-slope structural evolution, encompassing out-of-sequence thrusting and development of melange-style fabrics. Fluid compositions indicate the presence of two fluid regimes separated by the top of the decollement zone. Isotopic composition of methane from the decollement zone indicates it taps deeply sourced fluids.

Successful drilling in the Northern Barbados Ridge area resulted from the presence of relatively thin, dominantly fine-grained sediments, moderate water depths, and excellent biostratigraphic resolution. These conditions are duplicated at few other localities, which, with the considerable background of drilling and site surveys, argues for additional penetrations in this area. Although, the drilling during Leg 110 was notably successful in defining the geology, down-hole tools functioned poorly. Emphasis in future drilling should be directed towards determination of in-situ physical and hydrogeologic conditions in order to better understand the geologic features developing in the cores.

Proposal

Future drilling across the Northern Barbados Ridge should be focused away from the immediate region of the deformation front, because this area has been relatively well explored and penetrations here are more difficult owing to the slightly lithified condition of the sediments. The four proposed sites consist of two located moderately up slope but still capable of reaching the decollement and two further westward designed to investigate the continuing evolution of the accretionary prism. The specific sites (located on Figures 1 & 2) are:

NBR 1) At the position of Leg 110 Site 671, this hole is designed to re-penetrate the decollement to the permeable sand layer in the underthrust sequence, and if possible continue to the oceanic crust. First priority would be given to development of a profile of physical and hydrogeologic conditions including temperature, fluid pressure, permeability, and fluid-flow rate. Since the geology is well established from Site 671 to 700 m sub-bottom, coring would only be required for the basal 250 m of the hole.

NBR 2) Located nine km west of the deformation front and 900 m above the decollement, NBR 2 is designed to provide a second sampling of conditions along the decollement surface and perhaps penetrate into the underthrust sequence. Principal goals will be definition of the structural evolution of the decollement as well as making a series of geophysical, geochemical and hydrogeological tests along this surface to establish gradients in temperature, chemical anomalies, and fluid pressure relative to the penetration at NBR 1. These gradients when combined with permeability measurements will provide a regional measure of flow rate and establish a basis for reasonable estimates of heat and chemical fluxes along this prime dewatering conduit.

NBR 3) Drilling at this site is intended to penetrate the top of a potentially underplated sequence lying several hundred meters above the decollement surface. A hole here hopefully would define the structural characteristics of a recently emplaced duplex while providing a basis for evaluating the continuing structural and hydrogeologic evolution of the accretionary prism.

NBR 4) A 1 km penetration at this location, 20 km arcward of the deformation front, can potentially supply information on the continuing complicated structural development of the accretionary prism. At Site 674, 3 km seaward of NBR 4, drilling 450 m documented the development of melange-style structures, extensive thicknesses of scaly fabric, out-of-sequence thrusting, and widespread carbonate veining, all in rocks emplaced since 5 my ago and with porosities remaining at about 50%. NBR 4 would investigate the continuation of this relatively rapid evolution of a complex structural style with declining increments of porosity. A coupled set of hydrogeologic and pore-water chemistry studies is also proposed.

Downhole Experiments and Logging

A full suite of logs plus a number downhole tools would be utilized in each of the above holes. The down-hole experiments would initially be directed towards measurement of pore pressure, permeability, and flow rates. The availability of a packer and the borehole televiewer can provide the basis for measurement of the orientation and magnitude of stress. The Geoprobe Tool with its included packer, now under development by Dan Karig for use in the Western Pacific, could provide the above mentioned measurements. The intended time frame of Caribbean drilling would allow for one or two more development cycles for this tool and hopefully result in reliable measurements. The present availability of the "side-entry sub" would presumably permit logging in holes that closed off during Leg 110 ODP.

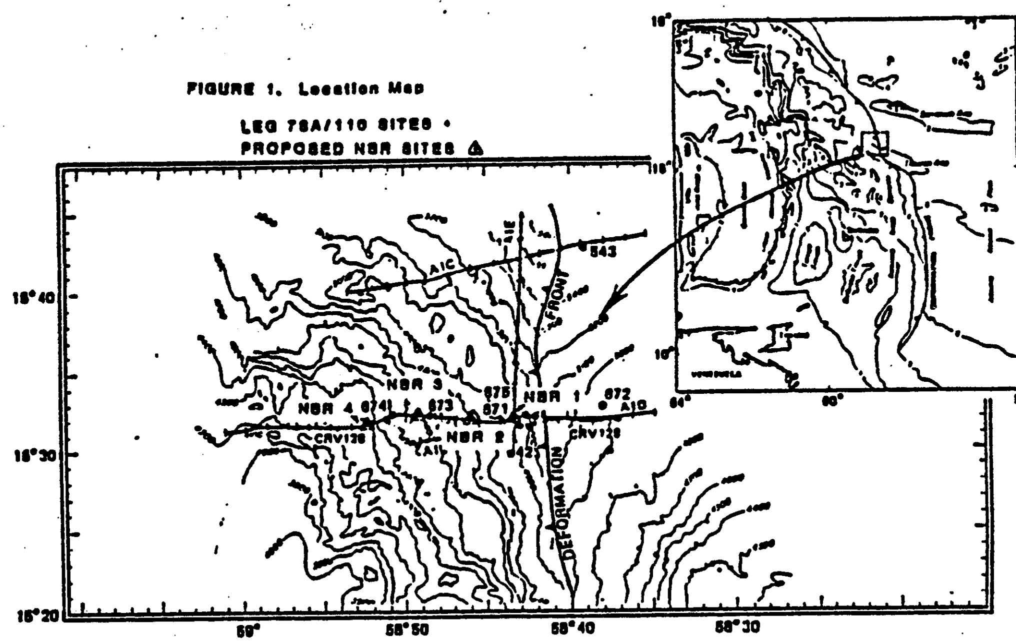

FIGURE 1. Location Map

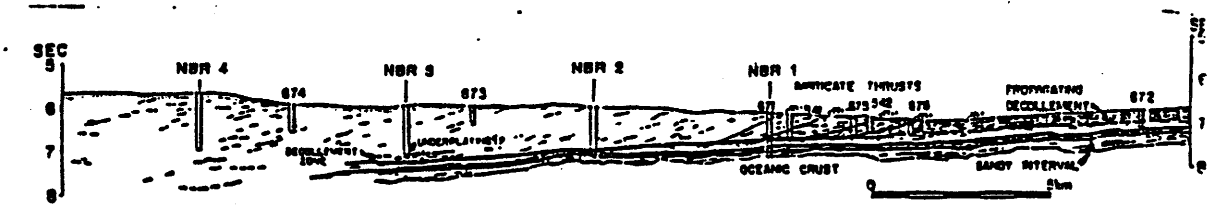

FIGURE 2. Proposed Drilling Sites NBR 1-4.

14 Frederick Nagle (University of Miami):

Two deep holes, one in the Venezuelan Basin and the other in the Colombian Basin, both below B". 14-1 14-2

15 ODP DRILLING SITE PROPOSAL: YUCATAN OR GRENADA BASINS

BY JAMES PINDELL

It is generally clear that the eastward-migrating Caribbean Plate, relative to the Americas, has entered the inter-American gap from the Pacific since the Late Cretaceous. A better understanding of this migration resides in studies that will (1) enhance our knowledge of the progressive rate of migration, and (2) help resolve the details of intra-Caribbean tectonic "developments" pertaining to Caribbean-American interactions during the migration. The first, progressive migration, can best be addressed from on-land stratigraphic studies of the timing of tectonic interaction between the autochthonous Proto-Caribbean continental margins, and the allochthonous, usually overthrust, oceanic/arc complexes of the Caribbean Plate, and thus is not greatly assisted by offshore drilling. The second, development of tectonic features associated with migration, includes such aspects as the formation of the Yucatan Basin, the Cayman Trough, the Grenada Basin, the Puerto Rico Trench, and the northern and southern Caribbean strike-slip plate boundary zones. Having developed by typical plate-boundary processes, studies of these features will also serve as examples for global tectonic processes. Of the areas mentioned, I favor drilling either or both the Yucatan and (15-1) (15-2) Grenada Basins, for the reasons below, and also for unstated reasons against the others. In the hope to augment other proposals that will likely address local and specific reasons to drill both these areas, my arguments for drilling either area are regional, helping to resolve Caribbean evolution and also to provide examples of an important tectonic process.

My proposal is based upon the assumption that the Caribbean Plate is of Pacific origin, having entered the inter-American gap between the Yucatan block and Colombia in the Late Cretaceous. In any such model, three possible modes of formation exist for both the Yucatan and Grenada Basins: (1) they are related to the original, probably Early Cretaceous formation of the Caribbean oceanic plate in the Pacific, (2) they are trapped remnants of Proto-Caribbean (Late Jurassic-medial Cretaceous) oceanic crust, and (3) they are intra- or back-arc basins formed DURING Caribbean evolution, but after plate-formation, by rifting within Caribbean island arcs. Assuming a Pacific origin for the Caribbean Plate, the map-view shapes of both the leading edge of the migrating Caribbean Plate and the margins of the pre-Cenozoic, Proto-Caribbean oceanic basin will play an important role in the tectonics of the entrance and subsequent migration. By the Late Cretaceous, the Proto-Caribbean Basin clearly had developed a stable configuration: the Yucatan block had become fixed to North America, and relative motions between North and South America had ceased. The western and southern margins of the basin were, respectively, the eastern Yucatan block and northern South America. The trends of these margins, respectively, were (and still are) north-northeast, and east. Thus, the entering Caribbean Plate first must have passed northeastward through a constriction between the Maya Mountain promontory of the Yucatan block and northwest Colombia, and subsequently must have migrated progressively into the northeastwardly-widening Proto-Caribbean oceanic basin.

Two results were possible. First, the crust of the Proto-Caribbean basin could have been progressively cut by two parallel transforms (railroad tracks)

- 1 -

to accomodate a northeastward-migrating Caribbean Plate that maintained the width of the Yucatan-Colombia constriction. This would produce an allochthonous Caribbean Plate amid oceanic crustal remnants of the Proto-Caribbean along the eastern Yucatan margin and/or northern South America. Second, the Caribbean Plate could have "expanded" to accomodate the northeastwardly-widening shape of the Proto-Caribbean Basin, so that all of this basin was subducted. As I shall outline in my address, the areas of expansion may be represented by the Yucatan and Grenada Basins, which may have developed by intra- or back-arc spreading (or intra-crust stretching) processes that occurred within the leading arc complex of the Caribbean Plate, between Maestrichtian and Middle Eocene time, as the Caribbean Plate filled the inter-American gap. Thus, Maestrichtian through medial Eocene ages from the basements of either basin would associate the basins with Caribbean-American plate interaction, rather than with either the Proto-Caribbean basin or the original creation of the Caribbean Plate. Most existing lines of evidence point to an early Paleogene age for development of the two basins.

The main objective from the perspective of Caribbean evolution for either site is to reach basement (or oldest sediments) and to determine the age and character. Maestrichtian through medial Eocene ages would indicate intra-arc spreading processes. Also, it would be hoped that sufficient seismic reflection, gravity and magnetic records be recorded during site evaluation to determine crustal and/or tectonic fabric (extension direction in either oceanic or attenuated arc crust). Existing data and some paleogeographic models favor directions of opening for the Yucatan and Grenada Basins of northwest and north-south, respectively.

Regarding tectonic process, if Maestrichtian through medial Eocene ages of basement are proved and the direction of extension can be determined, the mechanics and kinematics of the two intra-arc rifting events can then be determined. The results will provide examples of:

(1) the relationship of oblique arc-continent collision and intra-arc rifting and basin formation in the colliding arcs,

(2) the effects of transform drag and subduction pull upon arc complexes, showing that it is kinematically "easier" to initiate intra-arc rifting (warm, weaker rocks) than it is to create transform faults in previously-existing oceanic crust (Proto-Caribbean).

These results will have direct bearing on the tectonics of terrane formation, migration, dissection, and emplacement.

- 2 -

16 A Proposal for a Sequence of Drillholes in the Cayman Trough

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The Cayman Trough has long been recognized as a critical element of Caribbean reconstructions, particularly Tertiary reconstructions. The particular structure of the oceanic spreading axis within the Trough has prompted series of detailed near-bottom surveys of this axis to examine structure and lithology [e.g., CAYTROUGH, 1979; Stroup and Fox, 1981]. Current studies of the opening of the Trough suggest further that the history of this opening may have application to similar small ocean basins worldwide; that the history of this opening, particularly its thermal and tectonic history, may provide a generic model for all small ocean basins of similar type.

We propose to drill a series of six holes along the length of the Cayman Trough to further examine this opening history, and to test and refine current models of Trough evolution. The approximate locations of these proposed sites are shown in Figure 1. Each of the holes would be relatively shallow (< 1 km) but all would penetrate basement (Figures 2, 3). The primary objective of drilling at all sites is to establish basement age, the secondary objective to sample both basement and the overlying sedimentary section. At sites A and F, located respectively within the west and east rift margins (see Figure 1), the sedimentary sequence should yield information on the magnitude and timing of margin subsidence and extension. The age of rifting as determined at these two sites, compared with the age of oldest oceanic crust as determined at site E, should provide constraints on the duration of the rifting process. This will establish when the Cayman Trough originated as an extensional system, in contrast with when it evolved into an oceanic spreading system, currently estimated as 50 Ma (Middle Eocene) by Rosencrantz et al. [in press]. Sampling sediments at sites B, C D and E within the Trough will provide information on the type of, and rates of, pelagic sedimentation in the region. These samples will also provide information the extent and type of hydrothermal circulation at very slow spreading axes.. An additional objective for hole B in the western Trough includes dating the first influx of clastic sediments from the west.

This direct sampling and dating of basement and overlying sedimentary sequence within the Cayman Trough has the following major applications:

1. *Certification of the magnetic anomaly sequence:* Macdonald and Holcombe [1978] and Rosencrantz et al. [in press] each have analysed marine magnetic anomalies within the Cayman Trough, and have reached distinctly different conclusions. Macdonald and Holcombe [1978] say that magnetic anomalies show that the Trough opened at a rate of about 20 mm/yr since 2.4 Ma, and at 40 mm/yr between 8.5 and 2.4 Ma They argue that magnetic anomalies older than 8.5 Ma (anomaly 4A; Late Miocene) cannot be reliably identified. Rosencrantz et al. [in press], on the other hand, argue that recognizable anomalies are present back to anomaly 20 (Middle Eocene). The sequence of anomalies indicate that the Trough opened at about 30 mm/yr between the time of Trough opening, estimated at between 45 and 50 Ma (Middle Eocene), and 30 Ma (Late Oligocene), and at 15 mm/yr between 30 Ma and the present. Direct measurement of crustal age will resolve the difference between the two models, and the implied differences in Caribbean plate position through the Tertiary.

The importance of an accurate interpretation of Cayman Trough opening history to reconstructions of Caribbean history cannot be overemphasized. Because the Trough contains a spreading center which has opened continuously since Eocene time and has generated marine magnetic anomalies [Rosencrantz et al., in press], its opening history, described in terms of magnitude, rate and direction of opening, provide information essential to tracking the motion of the Caribbean plate. This history applies not just to relative motion between the adjacent North American Plate, or to the age, duration and style of Eocene and younger tectonic events mapped along the northern plate boundary. It also applies to the South American-Caribbean plate boundary, because North American motion relative to South America may be resolved through their respective motions relative to Africa. Precise reconstructions of the Cayman pre-rift (Early-Middle Eocene) positions of the North American, South American and Caribbean plates will provide a solid base from which to work backward through the complexities of Late Cretaceous Caribbean evolution.

2.) *Mechanics and timing of the rifting sequence* : In terms of tectonic structure and bathymetry, the Cayman Trough is relatively simple, consisting of bounding transform faults connected by a spreading axis. The western rift margin is currently buried beneath sediment, but may be mapped with seismic reflection data. The eastern margin is relatively free of sediment (Figure 3), and its structure can be mapped with SEABEAM or a side-scan system. (The current French Caribbean survey - SeaCaribe II - will in fact map part of this margin during November and December of 1987.) Consequently, it is already possible to match the structure of these conjugate rift margins exactly. The results of drilling at site F, within the eastern rift margin, compared to the age of oldest ocenic crust obtained by drilling at site E, should tell us a great deal about the evolution and timing of this rifting, particularly about its duration. Differences in crustal subsidence and deposition within the eastern (site F) and western (site A) rift magins may provide estimates of rifting asymmetry. Basement samples collected from these two sites may be correlated to samples of equivalent age in Guatemala and Jamaica This would provide a better view of prerift paleogeography across the region. If the Cayman Trough initially evolved as a pull-apart basin, then these sites will provide important information on the evolution of this type of tectonic structure.

3. *The thermal evolution small isolated ocean basins:* Within the Cayman Trough, basement depths are greater and crustal heat flow is colder than predicted by subsidence-age and heat flow-age relationships for typical crust within large ocean basins [CAYTROUGH, 1979; Rosencrantz and Sclater, 1986; Rosencrantz et al., in press]. Both are consistent, however, with a crustal cooling model which accomodates lateral as well as vertical heat loss from the accreting lithospheric slab [Boerner and Sclater, 1987; Rosencrantz et al., 1987]. This model expresses crustal subsidence and heat flow as functions of slab age and width. Sampled crustal ages, combined with existing bathymetric and seismic reflection information and new precise heat flow surveys, will directly test the validity of this analytical model, which has wide application to small, isolated ocean basins worldwide.

4.) *Sedimentation rates:* Sediments within the eastern Cayman Trough drape the underlying basement. These are apparently (wholly?) pelagic in origin. Sampling these sediments at sites C, D and E could provide a baseline measurement of the pelagic contribution to deposition throughout the region. These results could be compared to results of upcoming projects to investigate carbonate sedimentation on the adjacent Nicaragua Rise [A. Droxler; Rice University; A. Hine, University of Southern Florida]. Sediments in the western Trough, on the other hand, consist predominantly of clastics, with an apparent western (Central American) source. These clastic units extend into the Yucatan basin to the north. Consequently, dating this sequence has implications for depositional processes within the region as a whole.

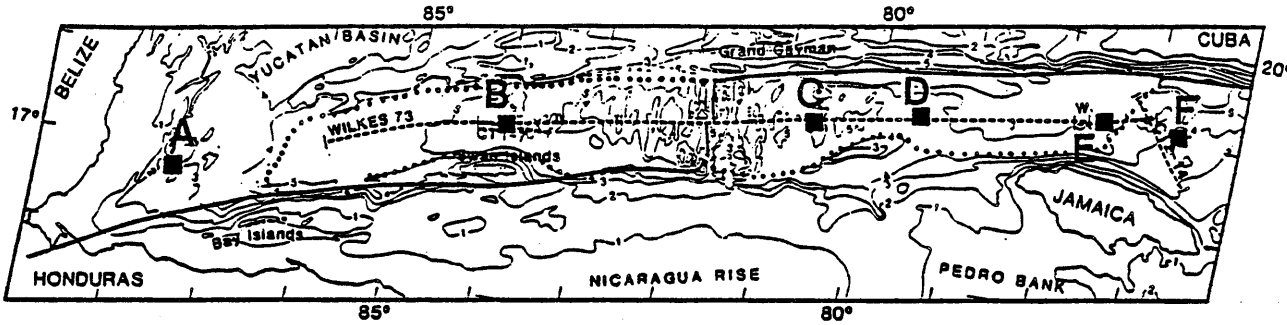

Figure 1: Approximate locations of proposed drill sites, A through F, shown as filled squares. The locations of seismic profiles shown in Figures 2 and 3 are marked as dashed lines. The heavy solid line marks the position of the present plate boundary, and the dotted line outlines the approximate extent of oceanic crust. This and the following two figures are adapted from Rosencrantz et al., 1987.

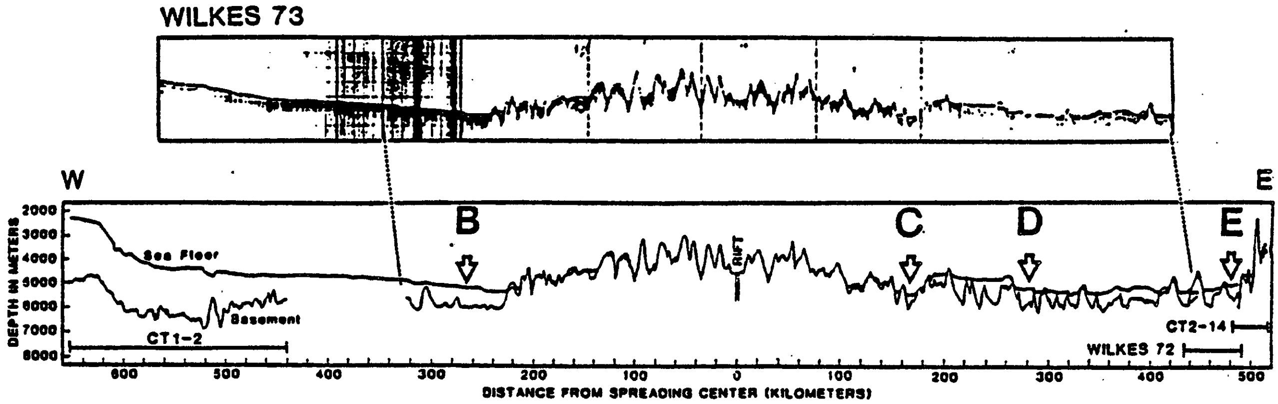

Figure 2: Simplified profile of the Cayman Trough with the approximate locations of proposed drill sites superimposed. This profile is largely based upon the Wilkes 73 single channel seismic reflection profile shown at top [Holcombe et al., 1973].

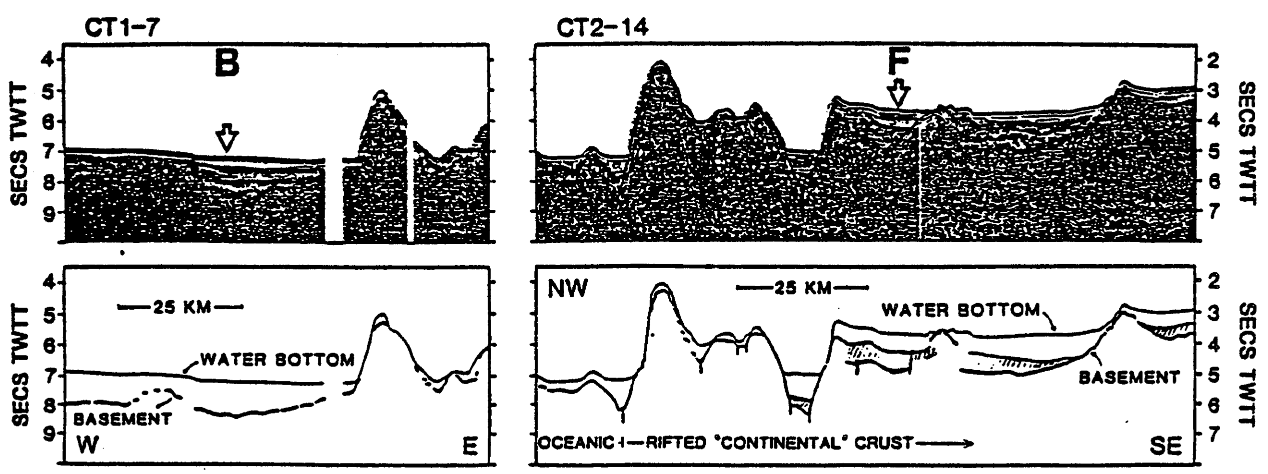

Figure 3: University of Texas Institute for Geophysics multichannel seismic profiles from the western Cayman Trough (CT1-7) and eastern rift margin (CT2-14), with proposed drill sites B and F superimposed. The line drawing beneath each profile is a simplified structural interpretation. The unit shown as hachured in profile CT2-14 is interpreted to represent synrift sediments.

17

Caribbean drilling possibilities and priorities

J.B. Saunders, Basel, 1987

We have to justify drilling in the Caribbean by identifying problems of global interest that can either a) only be tackled in the region or at least b) can best be tackled in the region.

Certain areas and problems, though of extreme interest in their own right, and of importance to an understanding of the region, nevertheless may fail because they do not get the necessary widespread support within the framework of the present JOIDES panels and with the COSOD type of scientific structuring.

With that in mind, and looking at some ot the major scientific questions still to be answered, we have:

1) <u>The crust of the Caribbean basins</u> (17-1-1) and the <u>Yucatan basin</u> (17-1-2) to determine:
a) age of first sedimentation on the newly formed crust
b) geographical position of the plates at that time
c) history of development up to the time of final accretion of crustal material.

2) <u>Early history of enclosed basins</u> to determine:
a) type of sedimentation in early rift basins
b) position of these basins at that time in relation to major continental masses
c) presence of oxygen depleted waters and deposition of organic rich sediments
d) possible deposition pf evaporites.

<u>Question</u>: can we learn things from these particular basins that can be of value elsewhere?

3) <u>Comparison of sequences in basins and on intervening ridges</u> (17-3-1)
a) to make a close comparison of the sediments in equivalent time slices in both situations particularly:
b) to determine the cause of unconformities in the deep ocean. Non-deposition? dissolution? erosion?

<u>Question</u>: is there anything that makes the Caribbean particularly able to give information that can be widely applied?

4) An increased refinement of <u>the time of closure of the equatorial connection between Pacific and Atlantic</u> at both deep and shallow water levels

<u>Question</u>: what reason can we give for improving the dating of this event beyond what we know today?

5) <u>Drilling on the West Indian Volcanic Arc</u> (17-5-1)

<u>Question</u>: can we develop a programme of drilling on or in the neighbourhood of the volcanic arc that will give us information of wide applicability and not jsut throw light on the development of this particular arc?
For instance, can we use the W.I. situation to document the complete development of a back-arc basin? Is the W.I. situation particularly suitable for such a study? Perhaps its relatively simple history and the availability of good evidence from the present sub-aerial volcanic chain.

6) An investigation of <u>the effects of shale diapirism</u> in the tectonic development of sedimentary piles (accretionary prisms, thick deltaic sequences).

Land and marine studies in a number of tectonically active areas around the World are highlighting the importance of shale diapirism either in the past or in on-going movements. One area that is particularly well known now is the West Indian accretionary prism and the areas of heavy sedimentation between it and the South American continent.

<u>Question</u>: can we develop a programme that can be carried out in this area and is designed to answer more general questions by extrapolation to other presently active areas (Makran, East Indies) and also to fossil situations preserved on the continents?

PRIORITIES

<u>Priority 1</u>:
I would rate as first priority the drilling of one or more deep crustal holes in the basins if we can show:
a) reasonable hopes of succeeding in penetrating deeply enough into the pre B" volcani-clastic (?) series to prove the provenance of the Caribbena crustal plate.
b) if we can chart the history of development of the uppermost crustal layers in a small ocean basin with anomalously thick crust.

This project has to be proposed in the wider context of the Mesozoic development of 'western Tethys' and the N-S opening of the equatorial Atlantic with all the concomitant oceanic connections.

Sites have already been proposed based on French survey work and CAR 4 is still a possibility, though it may be necessary to plan two sites - CAR 3 and CAR 4 - as the French have done in order to understand the varying nature of the basement of the Venezuela Basin.

<u>Priority 2</u>:
Sites to be identified to study <u>shale diapirism</u> associated with the West Indian accretionary prism. This is a proposal by Bernard Biju-Duval with which I strongly agree. French and British records of mud/shale diapirs are now good enough to make this a viable proposition and new testing methods can be visualised (packers for pressure testing and logs for measuring stress fields, for instance).

<u>Other Priorities</u>:
I would prefer to identify these at the meeting. I believe they will include:

Investigation of Mesozoic organic-rich sequences in the Venezuela Basin. The particular value to stress here will have to be correlation with onshore black shales and limestones in Trinidad, Venezuela, Colombia and other circum-Caribbean countries. We must investigate at the meeting whether significant new information can be expected after the many studies already published on the subject.

We could also look at a study of the Eocene/Paleocene cherts and siliceous oozes (Horizon A"). This would depend on the availability of coring tools able to obtain adequate material under these difficult conditions.

Perhaps we can also work up something on late Neogene sedimentary patterns linked to climatic changes and the consequent changing influx from the surrounding landmasses.

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18 S. O. Schlanger: Drilling in the Western Venezuelan Basin at Site CAR-4

Objectives: 1) Age and Origin of the Caribbean plate

2) Atlantic-Pacific Paleoceanographic Connections

Introduction and Background: Mattson (1969) first proposed that the Caribbean was a detached relic of the Darwin Rise, the latter being the name given by H.W. Menard (1964) to a large, paleobathymetric high, on what is now the Pacific plate, caused by the effusion of huge volumes of volcanic rock during Mesozoic time. Since the 1960's two drilling programs, one in the Nauru Basin (Legs 61 and 89; see Larson and Schlanger et al., 1978, and Moberly and Schlanger et al., 1986) and a second in the Caribbean (Leg 15, Saunders et al., 1973) have revealed in both regions the presence of thick sections of Cretaceous basalt showing gross similarities. These results have led a number of workers to argue, following Mattson's idea, that the Venezuelan Basin in particular is actually an abandoned piece of the Farallon plate, or another part of the ancestral Pacific.

Pacific Data Related to the Venezuelan Basin: Figure 1 (upper) shows the composite section drilled on Legs 61 and 89 in the Nauru Basin at Site 462. Figure 1 (lower) shows the interpretation of the seismic stratigraphy, based on drilling results, of Site 462. From ~560 m sub-bottom depth to at least 1209 m a section of sills (?) and sheet flows of a composition between normal MORB and transitional basalt (Batiza et al., 1980) lies below a Pleistocene to mid-Cretaceous sediment cover. The upper part of the basalt section contains numerous intercalations of largely volcanogenic siltstone; deeper in the basalt complex thin streaks of sparsely fossiliferous bathyal sediments of Aptian age occur. The igneous history of the Nauru Basin (Schlanger and Moberly, 1986) shows volcanic events, of post-plate formation age (~Oxfordian), at ~130 Ma, ~100-110 Ma, and ~75 Ma. Drilling results in the Caribbean indicate a potentially similar volcanic section. Recent MCS surveys across the Nauru Basin (cruise of N/O Charcot, Spring 1987) show that the actual thickness of the Cretaceous volcanic section may reach 3 km. Surveys of the CAR-4 site show approximately 700 m of Cretaceous basalt sills (?)

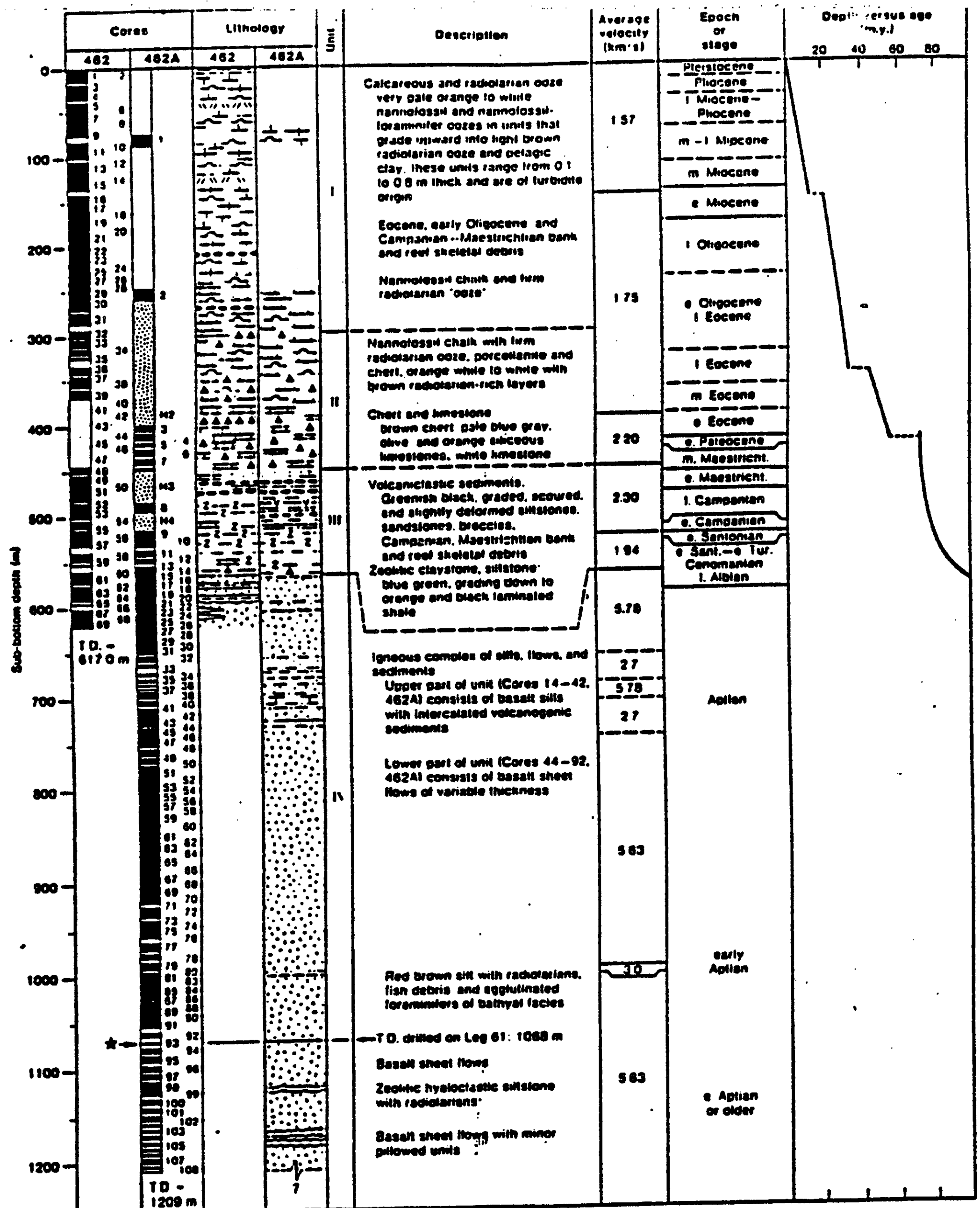
and flows. Therefore, one could argue that at CAR-4 these eruptions were farther from the eruptive centers than were the Nauru Basin volcanics. However, the sequence and timing of the volcanic events may be preserved in the western Venezuelan Basin.

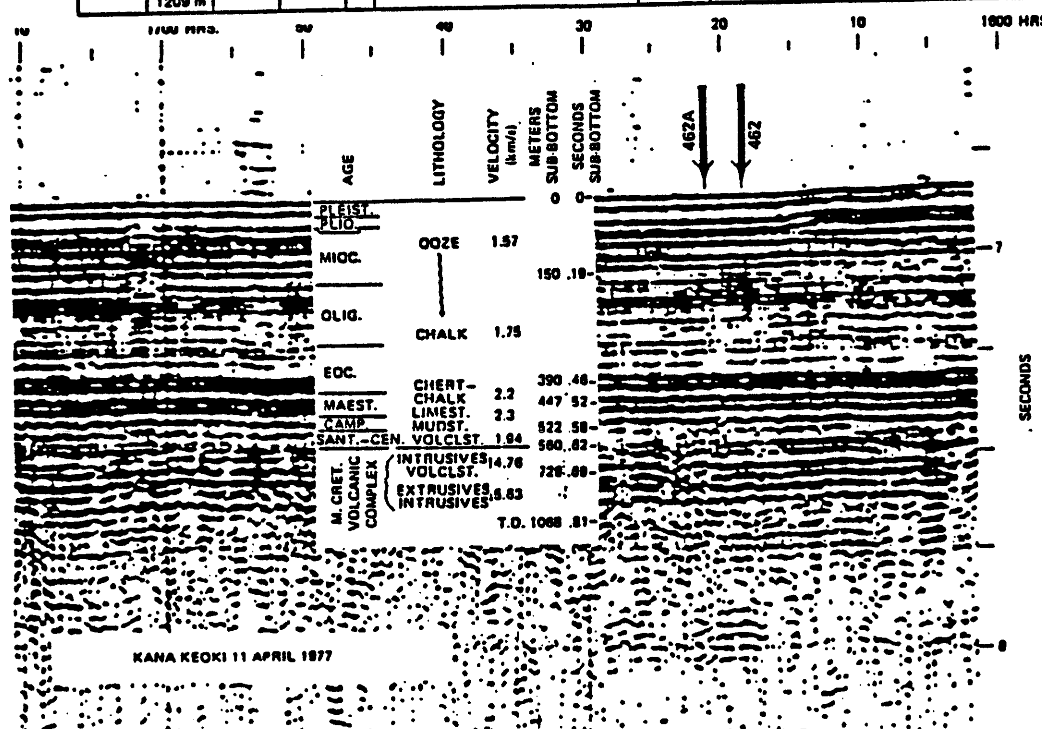
Further support for the idea that the Venezuelan Basin had Pacific oceanographic connections lies in the distribution from the Caribbean, through island "stepping stones" in the Line Islands and the Nauru Basin, to as far west as Papua, New Guinea of the Late Cretaceous (Campanian-Maestrichtian) *pseudorbitoid* (large benthic shallow-water foraminifera) fauna described by Premoli-Silva and Brusa (1978).

CAR-4 Drilling and Implications: In order to test the arguments behind the objectives stated above, a deep, continuously cored and logged hole at CAR-4 that will definitively penetrate the Cretaceous volcanic complex and characterise the presumed "igneous" basement (see Figure 2 of the Caribbean Working Group Report of Sept. 5, 1985) is needed. An entire Leg will be needed to accomplish this kind of penetration, coring and logging.

The data obtained on: 1) the timing, extrusion mechanisms and petrochemistry of the Caribbean volcanic sequence, 2) lithology and derivation of the associated and overlying sediments, and 3) the Caribbean-Pacific faunal affinities will allow us not only to test the hypothesis that the Venezuelan Basin is a piece of the ancestral Pacific, probably a fragment of the Farallon plate, but will provide valuable information on the extent of mid-plate volcanism during the Cretaceous (which is emerging as a global phenomenon) and the mechanisms involved in such voluminous off-ridge (?) volcanism. Faunistic comparisons and the comparative study of the sedimentary sections will reveal the history of Atlantic-Pacific connections in terms of paleocirculation and paleoclimatic histories.

Thus, the implications of successful drilling at CAR-4 transcend simply regional problems but are potentially global in nature (see also the Caribbean Working Group Report of Sept. 5, 1984).


Cores
462
462A
Lithology
462
462A
Unit
Description
Average velocity (km/s)
Epoch or stage
Depth versus age (m.y.)
20 40 60 80
Sub-bottom depth (m)
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
T.D. = 617.0 m
T.D. = 1209 m
I
II
III
IV
Calcareous and radiolarian ooze very pale orange to white nannofossil and nannofossil-foraminifer oozes in units that grade upward into light brown radiolarian ooze and pelagic clay. These units range from 0.1 to 0.8 m thick and are of turbidite origin
Eocene, early Oligocene and Campanian–Maestrichtian bank and reef skeletal debris
Nannofossil chalk and firm radiolarian "ooze"
Nannofossil chalk with firm radiolarian ooze, porcellanite and chert, orange white to white with brown radiolarian-rich layers
Chert and limestone brown chert pale blue gray, olive and orange siliceous limestones, white limestone
Volcaniclastic sediments. Greenish black, graded, scoured, and slightly deformed siltstones, sandstones, breccias. Campanian, Maestrichtian bank and reef skeletal debris
Zeolitic claystone, siltstone: blue green, grading down to orange and black laminated shale
Igneous complex of sills, flows, and sediments
Upper part of unit (Cores 14–42, 462A) consists of basalt sills with intercalated volcanogenic sediments
Lower part of unit (Cores 44–92, 462A) consists of basalt sheet flows of variable thickness
Red brown silt with radiolarians, fish debris and agglutinated foraminifers of bathyal facies
T.D. drilled on Leg 61: 1068 m
Basalt sheet flows
Zeolitic hyaloclastic siltstone with radiolarians
Basalt sheet flows with minor pillowed units
1.57
1.75
2.20
2.30
1.94
5.78
2.7
5.78
2.7
5.63
3.0
5.63
Pleistocene
Pliocene
l. Miocene–Pliocene
m–l Miocene
m Miocene
e. Miocene
l. Oligocene
e. Oligocene l. Eocene
l. Eocene
m. Eocene
e. Eocene
e. Paleocene
m. Maestricht.
e. Maestricht.
l. Campanian
e. Campanian
e. Santonian
e. Sant.–e. Tur. Cenomanian l. Albian
Aptian
early Aptian
e. Aptian or older


1700 HRS.
40
30
20
10
1600 HRS.
AGE
LITHOLOGY
VELOCITY (km/s)
METERS SUB-BOTTOM
SECONDS SUB-BOTTOM
462A
462
PLEIST.
PLIO.
MIOC.
OLIG.
EOC.
MAEST.
CAMP.
SANT.-CEN.
M. CRET. VOLCANIC COMPLEX
OOZE 1.57
CHALK 1.75
CHERT-CHALK 2.2
LIMEST. 2.3
MUDST.
VOLCLST. 1.94
INTRUSIVES 4.78
VOLCLST.
EXTRUSIVES 5.63
INTRUSIVES
0 0
150 .19
390 .46
447 .52
522 .58
560 .62
726 .69
T.D. 1068 .81
7
8
SECONDS
KANA KEOKI 11 APRIL 1977

19

PALEOECOLOGICAL AND NEOTECTONIC STUDY OF CARIACO BASIN, CENTRAL-EASTERN VENEZUELAN CONTINENTAL SHELF

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The Cariaco basin extends for over 200 km in an east-west direction, south of Tortuga island, and has a widt of up to 70 km (see Schubert, 1982, for details). It is bounded by the Morón fault zone in the north and by the El Pilar fault zone in the south (Fig. 1), and its origin has been attributed to right-lateral strike-slip movement on these faults, forming a pull-apart basin in the area of the right stepover in the Morón-El Pilar fault system. This anoxic basin consists of two deeps which reach depths of slightly over 1400 m. A few seismic reflection profiles have been obtained across the basin (Fig. 2), which show that these deeps are filled with a thick sedimentary sequence (at least 1 km), which was partially drilled during Leg 15 (Site 147) of the D. S. D. P., and a continuous core, 162 m in length, was obtained. A study of planktonic foraminifera (Rögl & Bolli, 1973) suggested that the bottom of the core is located within Zone V, and the whole core represents the interval between Zones V and Z of Ericson & Wollin. An extrapolation of sedimentary rates and two absolute ages suggest that the core spans the last 320,000 years.

It is here proposed that another core be obtained through at least the Quaternary section, in order to determine: 1. The paleoecologic evolution of this area of the southern Caribbean during the Quaternary, through the study of planktonic foraminifera and other organisms, and fossil pollen (these studies will be undertaken by the appropriate specialists). This study will be a major contribution to understanding the paleoclimatological evolution of this part of northern South America and the southern Caribbean, during glacial-interglacial times, a much debated subject at present. 2. Sedimentary analyses, combined with the results of 1. should provide a basis to determine when the pull-apart basin began forming and, thus, how much offset has occurred along the Morón-El Pilar fault system, and how old it is. This, in turn, should provide quantitative constraints on the neotectonics of this region.

and their climatic interpretation: Init. Rep. Deep Sea Dril. Proj., XV: 553-615.

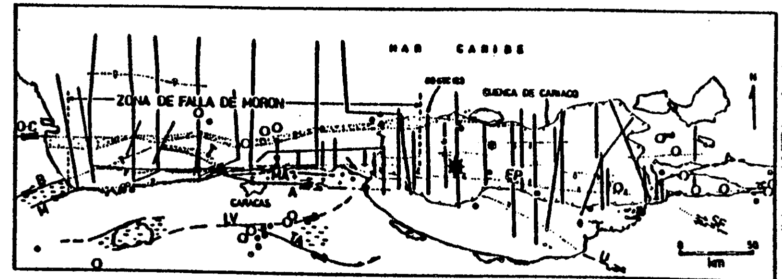


Fig. 1. Regional faulting of the central-eastern continental shelf of Venezuela, based on acoustic reflection profiles (solid lines). A: Avila fault zone; B: Boconó fault zone; M: Morón fault; EP: El Pilar fault zone; LV: La Victoria fault zone; MA: Macuto fault; O-C: Oca-Chirinos fault zone. Small star: Site 147, Leg 15 (D.S.D.P.); large star: proposed site. 19-1

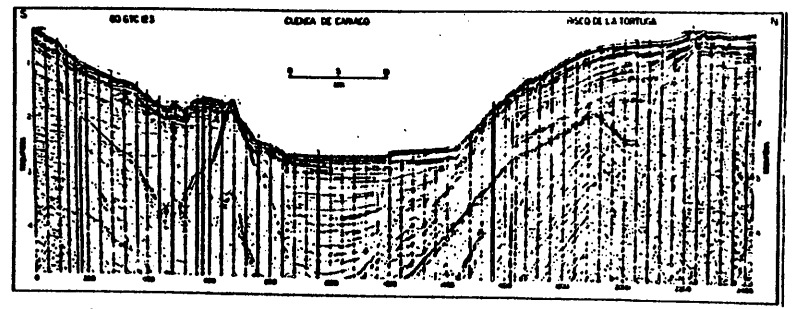


Fig. 2. Acoustic reflection profile (80 GTC 123; courtesy of Maraven, S. A.) across the western Cariaco basin (see Fig. 1 for location). Note the thick sedimentary fill offset by recent faulting.

20 DRILLING SITE PROPOSALS

for ODP Caribbean Workshop
Pamela L. Smith

1. Southern Tobago forearc basin

Immediately north of the 'Tobago Platform' (map site #1, seismic section 1).

Objective: To intersect the entire stratigraphy of the Tobago Trough basin, as well as of the 'Tobago Platform'. Characterizing and dating horizons mappable throughout the forearc basin would lead to vastly improved knowledge/interpretation of sedimentary facies and depositional patterns, sedimentation and subsidence rates, and timing of regional tectonic events. Quantification of these parameters is needed to constrain timing of Cenozoic plate motions in the southeastern Caribbean, and some or all of the results would be relevant to understanding other forearcs.

Many different results are all possible: 1/ the entire wedge of basin strata that lap/pinch out onto the platform could be identified and dated, and carried seismically throughout the basin; 2/ ages, lithologies and regional significance of horizons A and B and other interpreted reflectors could be established; 3/ dates could be obtained on both sides of unconformity on Tobago Platform, and related by seismic to the Neogene unconformity developed farther south; 4/ identity of the BSR could be established; 5/ existence of regional tectonic boundaries between rock units in the basin might be revealed by fabrics or relationships in cores; 6/ some information probably could be acquired from core about the fabric of the deep, apparently deformed rocks beneath the north edge of the Tobago Platform; 7/ basement that is mappable throughout the southeast forearc basin, and is apparently different from crystalline basement, could be identified as sedimentary, metamorphic or igneous and its age could probably be determined, leading to a new understanding of the origin of elements of this forearc system; 8/ wherever seismic lines permit carrying Tobago Trough reflectors across the arc, toward the Trinidad/Venezuelan shelf or into the Atlantic, identities and ages of horizons in other parts of the Caribbean or central western Atlantic could be constrained.

Advantages of this site: lies at the base of a very gentle grade, with no features of structural deformation apparent in the vicinity; velocity of the upper 1.5-2 sec TWT of sediment is very slow, indicating easy drilling, and remainder of section is typical velocity; section above acoustic basement appears entirely stratified, likely to be 100% sedimentary; seismic section gives no indication of overpressured horizons or other potential complications.

2. North end of Tobago forearc basin

Adjacent to boundary between thick, flat forearc basin strata and acoustically opaque Barbados Ridge basement (map site #2, seismic section 2).

Objective: To penetrate forearc basin section and investigate whether the seaward basin barrier is formed by significant structural relief against accretionary basement.

The rear edge of accreted prisms is rarely exposed to field study and is generally opaque to the seismic method because of its structural complexity. In several forearc systems this rear edge has been uplifted at a late stage but it is not known if late uplift initiated vertical displacement between accreted basement and forearc basin basement, or if structural relief pre-existed later structures — or if both are true. The faults associated with the rear prism edge have likely served as conduits for fluids expelled from depth at some stage, but virtually nothing is known about fluid migration in the older sector of an accreted sediment prism.

A deep drillhole north of Barbados and northwest of the Barbados Ridge crest would penetrate some or all of the stratal section continuous into the Tobago forearc basin, adjacent to the acoustic boundary against which basinal reflectors appear to terminate southeastward. A dense seismic network over this boundary already exists that ties to profiles that traverse the basin. Ideally the hole should be directed to intersect basin strata first and enter acoustic basement at depth. If that is not possible, the deep hole could be drilled in basinal section and be complemented by shallow drilling into adjacent shallow acoustic basement where sediment cover is <<1 sec thick.

In addition to obtaining a near-complete basinal stratigraphic section, such a hole could recover information about 1/ the nature of ridge acoustic basement, 2/ structural features of the acoustic boundary it forms, 3/ gradients in lithology and deformation across the boundary, and 4/ fluids associated with displacement surfaces at the boundary.

3. West flank of Barbados Ridge southwest of Barbados, within 'IFDB'

Along the southeast flank of the Tobago forearc basin, where Chain 75 crossing suggests narrow basins ~10 km across between apparent ridges of acoustic basement (map site #3, sesimic section 3).

Objective: To test conflicting models of forearc tectonic development (Torrini and Speed, in pres; Smith 1987). Is there a seaward verging décollement at any level between forearc basin flank sediments and accretionary prism? Is subsided slope basin fill on the seaward basin flank blanketed unconformably by forearc basin fill? Does some other relationship prevail? What was the Paleogene paleogeography of this sector of the forearc system? How significant is shortening at the 'rear edge' of the prism in the total shortening across a deforming accretionary prism?

A hole at this site would penetrate several unknown seismic sequences and their boundaries, and the resulting 'ground-truth'-ing of seis-strat relationships could be carried seismically along much of the IFDB and to the ridge crest. The horizon(s) that separates forearc basin strata from accretionary basement, or from fill of basins between basement ridges, could be dated and tied to seismic, and studied in core for evidence of features of a tectonic surface. Nature of the basin fill between basement ridges could be identified, and perhaps its deformational fabric assessed — folded? sheared? cleaved? etc. Additionally, much of the forearc basin section that is offset across the deformation front could be identified and dated, and these results carried by seismic across the basin and into other parts of the Caribbean or central western Atlantic, including enhanced knowledge of the tephrochronology and biostratigraphy of the basin section.

Advantages of this site: seafloor, though sloping, shows no seismic evidence for slump-type disturbance of local tectonic activity; thickness of sediments to be penetrated above target and acoustic basement is relatively small, ~1140 m, and appears to be almost entirely young low-velocity section.

1 2

4. Barbados Ridge crest, in slope basin offshore west Barbados

Several (three? six?) hydraulic piston cores on the Barbados Ridge crest, in shallow water, to penetrate slope basin strata to acoustic basement (map site #4, seismic section 4).

Objective: To intersect stratigraphy of the slope basin immediately offshore the west coast of Barbados and relate it to outcrop geology of Barbados and to cores already obtained from the ridge.

The fill of the oldest(?) accessible Barbados Ridge slope basin could be sampled in several localities, probably to the contact with accretionary basement if 300-400 m are penetrated. Correlation of some or all of the slope basin sediments with the outcropping Oceanics and/or with sediments in the Barbados subsurface, as well as to other cores, could be tested. The stratigraphic history of the slope basin could be assessed in detail, using ties to seismic and seis-strat analysis, to reveal development of unconformities, tectonic boundaries if present, lateral facies transitions, and importance of pelagic sedimentation and re-sedimentation. The degree of deformation in older slope basin sediments could be evaluated. Core recovered from the contact with acoustic basement should contain some information about that boundary, which produces the strongest regional seismic discontinuity on the Barbados Ridge — is it tectonic? unconformable? The BSR would be penetrated. Ash and other volcanogenic layers penetrated in the basin stratigraphy would enhance accurate dating of the sediments and assessment of distal volcanic deposition in the forearc.

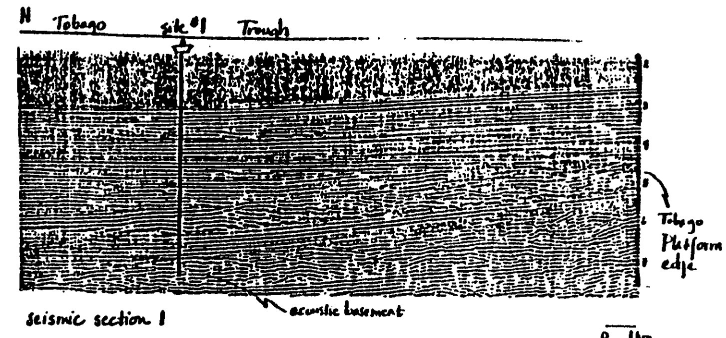
Advantages of these sites: water depths are shallow; seismic suggests the sediment fill is mainly low velocity, <1700 m/sec, therefore easily penetrated.

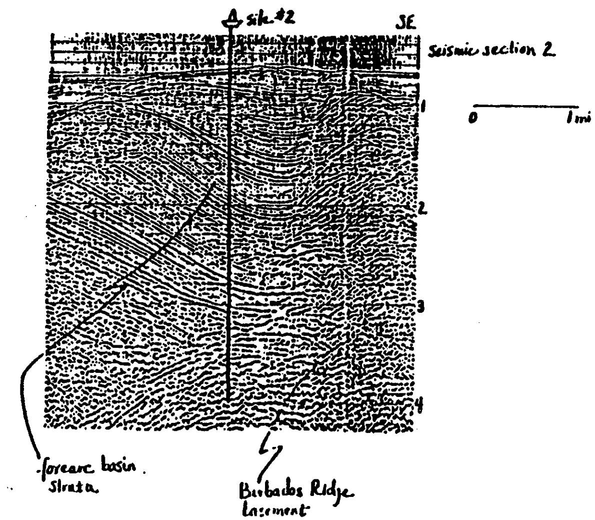
5. Arc Platform, Grenada to St. Vincent

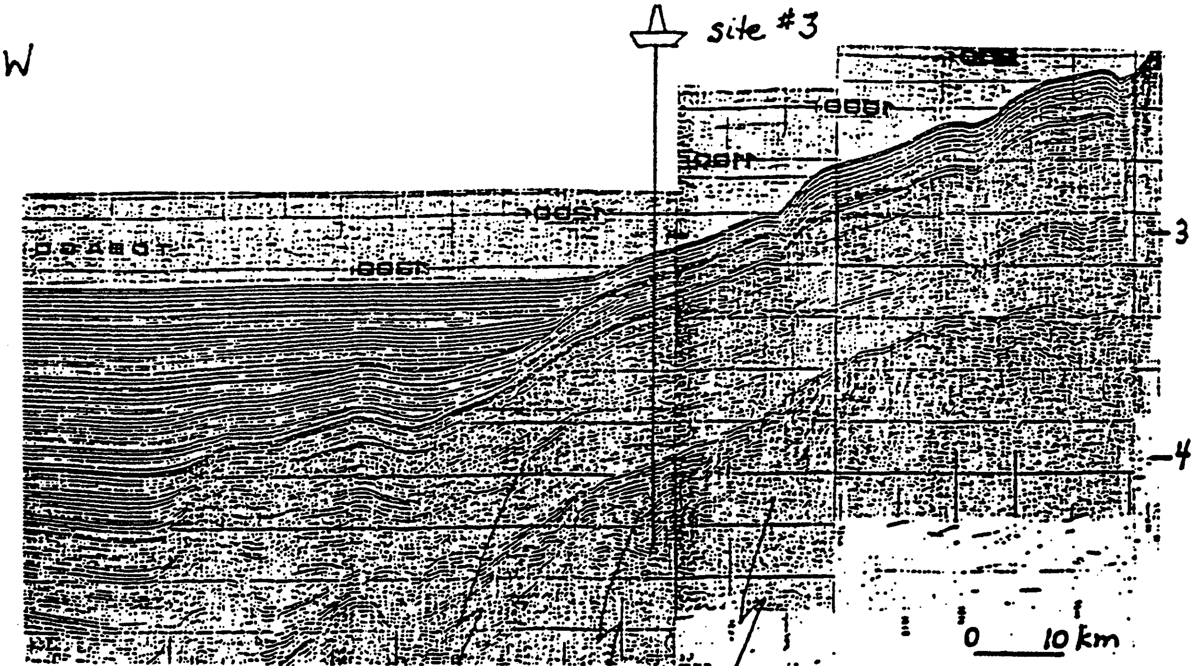
A single deep hole to sample rocks of the arc platform, in the area of the Grenadines or south from Grenada (map site #5a,b, seismic section 5).

Objective: To obtain a new sample of a nearly unknown sector of the eastern Caribbean, to integrate onshore geologic observations with offshore seismic analysis and permit extrapolation of the interpreted rock relations away from the arc platform.

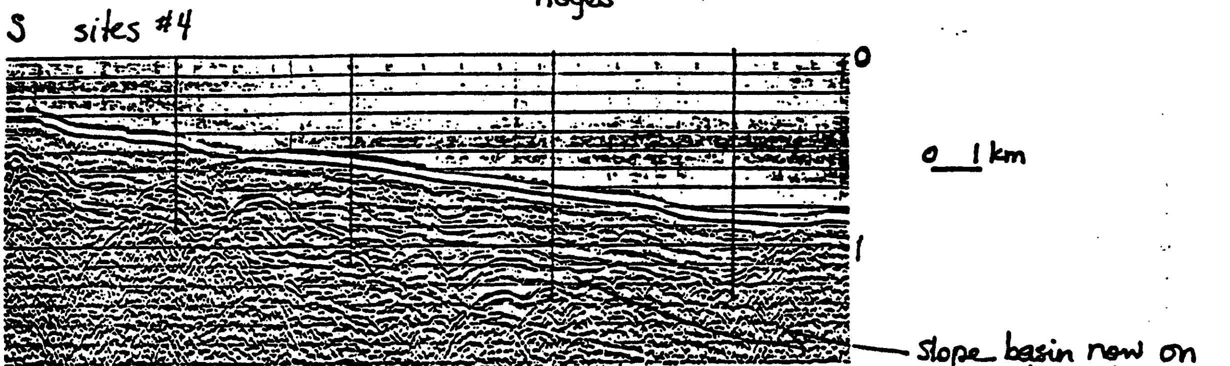
New field work by Speed and Larue (1986) and Speed and others (1987) shows that the platform on which Neogene southern Lesser Antilles volcanos stand may be constructed mainly of deformed sedimentary rocks, the oldest at least Eocene. We expect to obtain soon excellent MCS data along the east edge of the platform from St. Lucia to Grenada; the drilled hole would provide a geologic tie both with those seismic data and with rocks mapped on Grenada and certain Grenadines by Speed and others. The seismic grid then would facilitate correlating drilled rocks as far as they extend onto the arc platform and across the platform into the Grenada Basin, as well as throughout the Tobago forearc basin. Sufficiently deep data from such a hole would constrain the age of oldest forearc basin sediments and therefore much of the timing of Cenozoic southeastern Caribbean events, as well as illuminate the relationship of deformed Paleogene sedimentary rocks of the arc platform to undeformed, but apparently coeval, Tobago Trough fill. Expected results include: 1/ establish what rocks are present beneath the platform — sedimentary? igneous below? any degree of metamorphism? deformed? - mildly or intensely? 2/ determine ages of drilled strata where possible — are significant hiatuses present? How old are deepest rocks reached? What sedimentation rates are implied by thicknesses? 3/ if the sedimentary rocks of the arc platform are significantly deformed and/or tectonically displaced, a drillhole should intersect repeating strata or hiatuses. 4/ in the case of site 5b/, it may be possible to address the question of possible normal fault displacement between the arc platform and forearc basin; the proposed site is on the footwall of a seismic feature interpretable as a now-inactive fault.







seismic section 3



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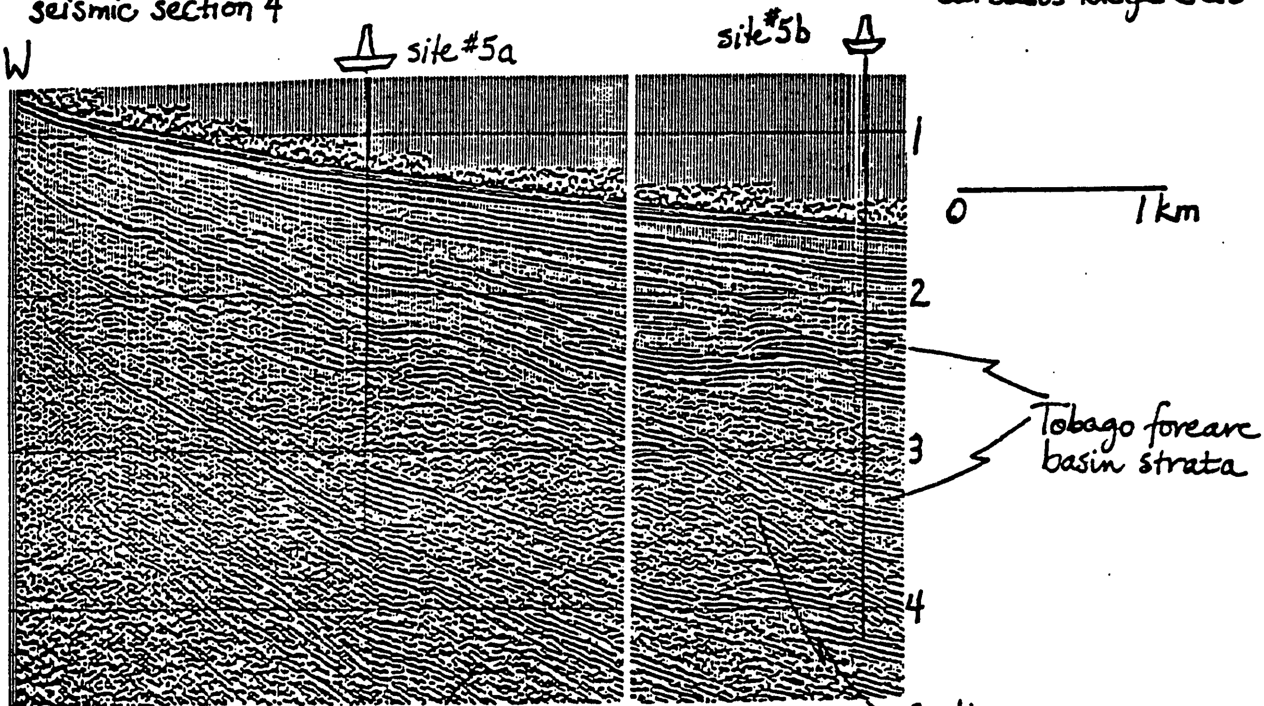


seismic section 5

21 R. Speed: Caribbean Scientific Drilling Targets (in priority)

1. **Cayman Trough:** The displacement history of the Cayman Trough is the best gauge of whether the Caribbean plate came wholly or partly from the Pacific and when. The objectives are to obtain data on sediment age, thickness, and facies that will improve our understanding of the magnitude, distribution, and timing of displacement by predrift extension and by seafloor spreading.

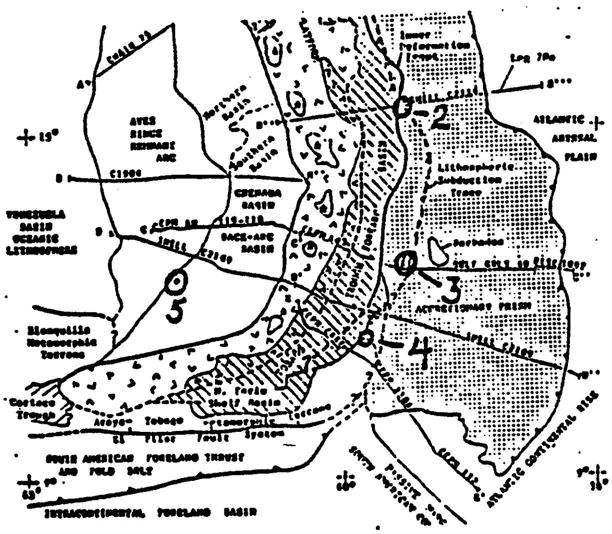
2. **Tectonic History of the Leading Edge of the Caribbean Plate:** The Lesser Antilles arc has existed in its current form as the leading edge of the Caribbean plate (Fig. 1) only since early Neogene time. Before this, the plate's leading edge is poorly defined and is likely to have been a composite of terranes and quite differently oriented tectonic boundaries. I submit that the history of the arc at latitudes of Dominica and Barbados has differed considerably, reflecting the following kinematic phenomena: NAm-SAm plate boundary, eastward relative motion of Venezuelan Basin lithosphere, coalescence of discrete pre-Neogene terranes such as eastern Greater Antilles and southern Lesser Antilles, and development of Grenada Trough. Differences in the tectonic development of the present leading edge, and in turn, modern Caribbean plate tectonics, may be recorded in forearc basin strata and basements on the east side of the Lesser Antilles arc. For example, I argue that the forearc north of Martinique may be entirely of Neogene tectonic age whereas that to the south began in Eocene or earlier times (Speed et al., 1987). I propose to drill the relatively thin (<2 km) forearc basin succession east of Dominica or Guadeloupe to acoustic basement (Fig. 2) and to compare these data with onland, seismic, and drilling data on forearc basin strata at the latitude of Barbados.

3. **Inner Forearc Tectonic Wedging:** Seismic profiling in the southern forearc of the Lesser Antilles shows well a regional structure that may exist in the inner (arcward) zones of many forearcs of the world. The structure appears to be the arcward wedging of the accretionary prism into the forearc basin. In general, the inner prism tip appears to be inserted at an intermediate stratigraphic level in the forearc basin succession, but varies its detachment horizon, and the floor thrust may locally follow basement or on the other hand, become emergent (Torrini and Speed, 1987). The proposed process, which may be global, can be tested by drilling through the roof sequence, prism tip, and floor sequence of forearc basin strata (Fig. 3). The data should also improve our understanding of physical properties of rock at the wedge horizon, dating of horizons in the forearc basin (where horizons in the floor sequence can be traced onto the Tobago Trough), and the linkage between deep strata of the forearc basin (Tobago Trough) and the allochthonous Oceanic beds of Barbados.

4. **Tobago Terrane vs. Accretionary Prism: Tectonic Relationships:** The Tobago terrane (Fig. 4) is composed of Cretaceous crystalline rocks that are exposed on Tobago island and probably extend west toward Margarita as the forearc basin basement. Rocks of the Barbados accretionary prism lie north and east of the Tobago terrane but the tectonic relationships of the two are uncertain. The Tobago terrane may be wedged into or over the prism or may be simply an extra large accreted object within the prism (Speed, 1986). The history of the southern Lesser Antilles and of motions between Caribbean terranes and continental South America must accommodate the juxtaposition of the prism and the Tobago Trough. Holes drilled north and just east of Tobago island may provide requisite data: whether prism rocks or forearc basin strata lie above the north flank of the Tobago terrane and the age, origin, and deformation of rocks just east of the geophysically identified southeastern edge of the Tobago terrane.

5. **Origin of the Grenada Basin:** The Grenada Basin (Fig. 5) lies west of the Lesser Antilles arc in a backarc position with the Aves Ridge flanking the basin's western margin. The Grenada Basin is floored by 12-15 km-thick oceanic crust and covered by >4 km of sediment. The age of the crust is Eocene or older according to heat flow and long-range seismic

stratigraphy. A major question is whether the Grenada Basin formed by backarc spreading, by arc jump, or by some other origin. The age of the basin and its structural connection to the Aves Ridge are necessary ingredients for an answer. A hole should penetrate a condensed section of mainly pelagic sediments on the western flank of the basin, continue through a zone of dipping reflectors that cover the Aves Ridge-Grenada Basin transition, and sample the subjacent basement. The ages of the basement and dipping reflectors should bracket the time of basining, and compositions in the two seismic zones may indicate the changing response of a possible remnant arc of the Aves Ridge to spreading in the Grenada Basin. The suprajacent pelagic section may yield a good biostratigraphic record to early Tertiary times; well preserved faunas are likely due to relatively shallow water depth and are known down to Pliocene in the vicinity at DSDP 148. Thus, the hole may fill in the gap in the Oligocene to late Miocene faunal record from prior Caribbean drilling. This hole may also date changes in water circulation between Atlantic and Pacific Oceans. Last, dating of the main basin fill section will permit seismic stratigraphic correlation throughout the Grenada Basin.



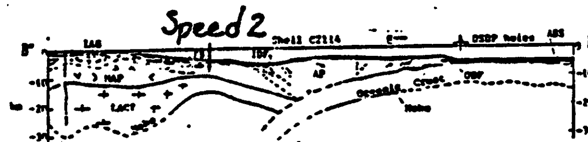


Fig. 2

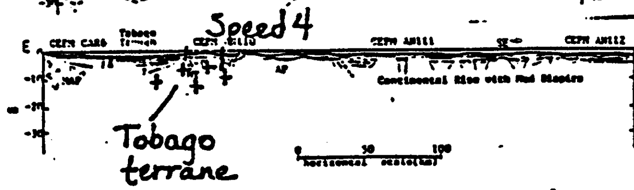


Fig. 4

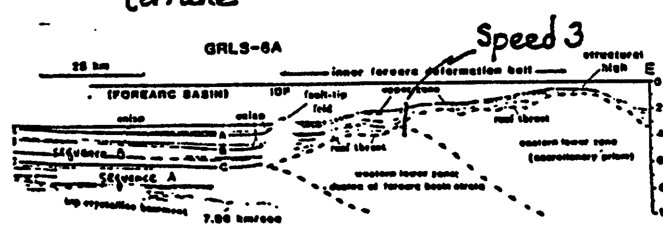


Fig. 3

Fig. 1 Southeastern Caribbean
R. Speed

22 PROPOSED DRILLING SITES IN THE CARIBBEAN SEA

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The major portion of the Caribbean plate shows many similarities with oceanic plateaus, it has unusually thick (10 to 15 km), bouyant, thickly sedimented oceanic crust that is 1-2 km shallower than predicted from normal thermal subsidence models. The geological complexities of the surrounding margins and the missing seafloor destroyed by subduction allow many possible models of Caribbean plate evolution. The evolutionary models fall into two broad categories, those where the plate is formed essentially in place between North and South America and those in which the plate is formed in the Pacific and transported into the region from the west (e.g. Malfait and Dinkelman, 1972; Burke et al., 1978; Pindell and Dewey, 1982).

The modern analogs of many allochthonous terranes in continental orogenic zones may be found in the oceanic plateaus (Ben-Avraham et al., 1981). Recent studies of the Pacific margin of North America have shown the importance of allochthonous terranes in plate tectonic evolution and mineral distribution (e.g. Coney et al., 1980; Albers, 1981; Berg, 1981; Hollister and Tooker, 1981; Jones et al., 1981; Tempelman-Kluit, 1981; Ben-Avraham and Nur, 1983).

The Caribbean provides a prototype model for the processes involved in the formation, transportation, storage and eventual obduction of oceanic plateaus and thus warrants further investigation by ocean drilling. The Duncan and Hargraves (1984) model of circum-Caribbean plate motions with respect to the hotspot reference frame and the modelling of magnetic anomalies by Ghosh et al. (1984) provide testable predictions concerning the age and geochemistry of the oceanic basement, the geochemistry and nature of the volcanism that resulted in the thickening and bouyancy of the Caribbean crust (B" event), and the progressive change of provenance of sediments. The Sr, Nd and Pb isotope study of B" basalts recovered by DSDP Leg 15 has shown that this volcanism probably had a hotspot origin with multiple basalt injections (Waggoner, in preparation; Sen et al., in press).

Recent expanded seismic profiling and multichannel seismic studies of the Venezuela Basin reported by Diebold et al. (1981) has shown that in the southeastern and oldest part of the basin there is an abrupt boundary between basement layers designated smooth B" and rough B". The nature of the rough B" reflector is unknown, but due to its more normal depth to Moho and seismic reflection characteristics it has been suggested to be oceanic crust produced at a spreading center. If it is indeed typical crust then it may represent a fragment of the seafloor destroyed elsewhere by subduction.

The highest priority for further drilling in the Caribbean should be sampling basement from both the area of smooth B" and rough B". Sampling basement will provide both age and geochemical constraints for testing models of the allochthonous nature of the Caribbean crust. Prior drilling has penetrated only the upper carapace of the B" volcanism which was responsible for thickening the Caribbean plate, therefore coring of the B" interval will provide further essential information on the nature of the hotspot volcanism, the timing and mode of emplacement (flows vs. sills), and comparison with other Pacific oceanic plateaus.

Proposed sites are divided on the basis of sampling objectives into two areas corresponding to smooth B" and rough B" reflectors. Sampling both of these reflectors should have the highest priority in any further Caribbean drilling.

<u>Smooth B" Reflectors</u>

1. ESP3 (15°N 67°25'W)

Reentry, APC, XCB, RCB	
Water depth	5000 meters
Total drill string	6600 meters
Total coring interval	1600 meters
Coring subintervals	
seabed to B"	700 meters sediment
B" to basement	800 meters basalt/sediment
basement penetration	100 meters basalt
Total sub-bottom penetration	1600 meters
Estimated time on site	52 days

Considerations:

This site and the highest priority rough B" site ESP1 are close to one another and along the same approximate flow line (as indicated by the proposed magnetic anomalies on map). Basement at this site is probably some of the oldest Caribbean crust based on the proposed 150 m.y. old magnetic anomaly identification just to the west (Ghosh et al., 1984). There are high quality multichannel seismic (MCS) lines, expanded seismic profiles (ESP) and single channel seismic (SC) lines for this site. Seismic stratigraphy is well defined and indicates layering beneath the B" layer. Drilling will sample a new sediment section at a time cost of 6 days over option #2 below.

2. Reoccupy Site 146/149 (15°06.99'N 69°22.67'W)

Reentry, RCB	
Water depth	3949 meters
Total drill string	5611 meters
Total coring interval	900 meters
Coring subintervals	
Previous penetration (seabed to B")	762 meters sediment
B" to basement	900 meters basalt/sediment
Total sub-bottom penetration	1662 meters
Estimated time on site	46 days

Considerations:

A reentry cone was placed during initial drilling of this site and it should be possible to reenter the hole using this cone. Hole conditions are unknown and may have deteriorated in the last 17 years. The sediment section above the B" layer has already been sampled and thus no new information will be gleaned. If the hole is in good condition then B" can be drilled more quickly. There may be some interest in sampling the fluids in the hole. The seismic lines available for this site are not as complete or of the same quality as those for site ESP3.

<u>Rough B" Reflectors</u>

1. ESP1 (14° 30'N 66° 15'W)

Reentry, APC, XCB, RCB

Water depth	5100 meters
Total drill string	7700 meters
Total coring interval	2600 meters
Coring subintervals	
Seabed to A"	900 meters sediment
A" to basement (B")	1700 meters basalt/sediment
Total sub-bottom penetration	2600 meters
Estimated time on site	90 days !!!

Considerations:

The sub-bottom drilling depth and basalt/sediment intercalated mixture will severely test the drilling ship capabilities, but this is one of the types of problems that the JOIDES Resolution was intended to tackle. There are no recovered samples of the rough B" material and its nature is unknown but of fundamental importance to understanding the evolution of the Caribbean plate. This site is in a magnetic quiet zone and is possibly on the oldest Caribbean crust. The velocity-depth profile is similar to that found in deep basins of the Atlantic and Pacific with normal crustal thickness. The depth to basement satisfies the age-depth requirements of the cooling slab model of Sclater et al. (1971) for Early Cretaceous crust. The site is along the same approximate flow line as ESP3. The relationship between smooth B" and rough B" is unknown, but the stepped Moho and abrupt nature of the boundary suggests fundamental differences in processes that created various segments of the Caribbean crust. There are high quality MCS, ESP and SC lines available for this site. The depth to basement increases towards both the south and east.

23 Lesser Antilles Volcanism: Deep Sea Drilling Objectives

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Abstract

Two ODP drilling sites are proposed to help resolve the question of whether the sedimentary signature in Lesser Antilles Arc magmas is acquired through contamination of magma source regions by subducted sediment at depths of 100 km or through assimilation of sediment in high levels of the arc crust by ascending magma. Resolution of this question has important implications for crust-mantle evolution. The first site would be located just east of the southern part of the deformation front and has as its objective assessment of the geochemistry of sediment potentially being subducted beneath the southern part of the arc. The second site would be located off-axis in the southern part of the Lesser Antilles arc itself. Its primary objective would be to assess the geochemistry of sediment available for assimilation in the arc crust.

A fair amount of isotopic and trace element data now exist for the arc. Sr, Nd, and Pb isotopic compositions are summarized in Figures 2 and 3. These figures illustrate the extreme range of isotopic compositions observed in the arc. Pb isotope ratios of many of the lavas plot outside the field defined by oceanic basalts (MORB and oceanic island basalts) as well as fields defined other arcs. They show a strong similarity to Pb isotope ratios from sediments from the Atlantic seafloor directly in front of the arc. Trace elements show a similarly wide range: rare earths, for example, range from slightly light-rare-earth depleted to strongly light-rare-earth enriched. White and Dupré (1986) attribute the unusual geochemistry of Antilles Arc magmas to inheritance from subducted sediment in the magma source regions. The Oronoco River appears to be the prime source of much of the sediment being subducted beneath the arc. Oronoco River sediment appears to be in part derived from the Archean Guiana Highland, which account for the radiogenic nature of Pb and Sr and unradiogenic nature of Nd in the sediment. Additional evidence for indirect inheritance of geochemistry by the Lesser Antilles Arc magmas from the Guiana Highland comes from the geographic distribution of isotopic compositions of both sediment and arc magmas (Figure 4): Pb and Sr isotope ratios decrease northward in both, apparently due to a waning of the Oronoco River contribution northward.

That the arc magmas contain a sedimentary component is beyond dispute. However, there have been differing interpretations of how magmas acquire this sediment. In contrast to the interpretation of White and Dupré, Thirlwall and Graham (1984) and Davidson (1986) consider assimilation of sediment in the arc crust by ascending magma to be a more important effect that sediment subduction. These authors have presented evidence suggesting coupled assimilation-fractional crystallization in Grenada and Martinique. In addition, Davidson notes that some arc magmas have Pb isotope ratios which are more radiogenic than analyzed sediment from in front of the arc. Provided the analyses available represent the range of Pb isotope ratios in the sediment in front of the arc, this observation argues against the sediment subduction—source contamination hypothesis.

White and Dupré (1986) and White et al. (in prep.), point out the Pb isotopic compositions of the Grenada lavas studied by Thirlwall and Graham (1984) are similar to those of Pacific Ocean sediment, and to some metasedimentary xenoliths from St. Vincent, but are different from Pb isotope ratios of other Lesser Antilles suites and from those of sediment in front of the arc. They argue on these grounds that the assimilation of intracrustal sediment of Pacific provenance that occurred in the suite studied by Thirlwall and Graham is unique (at least no other cases have yet been documented) and cannot account for the geochemistry of the arc as a whole. A suite from La Soufriere volcano of St. Lucia studied by White et al. (in prep.) has Sr and Nd isotope ratios as nearly as extreme as the Martinique suite studied by Davidson. However, in contrast to Davidson's results, White et al. found Sr—O and Nd—O isotope systematics were not consistent with assimilation—fractional crystallization: rather they indicated contamination of the magma source by subducted sediment. Furthermore, in their study of sediment from in front of the arc, White et al. (1985) found that, in addition to becoming more radiogenic southward, Pb in the sediment became more radiogenic with depth at Site 543. Extrapolating these two trends, they pointed out that the sediment with the most radiogenic Pb should occur in the unsampled deeper horizons south of Site 543, just north of the South American continental margin. Thus, according to White et al. (1985) and White and Dupré (1986), the observation that some Lesser Antilles lavas have more radiogenic Pb than the sediment cannot be used to argue against the sediment subduction—source contamination hypothesis.

The question of the origin of the sedimentary signature in Lesser Antilles Arc lavas is important because of its implications for island-arc magma genesis and crust-mantle recycling. Island arc magmas are petrologically and geochemically distinct from magmas generated in other tectonic regimes. There has been considerable debate as to whether slab-derived components, and particularly sediment, in island arc magma sources accounts for these distinctions. White and Dupré (1986) argue that the subducted sedimentary signature in Lesser Antilles magmas is so obvious not because there is more sediment being subducted, but because of the unusual geochemistry of the sediment in the region, particularly the extreme isotopic compositions. In their view, the results of their study can be applied to other arcs as well. This conclusion is obviously invalidated if the sedimentary signature is acquired through assimilation: thicker sediment in the Lesser Antilles arc crust may result in assimilation being more important in the Lesser Antilles than in other arcs.

The larger question involved is the degree to which the continental crust can be destroyed through subduction and recycling to the mantle, and the degree to which mantle heterogeneity might result from this recycling process. One view of crustal evolution holds that crustal mass has remained constant through much of Earth's history with additions of new crust being balanced by destruction and subduction of old crust (Armstrong, 1968). And White and Hofmann (1982) have suggested recycling of continental crust accounts for much of the geochemical variation observed in the mantle. These questions are of fundamental importance in understanding the operation of plate tectonics and evolution of the Earth. In Armstrong's view, the crust-mantle system is now in steady state: crust creation was a more or less one time event which was complete 3500 to 4000 Ma ago. If this view is correct, present plate tectonics processes are not responsible for creation of continental crust. Hofmann and White (1982) argued that crust-to-mantle recycling produces a heterogeneous distribution of heat-producing elements in the mantle which is responsible for initiating mantle plumes.

Geochemical, particularly isotopic, studies of island arcs are potentially one of the best ways of assessing the recycling flux of sediment, and hence continental crust, to the mantle. Such studies can readily assess the contribution of sediment to a magma: however, as illustrated by the present controversy in the Lesser Antilles, they do not *a priori* reveal how the sediment finds its way into the magma system. Thus in order to truly assess crust-to-mantle recycling in subduction zones, the contribution of sediment from assimilation must be determined.

Two ODP drilling sites are proposed. The scientific objectives of the proposed drilling program are to resolve the controversy of Lesser Antilles geochemistry and hence constrain the amount of crust-to-mantle recycling and models of island arc geochemistry. These objectives will be achieved by (1) assessing the geochemistry of sediment being, or potentially being, subducted beneath the southern Lesser Antilles, and (2) assessing the geochemistry of sediment available for assimilation in the arc crust. Additional scientific results will be sedimentation history of the Atlantic plate in front of the arc and the volcanic history of the Lesser Antilles Arc.

Lesser Antilles Site 1: Southern Deformation Front Site

The first site proposed is shown in Figure 5. It should be preferably located just north of an extrapolation of boundary between the South American Plate and the Caribbean Plate, and near, or just east of, the deformation front. The primary objective being to determine the nature and geochemistry of sediment in the southernmost part of the Atlantic plate being subducted beneath the Lesser Antilles Arc. Ideally, cores through the entire sedimentary sequence should be obtained (all horizons should be at least partially cored, but there need not be 100% coring downhole): the lowermost horizons are of particular interest. The thickness of the sediment in this area (5 km), may dictate shifting the site somewhat to the north and/or east. The ability to penetrate the entire sequence is more important than the exact location of the site. Some minimal penetration of basement (50 m) is also desirable. In order the assess the geochemistry of the subducting oceanic crust beneath the southern part of the arc. The primary data to be acquired is Pb isotopes and other geochemical parameters of the sediment. Petrological evaluation of the sediment will also be important.

Essentially this site is a test of the postulation of White et al. (1985) that the most radiogenic Pb being subducted beneath the Lesser Antilles should be found in deep sedimentary horizons at the southern end of the arc. More importantly, it is a test of whether sediment being subducted beneath the southern part of the arc has sufficiently radiogenic Pb to account for radiogenic nature of Pb in Lesser Antilles magmas. The result is crucial to resolving the assimilation versus subduction controversy discussed above.

In addition to the strict geochemical objectives of the site, drilling may provide some interesting insights in to sediment history and accretionary wedge tectonics. These sedimentary sequence thickens markedly southward along the deformation front, and deformation may differ from that at the northern drilling sites. White et al. (1985) concluded from Pb isotopic compositions that the Guiana Highland has been an important source of sediment at Site 543 since the Cretaceous. It would be interesting to test this hypothesis by obtaining and analyzing appropriate samples.

Lesser Antilles Site 2: Grenadine Arc Crust Site

The second proposed site would sample the Lesser Antilles Arc crust itself. The primary objective would be to determine the nature and geochemistry of sediment in the arc crust. A secondary objective would be to obtain a record of the volcanic history of the arc. A location in the Grenadines is suggested here, but any suitable site south of Martinique would be satisfactory. Since the volcanic horizons making up the arc crust would be thinner off axis, the site would be preferably located to the east or west of the arc axis. Geophysical studies would be required to determine the exact location of the site, and whether any such hole would have a reasonable chance of fulfilling the above objectives.

The oceanic crust upon which the Lesser Antilles arc is built was presumably formed in the Pacific. Thus the lowermost sedimentary horizons should be of Pacific provenance and geochemically distinct from sediment in front of and potentially being subducted beneath the arc. Much of the later sediment in the arc crust is likely to be volcanogenic, and assimilation of this material would not account for the radiogenic nature of Pb in Lesser Antilles arc lavas. Presently, Oronoco River sediment reaches the Demerara Abyssal Plain via turbidite currents; little, if any, of this material is deposited in the region of the arc itself. A simple uniformitarian approach would reach the conclusion that this geochemically unusual sediment does not exist in the arc crust and hence would not be available for assimilation by ascending magmas.. This unique geochemical signature could, in this interpretation, reach the magmas only by subduction to the magma generation region. However, if South American drainage patterns were different in the early Tertiary and Late Cretaceous, material derived from the Guiana Highland could have been deposited in the region of the present Lesser Antilles arc. Analysis of sediment cored from a well located drilling site could resolve this question, and hence go a long way to resolving the sediment assimilation versus sediment subduction debate.

This site would be one where maximum penetration is desirable. Preferably, it would reach oceanic crust basement. In order to do this, it would presumably have to be sited well off axis, where the arc volcanic sequence is relatively thin. Nevertheless, much of the arc history might be preserved in volcanogenic sediment. Thus questions of the arc volcanic history and initiation of subduction and volcanism in the Lesser Antilles Arc could be addressed by this site.

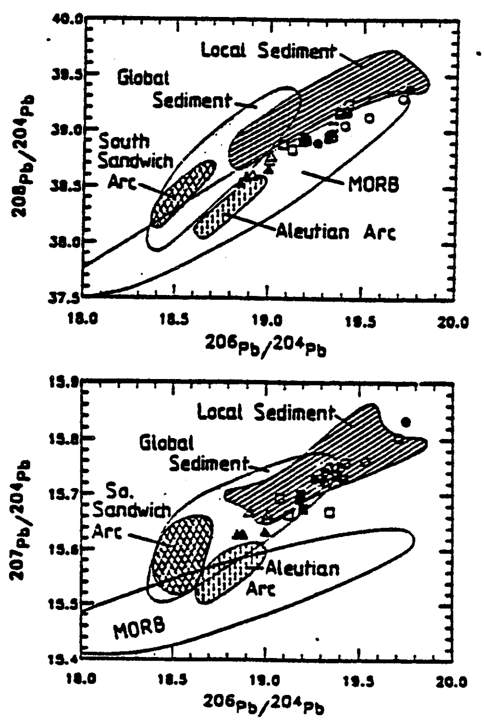

Figure 2. Pb isotope ratios in Lesser Antilles lavas. Also shown are Pb isotope ratios of sediment in front of the arc (local sediment) and sediment from other regions (global sediment). Pb isotope ratios from two other arcs shown for comparison. From White and Dupré (1986).

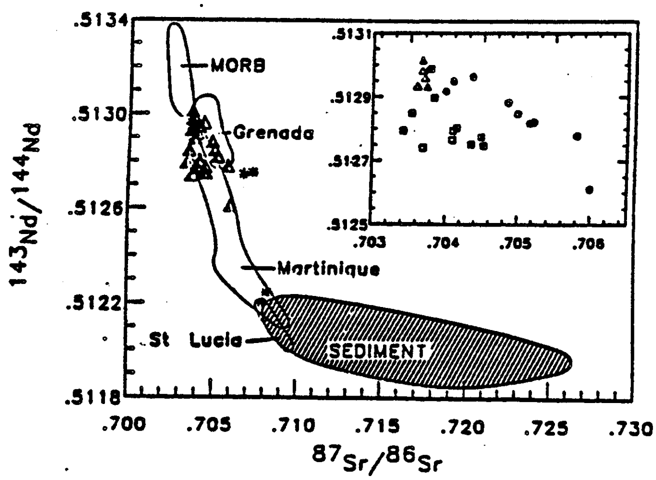

Figure 3. Sr and Nd isotope ratios in Lesser Antilles volcanics sediment in front of the arc. Also shown are fields for Martinique (from Davidson, 1986) and Soufriere of St. Lucia (from White et al., in prep.). From White and Dupré (1986).

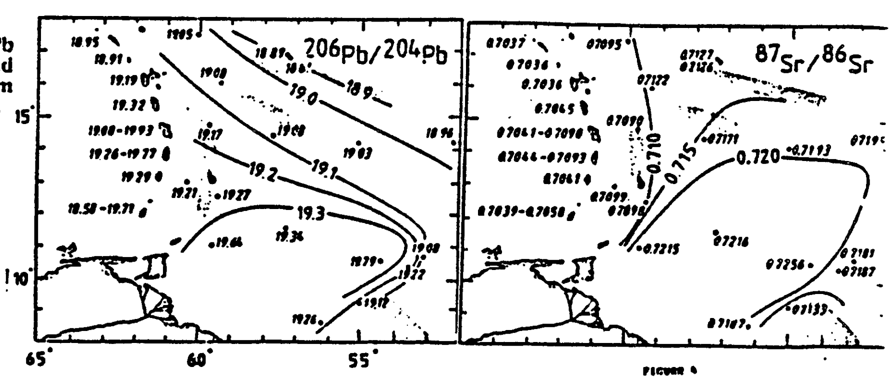

Figure 4. Pb and Sr isotopic variations in sediments from piston cores in the Demerara Abyssal Plain–Barbados Ridge region and in Lesser Antilles volcanics. From White and Dupré (1986).

24 ODP Objectives for the Gulf of Mexico - Caribbean Region

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The primary seaway connections between the Atlantic and Pacific Oceans were through the Gulf of Mexico during the Jurassic and through the Caribbean Sea during the Cretaceous and Tertiary. One of the major objectives of the Ocean Drilling Program in the Gulf-Caribbean region must be directed towards understanding the crustal evolution and sedimentation history of this major paleoceanographic gateway. Geologic studies around the rim of the Gulf-Caribbean, geophysical surveys, and regional plate kinematic studies now provide a better framework for understanding this region. Yet, little is known about the sediment character and distribution patterns, paleoenvironment, and basement structure and composition of the pre-mid Cretaceous rocks of these two basins. Drill holes must be sited in locations where they can penetrate the Mesozoic deep-water strata of both the Gulf of Mexico and the Caribbean Sea. These must not be sediment-starved sites or basement highs, because it is important to obtain as complete a sedimentary record as possible. Basement rocks need to be sampled in order to evaluate the age and crustal framework of each of the sub-basins in the region. This drilling must be carefully integrated into regional geophysical studies; downhole geophysical studies as well as geologic studies are essential for calibrating the regional geophysical data.

Potential drill sites have already been proposed by the Caribbean Working Group at their March 1984 meeting in Barbados and several of these sites clearly meet the objectives outlined above. A deep penetration site in the Yucatan Basin (YBI-1a) is a primary target, and it was initially considered for Leg 101 of ODP. A nearby site on the north side of the Campeche Escarpment into Jurassic deep-water strata of the Gulf of Mexico is another viable location. Extensive multichannel seismic surveys already exist in both regions. The previously proposed CAR-3, CAR-4, and CAR-5 sites in the central and eastern Caribbean meet many of the criteria required to fulfill the objectives outlined above, and they should be reconsidered now in the framework of new geologic, geophysical and plate-tectonic framework data. The deep Mesozoic strata in the Colombian Basin must also be sampled in a region away from the thick sedimentary wedge of the Panama-Columbian margins. A site north-northeast of DSDP site 154 on the southeast side of the Nicaraguan Rise needs to be investigated. In addition, there needs to be a site in the Atlantic Ocean Basin near the Atlantic entrance to this gateway. This site would be north of the Bahamas and within the Mesozoic seafloor spreading lineation zone. Most of these sites will be deep penetration sites (greater than 2 km of sedimentary strata), but their thick sedimentary units represent the primary record of this important Mesozoic oceanographic gateway.

25

JAMAICA PASSAGE

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Bathymetric, seismic, magnetic and gravity surveys along sections of the Jamaica Passage have been carried out by a number of oceanographic research vessels including the R.V. Goswold (1968, 1969), R.V. Discoverer (1972), HMS Hacla (1972), R.V. Eastward (1973) and R.V. Atlantis (1978). The data show that the area is dominated by a series of structurally controlled NE-SW trending ridges and troughs (Horsfield and Robinson 1974). The NE-SW structural trends do not extend onto the islands of Jamaica and Hispaniola which instead display prominent NW-SE and E-W lineaments. Case et al (1984) have shown that the Jamaica Passage comprises several geological provinces. The Navassa Trough, along which is located the E-W trending Plantain Garden-Enriquillo fault zone (Mann et al.,1983), divides the southern Nicaraguan Rise from the Southern Haitian, Massif de la Hotte and Cayman Transform provinces to the north.

We propose that by drilling on one of the prominent NE-SW trending ridges in the Jamaican Passage located north of the Navassa Trough, preferably in Case et al's (1984) Massif de la Hotte Province, would provide important geological information on the Post-Cretaceous tectonics and sedimentation history of the region. Sclater and Rosencrantz (1986) postulate that these NE-SW structures are related to the early rifting of the Cayman Trough. Therefore an ODP site on the Grappler Horst (Burke et al.,1980) would provide inter alia more geological data on the evolution of the Cayman Trough and the possible onset of E-W displacement between the North American and Caribbean Plates.

27 ODP PHOPOSITIONS IN THE CARIBBEAN ZONE

By Alain MAUFFRET

DATATION OF THE OLDEST CRUST

In the Central and West Pacific (Nauru and Mariana basins , Hess Rise) is located the oldest piece of oceanic crust in the world .. The datation of the M series and Jurassic Quiet Zone is a prime ODP objective . However most of the old crust of the Central Pacific (about 30 Millions sqare Km) is covered by a thick mass of flows erupted in several episodes: Valanginian, Aptian - Albian and Campanian and a window has to be found to reach the old ocanic basement .

In the Caribbean zone a similar mass of flows (Turonian to Campanian and as old as Albian on land) is underlain by older series and the seismic profiles from Nauru basin and Caribbean basins are identical : below a flat horizon (B", top of the Cretaceous volcanic layer) some deeper reflectors can be observed (volcanic sills or oceanic crust). In the southern colombian and venezuelan basins a rough basement could be the old oceanic crust preserved of the volcanic flows .The magnetic anomalies are not yet clearly identified but a M serie is probable .

The Mesozoic eastern part of the Pacific has been subducted under the America plates and if the Carribean plate is a piece of the Pacific plate kinematics and paleogeography of the entire area (from the western Pacific to the Caribbean basins) could be improved by datation of the old series and determination of their paleolatitude (10° further South or more).

The influence of a giant intraplate volcanic eruption on the paleoenvironment and sea level is also important to know .

Just after the volcanic eruption an anoxic event occurred in the Caribbean zone (from Turonian to Santonian). The black shales are generaly older in the Atlantic (Albian) and in the Pacific(Cenomanian- Turonian boundary).When did begin the anoxic event in the Caribbean ? What is the relationship between Pacific and Atlantic oceans at this time ? .

In summary a drilling objective through the B" horizon may allow to respond to several thematic problems .

THEMES

1- Datation of the oldest crust .
2- Kinematics of the Pacific and link with the Caribbean plate
3- Seaway between Tethys and Pacific and paleoenvirnoment .
4- Intraplate volcanism .
5- Kinematics of the Carribean plate .

SITES SURVEY

. Many sites can be selected on the IFP and Austin seimic lines in Venezuelan and Colombian basins , on Beata ridge or Mono rise .

27-1

TRANSFORM MARGIN AND PULL-APART BASINS

THE Caribbean zone is an ideal place to study a transform margin in activity and pull-apart formation . In Cayman trough a spreading center (27-2) was emplaced between two transform faults. A complete study of the process: volcanism,rapid subsidence , heat flow , high subsidence rate , is necessary to understand the old transform margin (Central Atlantic, Spitzberg). The magnetic pattern of Cayman trough is not clearly understood and a datation of the ocean floor is necessary to improve the kinematics of the Caribbean plate .

In the Anegada passage , between St Croix and Virgin islands(Figure) lie (27-3) two typical pull-apart basins which are 4500 and 3000 metres deep respectively . Separating these two basins a volcanic high looks like the Ararat volcano in Turkey which was emplaced in the centre of a pull-apart basin . A refraction profile evidences a shallow high velocity (7.3 Km/s) layer below the volcanic high . In the western(Virgin) basin the crust is also very thin and the multichannels seismic lines show a deep decollement where the listric faults die out which can be correlated with the 7.3 Km/s refractor .The eastern(St Croix) basin is shallower than the western basin and is probably less mature . A comparison of rate of sedimentation (which are much higher in a pull-apart basin than in common distensive basin), subsidence , heat flow and volcanism could be useful to understand the processes of formation from a juvenile stage (eastern basin) , a mature stage (western basin) to a spreading centre (Cayman trough) .

THEMES

1- Transform margin. Structure and evolution .
2- Sedimentary model of pull-apart basins : subsidence , sedimentation rate
3- Volcanism .
4- Kinematics of the Caribbean plate .

SITES SURVEY

. Cayman trough will be surveyed during the Seacarib 2 cruise (digitized seismic profiles ; seabeam, gravity and magnetism).

Anegada passage was surveyed during the Seacarib 1 cruise (digitized seismic profiles, seabeam , gravity and magnetism)

Martin Meschede & Wolfgang Frisch

Proposal to drill in the Caribbean Sea - Scientific Objectives

Two drilling sites in the Caribbean Sea, one in the Lesser Antilles arc with the main interest in the mechanical behaviour of subduction zones, and the other in the central Colombian basin with main interest in a probable sedimentary response to the Caribbean "sill-event" are proposed.

The mechanical behaviour of rocks in subduction zones is still poorly understood. Mineral deformations and metamorphic alterations within the accretionary prism are not clear and the distribution of stress and strain is difficult to determine and could be analyzed directly in cored material. Investigations on crystal defects (e.g. in quartz or olivine), illite crystallinity, degree of vitrinite reflexivity etc. would be helpful. Observations on processes like mineral deformation, pressure solution or intracrystalline deformation would become directly accessible.

28-1 The Lesser Antilles arc is an island arc with active accretion in contrast to the Middle America Trench off Guatemala, where accretion is not observed. A possible drill site for structural investigations in the Caribbean could be the Lesser Antilles arc east of Guadeloupe Island in continuation to Leg 110. A later drilling site should penetrate through the Middle America Trench near Leg 84 Sites comparing the structural style of this convergent plate margin without accretion (Aubouin et al. 1982) with the "normally" accreting Lesser Antilles Arc.

The "sill-event" occured during Late Cretaceous in the Caribbean Sea. The oceanic crust was thickened from 8 up to about 15 km during a short time span (Burke et al. 1978). This event is probably responsible for the accretion of oceanic terranes at the Pacific coast of Costa Rica and Panama. Main questions on this problem are: Do the sediments overlying the basaltic layer of the central Caribbean basin (drilled in the Leg 15 Sites, Donnelly et al. 1973) reflect the time and process of crustal thickening? Is there any other sedimentological or structural response to this significant event in the Caribbean? Is the "sill-event" related to the accretion of ophiolite complexes in Middle America?

28-2 A possible drilling site for questions related to the "sill-event" could be proposed within the Colombian basin between Sites 153 and 154 (Leg 15) or 502 (Leg 68). An accessory point at this site would be a sedimentological and stratigraphical investigation of the Magdalena fan north of Colombia.

29 Potential ODP Caribbean Drilling Sites

M.R. Perfit
University of Florida

The northern Caribbean plate boundary is an ideal place to investigate a variety of tectonic environments that have evolved over the past 100 Ma. Some of these environments are unique on a global scale and extremely important to understand before the geologic evolution of the Caribbean can be ascertained with any confidence. The three major areas of interest are the: 1) Yucatan Basin, a possible back-arc basin or trapped piece of oceanic crust, 2) the Cayman Trough, a relatively young piece of ocean floor forming along the present transform plate boundary, and 3) the Puerto Rico Trench, the bathymetric expression of a subduction zone associated with Late Cretaceous to Eocene arc volcanism in the Greater Antilles.

With the exception of the Yucatan Basin, these features have been fairly well-studied by geophysical techniques, dredging and submersibles. Our present knowledge suggests they are all related to initial convergence and later transcurrent motion of the Caribbean plate relative to the North American plate. The benefits in drilling all of these localities include the opportunity to investigate the evolution of a convergent trench-arc-backarc system into one that is primarily transcurrent, associated with rifting, basin formation and sea-floor spreading. The spatial relationships and sequential formation of these features could allow us to place much tighter constraints on the development of the northern Caribbean plate boundary and convergent plate boundaries in general.

Geochemical data obtained from basement cores could also provide important information regarding the 1) composition of intra-arc oceanic crust (Yucatan Basin), 2) magmatic evolution in young intraoceanic rifts (Cayman Trough), and 3) components involved in subduction beneath island arcs (Puerto Rico Trench). Additionally, the ages and provenance of sediments overlying basement will allow us to more accurately reconstruct the paleoceanographic and tectonic evolution of the Caribbean plate. This in turn has great significance for paleontologists and biogeographers whose research on the biological evolution in the Americas has largely been hindered by paleographic reconstructions.

Many important objectives could be met by drilling a series of three to six holes along the northern Caribbean plate boundary. Below, I suggested drilling three (3) sites that would help achieve the objectives discussed above.

(29-1) Site 1. Y1 - Western Yucatan Basin

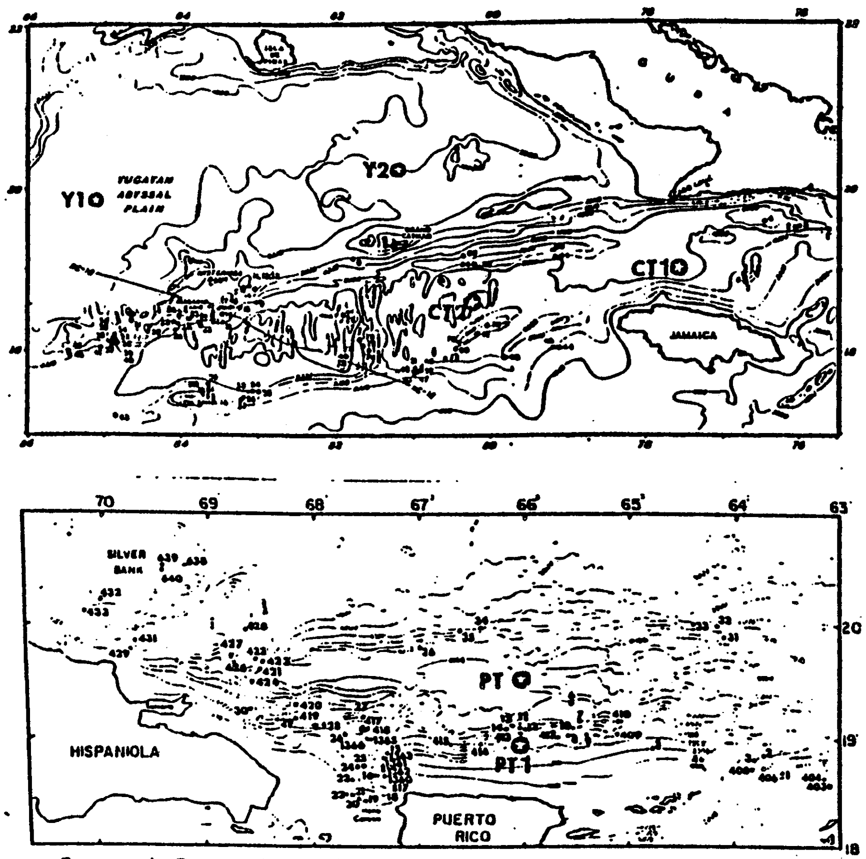
A relatively thick sedimentary section could provide paleoceanographic/tectonic history related to the opening of this basin (or trapping) since at least Cretaceous time. The opening or entrapment is intimately related to the separation of parts of Cuba from the Greater Antilles and Cayman Ridge. We don't understand how it is related to the inception of the Cayman Trough. The composition of basement rocks will be important to see if there are any arc-like signatures. A second site in the eastern Yucatan Basin should also be considered (Y2).

(29-2) Site 2: CT1 - Eastern Cayman Trough

Dredging and submersible work near the present locus of spreading in the Cayman Trough have shown it to be relatively normal oceanic crust, although it has a thin layer 2. A number of hypotheses have been developed regarding the detailed history of the trough but much of this is based on poorly constrained geophysical data. We still don't understand how or why spreading began along this strike-slip boundary. Did spreading occur as island arc crust rifted an arc (Cayman Ridge-Nicaraguan Rise connection)? Was the composition of the initial magmas MORB-like or highly alkaline like those associated with recent drifting in Hispaniola? Drilling a hole into basement through the thick sedimentary section in the easternmost portion of the trough will provide a long stratigraphic section and hopefully recover igneous rocks that reflect changing magmatic conditions during the initial rifting. These rocks and sediments could be directly compared to those previously recovered from the central portions of the trough and adjacent rifted walls. A second held further to the west (CT2) into younger crust is also advisable in order to more precisely determine the history of spreading along the mid-Cayman Spreading Center.

(29-3) Site 3: PRT1 - Puerto Rico Trench (PRT)

The PRT marks the pre-Eocene locus of subduction along the northern plate boundary. Most other paleosubduction zones in the Caribbean (and world-wide) have been so tectonically disrupted that unraveling their geologic history is nearly impossible. Extensive dredging in the trench has shown that the north wall is old oceanic crust whereas the south wall is a subduction complex at least as old as Late Cretaceous. In order for us to understand the complex processes involved in arc magmagenesis we must know what components were subducted. Geochemical investigations of the sediments, igneous and metamorphic rocks would provide needed information to assess the role of subducted material in the generation of arc magmas. Here is an opportunity to drill into a subduction zone that has not experienced a great deal of post-subduction tectonism and may record the early history of convergence and arc building along the nothern margin.



Proposed Drill Sites Perfit 1987, Figures show locations of dredges along the northern Caribbean (Perfit and Heezen 1978, Perfit et al. 1980)

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HERMANN DUQUE-CARO

I would like to address some paleoceanographic problems which have been recognized in the land stratigraphy of the NW Colombian coastal margins which could help in justifying future drilling sites, particularly in the Colombian Basin side.

1.- Middle to late Miocene biostratigraphy, paleoceanography and paleobiogeography in the Colombia Basin side.

The middle to latest Miocene chronostratigraphic interval appears to be critical to understanding the tectonic and paleoceanographic history of the Caribbean region. However, the pre-latest Miocene biostratigraphy has not yet been recorded in the Colombia Basin. In the same fashion, very little is known of the middle to late Miocene chronostratigraphic interval (12.8 to 6.3 Ma) in terms of planktic organisms in NW South America, particularly along the northwestern margins of NW Colombia, facing on the Colombia Basin.

The last known data indicate the occurrence of late Miocene radiolarian assemblages both in the Colombia Basin (Site 502) and in the coastal areas of NW Colombia (Cartagena area). No radiolarian assemblages as young as late Miocene are known in the Venezuela Basin side which could suggest the development of a late Miocene circulation barrier between the Colombia and Venezuela basins.

On the other hand, recent biostratigraphic studies in the Pacific coastal margins (Atrato Basin) in NW Colombia indicate an abrupt paleoceanographic change between the Atlantic to Pacific water flow, associated with a partial emergence of the southern Central American isthmus during the late middle (12.8 Ma) to late Miocene (6.3 Ma). As a result, a distinctive and homogenous coastal Pacific benthic foraminiferal assemblages and southern extension of the cool California Current developed along the Pacific coastal areas of NW South America. These phenomena which restricted the water circulation between the Pacific and the Caribbean and apparently within the Caribbean must be reflected in both in taxonomic and planktic assemblage differences.

These data are justifying the critical importance a future site in the Colombia Basin reaching middle Miocene sediments as old as 12.8 Ma. (Zone N. 12) to solve these problems. (30-1)

31

A SOUTH CARIBBEAN TRANSECT

LESLIE BARKER/PHILLIP PAYNE
BARBADOS NATIONAL OIL CO. LTD.

'HE IMPORTANCE OF THE LESSER ANTILLES FOREARC SYSTEM, IN GENERALLY JNDERSTANDING PLATE MOTION MECHANISIMS AND INTERACTION BETWEEN PLATES, PARTICULARLY AT AREAS OF ACTIVE SUBDUCTION CANNOT BE OVER-EMPHASIZED.

DETAILED PROPOSALS FOR DRILLING THE LESSER ANTILLES FOREARC (LAF) HAVE ALREADY BEEN DOCUMENTED IN REPORTS OF THE CARRIBEAN WORKIN G GROUP TO O.D.P. IN 1984. HOWEVER, OF PARTICULAR IMPORTANCE IN THE LAF IS THE SIGNIFICANT AMOUNT OF DATA (BATHYMETRIC, SEISMIC AND BIOSTRATIGRAPHIC) ALREADY AVAILABLE ON THIS PRISM, WHICH CAN ASSIST IN ARRIVING AT CONCLUSIVE SOLUTIONS FOR SOME MAJOR PROBLEMS WITH RELATIVELY LITTLE MORE DRILLING. THE RESULTS MAY THEN BE APPLIED TO OTHER ARC AND ACCRETIONARY PRISM SYSTEMS WORLDWIDE.

THE GEOGRAPHY OF THE PRISM IS IDEAL FOR STUDYING A RANGE OF PROBLEMS. THIS PRISM STRETCHES FROM 11 DEG. - 12 DEG. N. WHERE IT OCCUPIES A BROAD THICK AREA SOUTH OF BARBADOS ISLAND TO THE THINNER NARROWER PRISM SECTIONS IN THE REGION OF 15 DEG. - 16 DEG. N.

THOUGH MUCH DATA HAS BEEN ALREADY ACQUIRED IN THE NORTHERN REGION OF THIS PRISM (DSDP 541, 542, 543 AND ODP LEG 110), NO DRILLING HAS BEEN DONE IN THE MORE INTERESTING AND PRESUMABLY COMPLICATED SOUT HERN SECTION, AND THUS THIS AREA REMAINS A PRIME TARGET FOR A TRANSEC T OF CAREFULLY SITED HOLES.

31-1

THE TRANSECT IN THE SOUTHERN PART OF THE LAF SHOULD BE DESIGNED TO SOLVE THE FOLLOWING PROBLEMS:

A. THE EVOLUTIONARY PROCESSES IN THE DEVELOPMENT OF THICK PRISMS PARTICULARLY METHODS OF SEDIMENT TRANSFER;

B. RESEDIMENTATION IN INTRA-PRISM BASINS;

C. STRUCTURAL STYLES ACROSS THE PRISM; AND

D. THE STRATIGRAPHIC RELATIONSHIPS BETWEEN THE NEOGENE TOBAGO TROUGH AND OTHER SMALLER BASIN SEDIMENTS, THE PALEOGENE SEDIMENTS OF THE PRISM, AND THE OLDER BASEMENT ROCKS SUCH AS THE ARAYA-TOBAGO META MORPHICS (META SEDIMENTS?)

32

DRILLING AT NEAR-TRENCH POSITIONS EAST OF LESSER ANTILLES FOREARC

By J.H. BEHRMANN IGL, Giessen University, Senckenbergstr. 3, D-6300 Giessen, West Germany.

Background and rationale

The area east of the Lesser Antilles islands is one of the best explored forearc regions in the world. Geometry and dynamics of accretionary wedge building are known from detailed geophysical investigations, theoretical studies, and previous ODP/DSDP drilling. However, study of the accretionary wedge itself only provides a historical and dynamic record of the sediments that have evaded subduction into the earth's mantle.

A major question to be addressed in geotectonics is how much sediment is subducted into the mantle at convergent margins. In principle the problem can be analysed using the following variables:

a) duration and rate of accretionary wedge building

b) rates and direction of plate convergence

c) compactional behavior of sediments (in order to compare volumes of sediments accreted, and those accretable or subductable per unit time).

d) sedimentation dynamics on the abyssal plain in front of the forearc.

Variables (a), (b) and (c) can be fairly well constrained from existing geophysical data, plate motion models, and theoretical compaction functions. Knowledge on (d) is critical, and is used to estimate how much sediment can be accumulated on a piece of oceanic plate during its travel from the mid-ocean ridge to the trench. This will be the amount either accretable and/or subductable. Sediment accumulation will be variable, depending mainly on the distance from terrigenous sediment sources, and on the nature of the pelagic sediment source.

Here I propose to study sedimentation dynamics in near-trench locations east of the Lesser Antilles forearc. The objective is to constrain variable (d) for geotectonic modelling of sediment contamination of the earth's mantle.

Proposal

Sedimentation on the Atlantic abyssal plain east of the Lesser Antilles is controlled by a pelagic background source and a southward growing terrigeneous component due to the Orinoco input. In Fig. 1 a sedimentation rate profile is constructed from existing DSDP/ODP borehole data east of the central Lesser Antilles forearc. Fig. 2 shows that a more general parabolic function for sediment thickness versus plate age in this area can be derived from the averaged data in Fig. 1. To average the data has the effect of removing local heterogeneities in the sedimentation pattern.

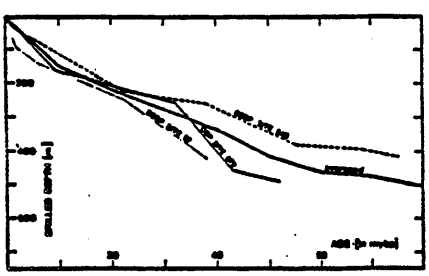

Fig. 1

Evolution of sediment thickness versus age east of central Lesser Antilles forearc from DSDP/ODP data.

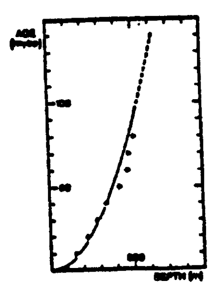

Fig. 2

Generalised sediment thickness as function of plate age. After data in Fig. 1.

As total sediment thicknesses are subject to large variations along strike of the Lesser Antilles forearc, additional stratigraphic information needs to be collected from near-trench sites closer to the South American continent (Sites MAC 1, MAC 2 on Fig. 3), east of the deformation front of the accretionary wedge. A third site (MAC 3 in Fig. 3) is to be drilled east of the "starved" part of the accretionary wedge towards the north.

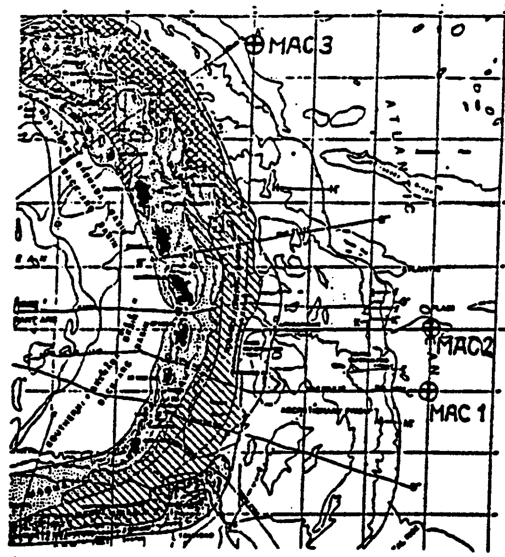

Fig. 3. Approximate location of proposed drillsites.

(32-1) MAC 1. Located at approximately 57°W-long, 13°N-lat. Water depth near 5000 m. Sediment thickness approx. 2-2.5 sec. dual travel time. Planned penetration: approx. 1000 m. Continuous or partial coring. Oceanic basement will not be reached, but valuable information can be gained on younger part of sedimentation history.

(32-2) MAC 2. Located at approximately 57°W-long, 14°N-lat. Water depth near 5000 m. Sediment thickness approx. 1 sec dual travel time. Contiuous or partial coring. Planned penetration: to oceanic basement.

(32-3) MAC 3. Located at approximately 60°W-long, 18°30' N-lat. Water depth near 6000 m. Estimated sediment thickness: 0.5 sec dual travel time. continuous coring. Planned Penetration: to oceanic basement.

Duration and technical requirements

The proposed drilling program can probably be accomplished during half a standard-sized ODP-leg (4 weeks). The project would seek technical and logistical cooperation with other drilling ventures in the Lesser Antilles or Western Central Atlantic areas to form a complete drilling leg or two interconnected half-legs.

The approach is "low-tech". Drilling goals can be achieved with existing equipment aboard "Joides Resolution".

Additional scientific benefits

Ocean history. Early evolution of the Central Atlantic. Radiometric dating and petrology of Cretaceous oceanic crust.

High resolution biostratigraphy of Cretaceous to present sediment sequences in Caribbean area.

Physical Properties. Establishment of gradients in physical properties in suite of logs showing variable terrigeneous input.

33 Caribbean Deep Seismic Reflection

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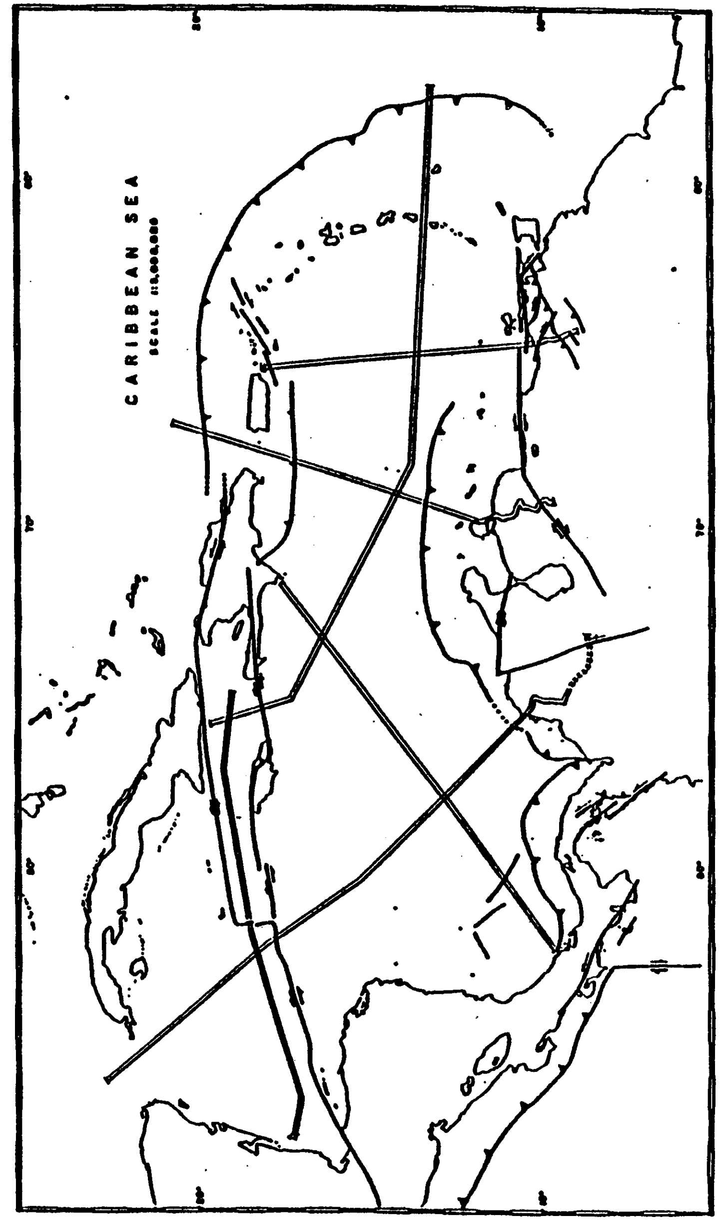
We propose to acquire a series of deep seismic reflection profiles across the Caribbean plate. These profiles would be acquired with techniques similar to those used by the BIRPS, COCORP, and ECORS programs, i.e., very large sources and long arrays to penetrate and record crustal and upper mantle reflectors down to 20 to 30 seconds two way travel time. The network shown in the attached figure spans the length and width of the present Caribbean plate and its boundaries, includes onland extensions of marine lines. The network is designed to both map the lateral continuity and thickness of the plate and to image the deep crustal structure of the present plate margins as well as that of the variety of tectonic features within the plate -extensional basins, island arcs, aseismic ridges, structural lineaments. These profiles will not only provide a frame on which we can hang current seismic reflection and refraction data, but will also establish a set of crustal baselines from which we may calibrate and interpret current regional remote sensed geophysical data, such as gravity, magnetics, heatflow, etc.

Throughout its history the Caribbean has acted as a gate, or valve, between the Atlantic and Pacific oceanic systems to the east and west, and between the North American and South American continents to the north and south. The alternate opening and shutting of oceanic seaways and continental land bridges has had profound effects on past ocean dynamics and paleoclimates as well as on biotic exchange between both the two continents and two oceans. Although the geology of the region, particularly the depositional record, should provide at least a partial history of this Caribbean gateway, this history has proved elusive. Part of the problem is that the overall tectonic history of the region cannot be resolved in sufficient detail.

The prevaling hypothesis of present-day Caribbean plate origin is that the plate is of Pacific origin and was inserted between the North and South American plates as they moved westward relative to the Pacific plates. The older (Cretaceous) Caribbean ocean basin was subducted westward beneath the inserted present-day plate. The tectonic structure of the present northern Caribbean plate boundary suggests that about 1000 km of left-lateral displacement has occurred between the present-day Caribbean plate and the North American plate. This observation supports the insertion hypothesis. However, an equivalent amount of conjugate right-lateral displacement is not in evidence between the Caribbean and South American plates. Strike-slip movement along faults parallel to the southern margin accounts for a few hundred kilometers of displacement at most. This suggests that the southern displacement zone has not yet been properly identified, that the plate boundary may be convergent rather than strike-slip, or that relatively little displacement has in fact occurred between the two plates. This latter alternative implies that the present-day Caribbean plate is or was recently part of the South American plate and has not been inserted from the Pacific.

A second problem with reconstructing the tectonics of the Caribbean is determing to what degree the current plate has been fragmented. There is increasing evidence that the northern boundary consists of a wide (100 to 250 km) deformation zone containing tectonic slivers and blocks, and possibly two small plates. Western Venezuela-northern Colombia may be undergoing similar fragmentation at present, with crustal blocks moving northward onto the Caribbean plate. This not only complicates resolving relative motions among the Caribbean and surrounding plates, but also raises questions whether the Caribbean "core" - Venezuela and Colombia Basins and Nicaragua Rise- has not itself undergone fragmentation in the past.

The seismic program we propose directly addresses these questions of crustal continuity and fragmentation, including the critical questions as to the nature of the geometry of Caribbean-South American margin. The lines should also resolve whether the plate is contiguous across the two dominantly enigmatic features of the central Caribbean, the Beata Rise and Hess Escarpment. Such information is critical to the two major drilling themes proposed for the Caribbean -paleogateways and mid-plate volcanism- and will provide quantitative constraints on the origin and tectonic environment of the region.



341 *Proposal submitted to the Caribbean Scientific Drilling*

Jamaica - November 17 - 21, 1987

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TITLE
"CENOZOIC EVOLUTION OF SMALL DETACHED CARBONATE BANKS AND THEIR DEEP PERIPLATFORM SURROUNDINGS IN THE TECTONICALLY ACTIVE SETTING OF THE NICARAGUA RISE"

The past decade has seen an explosion in our knowledge and understanding of the evolution of the shallow carbonate banks as well as their periplatform deep water surroundings in the Bahamas (reviewed by Schlager and Ginsburg, 1981, and Mullins, 1983. At the heart of this success has been the intergration of high resolution seismic reflection data with sediment/rock samples (piston cores, rock dredges, submersibles) and most recently, drill cores, recovered on ODP Leg 101 (Austin, Schlager, Palmer *et al.*, 1986).

We propose in this preliminary writeup to drill several ODP Sites (APC, XCB as well as rotary drilling) in the close vicinity of submerged carbonate-producing Pedro, Rosalind and Serranilla Banks located on the crest of the Nicaragua Rise in the Caribbean Sea, in order to extend our understanding of the evolution of carbonate banks and their periplatform deep surroundings to a new and very different setting.

This carbonate province differs from the Bahamian prototype in several important aspects: (1) The Nicaragua Rise is a tectonically active area in the vicinity of the Caribbean-North American plate boundary, whereas the Bahamian platforms are currently tectonically quiescent. (2) Pedro, Rosalind and Serranilla Banks are submerged by much more water (30 meters average depth) than the Bahamas (less than 10 meters average depth) and have therefore previously been thought to be a drowned, unproductive platform contrary to our preliminary findings. (3) Pedro, Rosalind and Serranilla Banks are somewhat smaller and more isolated from other sources of shallow carbonate sediments than Great and Little Bahama Banks, hence they should make a more simply understood carbonate province. Finally, (4) the carbonate province of the Nicaragua Rise is located within the tropical latitudinal belt, experiences steady northeasterly trade winds, and is not as influenced by winter cold fronts as are the more northern Bahamas.

In addition the carbonate province of the Nicaragua Rise is unique in many different aspects: This carbonate system is relatively <u>young</u>. Based on well data, we know that the Banks have evolved since the Eocene, whereas the Banks in the Bahamas began their buildup already during the Triassic. The carbonate province of the Nicaragua Rise may represent an early phase of carbonate platform development where the initiation of platform segmentation is perhaps the typical development of a carbonate system along a tectonically active basin (Caribbean, western Pacific Ocean), with possible lateral expansion, or on the contrary undergoing important erosion along their margins and thus becoming more dissected and segmented, by tectonically induced faulting, by marginal collapse, or by physical, biological and chemical erosion. Small, detached carbonate platforms controlled by underlying tectonically-derived structural features have been more common in the geologic past than the Bahama type, where banks occupying a passive tectonic setting, (1) have persisted for a very long period of time, (2) are enormous in size (width and thickness) and (3) are shallow, rimmed platforms. The carbonate province of the Nicaragua Rise would be therefore a better analog for fossil carbonate provinces as i.e., the small Ladinian platform in the Venetian Alps, the small detached platforms of the Upper Devonian in Alberta, Canada, or as the Triassic and Jurassic evolution of the carbonate systems along the northern Tethyan continental margin.

Finally, the carbonate platforms of the Nicaragua Rise are located in a key position during the entire paleoceanographic evolution of the western Caribbean, Yucatan Basin, eastern Gulf of Mexico and Straits of Florida. The Nicaragua Rise was the close witness of the closure of the Isthmus of Panama tentatively dated as early as middle Miocene (~ 16 m.y.) by Mullins *et al.*, 1987 or as late as early Pliocene (3.1 m.y.) by Keigwin, 1978. The Rise itself was perhaps a fully developed shallow carbonate barrier at some point during the Paleogene, preventing any northwestward surface water flow as the present Caribbean Current. These successive Cenozoic paleoceanographic events should be well recorded in the sedimentary sequences deposited in the deep surroundings of the shallow banks.

The existing seismic coverage of the carbonate province of the Nicaragua Rise is quite extensive. U.T. (Austin) has several multichannel seismic surveys of the area, as well as I.F.P. (Institut Francais du Pètrole, Paris) has numerous high resolution seismic profiles (1980 and 1982). There are currently two NSF funded research programs studying the carbonate province of the Nicaragua Rise: (1) Albert Hine and Pamela Hallock-Muller are working on the bank top as well as the upper slopes (0-200 m) of Pedro, Rosalind, Serranilla, and MisKito Banks, (2) Paul Baker and I just were awarded an NSF grant to study the deep periplatform surroundings of the Nicaragua Rise, by high resolution watergun seismic, coring, dredging and chemistry of the water column. This drilling proposal could well be combined with Donelly's proposal and the location of his proposed drilling Sites A, 20, 21, B and 21 would need to be adjusted based on the results of the different seagoing operations in 1988 and the study of the seismic profiles of U.T. (Austin) and IFP-CEPM (Paris); both sets are currently proprietary data.

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Drilling Site Proposal for the Caribbean Region
Ocean Drilling Program Workshop November 1987

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PALEOCEANOGRAPHIC EVOLUTION OF THE CARIBBEAN: MESOZOIC - TERTIARY

The Caribbean is one of the most comploex regions structurally, tectonically and paleoceanographically. Many questions still remain regarding its evolution, origin and migration of plates, formation of basins and ridges, paleoclimate and paleocirculation histories. A few strategically placed drill holes in regions yielding the best possible stratigraphic record could answer many of these questions and lead to a better understanding of global tectonics, paleoclimate and paleocirculation. The following drilling objectives are proposed.

OBJECTIVES:
1. Origin of Caribbean Plate
2. Atlantic-Pacific Paleocirculation
3. Basement age of Basins
4. Subsidence and uplift histories of basins and ridges

Each of these objectives can be achieved more successfully using a multi-disciplinary approach integrating structural, tectonic and sedimentologic studies with stratigraphic, paleoclimatic and paleoceanographic studies. There appears to be sufficient interest for such an approach as the earlier Caribbean Working Group (1984) has expressed similar objectives and at least 12 of the 27 proposals in the present Working Group address these objectives from different disciplines. (Proposals by Buffer et al. (2), Burkart (3), Donnelly (4), Draper (5), Hall (8), Mascle (12), Pindell (15), Saunders (17), Schlanger (18), Speed (21), Klitgord (24), Mauffret (27).

To obtain maximum paleoceanographic information drill holes must be located where relatively continuous sedimentation above the CCD is available and microfossils are well preserved. If such sections are made available the following information can be gained.

<u>Age Control:</u> based on planktic foraminifers and nannoplankton age control on the order of a few 100,000 years for Cretaceous to Eocene sediments and about 100,000 to 150,000 years for Oligocene to Pliocene sediments can be obtained.
<u>Paleodepth:</u> Subsidence and uplift histories can be determined from benthic foraminifera.
<u>Paleoclimate:</u> oxygen isotope data of foraminifers and faunal assemblage data (planktic foraminifers, nannoplankton and siliceous microfossils) can yield a detailed paleoclimatic history for Cretaceous and Tertiary sediments.
<u>Paleocirculation:</u> This type of information can be gained from Atlantic and Pacific faunal affinities, the carbon-13 record, and from hiatus patterns throughout the Atlantic, Caribbean and Pacific.

SUGGESTED DRILLING LOCATIONS (ODP Sites)

1. Cayman Trough	origin of Caribbean plate	21-1	35-1
2. Yucatan Basin	Cretaceous to Tertiary record	11-1, 15-1, 24-1	35-2
3. Colombia Basin	origin and history of	14-2, 24-5	35-3
4. Venezuela Basin	basins, paleocirculation,		
	Atlantic/Pacific faunal affinities	12-3, 18-1, 24-4	35-4

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Tectonics Panel: Proposal
for further seismic surveys of the
Colombian and Venezuelan Basins

In order to select the optimum drill site location to achieve our objectives, and develop adequate background data, it is recommended that studies and surveys in certain areas be conducted prior to drilling. In a few areas surrounding the Caribbean Sea workers have reported sedimentary and igneous sections that are strikingly similar to that of horizon B". We recommend that each of these outcrops (Haiti, Curacao, Costa Rica, and Ecuador-Colombia) undergo a systematic study to be compared with drilling results in the basin. The age and chemistry and overall character of the units above and below B" should be the primary characteristics to be sought for comparison. Particular emphasis should be placed on the "rough basement" that apparently underlies horizon B" in the Colombian and Venezuelan basins.

(36-1) Multichannel seismic data in the central region of the Colombian Basin has revealed a window in the horizon B" where the "rough basement" is observed to plunge beneath B". Additional MCS surveys should be conducted in this area to define with much greater precision the extent of the window and the nature of the termination of B". It has been suggested that the "rough basement" may extend on the lower reaches of the Nicaragua Rise in much the same way as do A" and B" to the north (Site 152). If this is the case then ancient (Early Cretaceous or even Jurassic sediments) may be cored at much shallower depths below the seafloor and without the added obstacle of thick turbidite. Surveys would also be directed toward investigating this possibility.

VIII. TECHNOLOGICAL RECOMMENDATIONS

Oriented Cores

An urgent need exists in ODP drilling for taking oriented cores. The applications are to many fields of investigation. Quite possibly the usefulness for large oceanic coastal plates is less than for smaller, more variable, and complex plates such as the Philippine, Caribbean, etc. The following are the main uses we foresee for oriented cores:

Paleomagnetism

Oriented cores providing well-oriented paleomagnetic vectors will help to solve the following tectonic and paleogeographic problems.

1. To demonstrate latitude of origin and azimuthal orientation of tectonic plate segments of sectors.
2. To distinguish equatorial approach - retreat from equatorial crossing for low latitude mobile plates such as Caribbean; this cannot be done using inclinations alone.
3. To identify major unrecognized plate boundaries in oceanic plates. For example inclination data alone (unoriented cores) may not be useful in recognizing such boundaries whereas declination divergence may be the single important clue. Particular plate boundaries to evaluate could be Hess Escarpment and Beata Ridge.
4. To compare on-shore paleomagnetic information, to correlate directions of plate motion relative to island arcs, to verify island arc polarity, etc.
5. To evaluate specific paleogeographic hypotheses, e.g., was the Caribbean part of the Pacific? Did it evolve *in situ*, etc.?
6. To aid in proper interpretation of marine magnetic anomalies by establishing calibration points where direction, intensity, and susceptibility of magnetization are meas-

ured (e.g. to interpret magnetic anomalies of the Yucatan, Cayman, Colombian, and Venezuelan Basins).

Application of Oriented Cores to Other Specialities

1. Structural petrofabric studies: fractures, slickensides, and microfabric elements for strain analysis and strain history, and for relating dynamics/kinematics to time and place in the larger regional tectonic setting.
2. Sedimentological/paleoceanographic studies: current flow directions may reveal appearance/disappearance of major water mass circulation barriers by influencing directions of flow in bottom waters.
3. Igneous petrology: source directions of magma may be deduced from anisotopy of magnetic susceptibility (AMS). This is useful for determining source of flows, dikes (and dike orientations, e.g. sheeted dikes), and sills, and possibly for determining source direction towards plumes/hot spots passed over by the site, etc.
4. Magnetostratigraphic and correlation studies: at low latitudes, paleomagnetic inclinations (i.e. from vertical cores) are useless for magnetostratigraphy; only paleomagnetic declinations (requiring oriented cores) can be used to establish magnetic stratigraphy in low latitudes, as in the Caribbean.

The basic technology is available from oil drilling technology, with minor adaptation to ODP requirements. Especially, we urge the use of gyrocompass or other non-magnetic method for determining sampler orientation, in conjunction with sidewall core drills of one inch core capacity. This is important to avoid orientation by, for example, spurious magnetic fields as can be encountered in basalt. The shock of explosive-driven explosive cores should be avoided, as it is likely to have adverse impact on AMS and possibly also on remanent magnetization and structure (by including new fractures for example).

The entire main core at an ODP site can be effectively oriented by having orientation calibration cores along its length. This greatly increases the amount of material available to all scientists requiring oriented materials.

Summary

Taking oriented cores can be applied globally. The technique is essential for the study of small, mobile, polysegment plates, especially for low latitude plates like the Caribbean.

Stress Measurements of the Caribbean Plate

The Caribbean Plate is bounded on the North and South by two continents. Seismic evidence indicates that the present motion of the Caribbean Plate is eastward with respect to both North and South America. Onland structural studies indicate that this has been active through the Neogene. The presence of submarine accretionary structures on both the north and south margins, in addition to analysis of Neogene structures, suggest that the plate is also subject to some degree of north-south compression. As the Caribbean is anomalously thick and less subject to subduction it is more likely to be under stress. It is suggested that as such, bore hole stress measurements should be made on all holes in the Caribbean interior. Such measurements will lead to a greater understanding of the deformation of a small buoyant plate sandwiched between the two contents. Moreover, they will tie in with Global Positioning System (GPS) experiments presently being conducted in the Caribbean and to onland neotectonic and seismic studies. The results will also help resolve the problem of the plate driving of the Caribbean. As the Caribbean plate is not connected to a subducting slab or major spreading center, its movement must be due to either different mechanical coupling at the Central American and Lesser Antilles trenches, or by drag and the base of the plate. The expected stress fields for each of these alternatives are sufficiently different that they can be distinguished by the proposed *in situ* stress studies, and hence can provide important insights into the dynamic aspects of plate motion.

Turbidite Drilling

To achieve the drilling objectives outlined in this document, holes will have to be drilled through about 2000 meters of sediment (oldest crust in the Venezuelan Basin and Yucatan Basin). A large part of the section to be drilled in the Yucatan Basin is likely to be turbiditic, but the courseness of the sand or silt or thickness of the beds is not know. However, we need to be prepared for poor drilling conditions since the total distance from the source (south-west) suggests that the turbidites at the site will be closer than distal.

IX: RECOMMENDATIONS: PRIORITY SCIENTIFIC PROBLEMS OF THE CARIBBEAN AND AN OCEAN DRILLING STRATEGY

Introduction

From individual proposals (section VII), panel deliberations (sections III-VI), and discussion in plenary session, the Workshop concluded with an appraisal of the most important geoscientific problems of the Caribbean for which ocean drilling is a necessary approach. The basis for assignment of problems as priority is their dual scope: thematic in the sense of forefront topics in earth processes and history, and at the same time, addressing major knowledge gaps in Caribbean geologic evolution. The thematic content of such problems is in line with that specified by COSOD, TECP, LITH, and SOHP white papers.

Eight leading problems are presented below without ranking together with recommended sites for ODP drilling. The sites (Fig. IX-1) are then placed in a drilling strategy with objectives and approximate durations. It is estimated that 9 drilling legs (2 month/leg) are needed to address adequately the eight problems. The drilling strategy is highly generalized; it does not include exact positions, hole specifications, or geophysical documentation. Such information is left to individual proposals for ODP legs which this report is intended to spawn.

Priority Problems of the Caribbean

• **Paleogateways of the Caribbean:** Paleogateways addresses the tectonics and history of development of deep and shallow seaways between the Atlantic and Pacific that record the breakup of Pangea and early drifting apart of North and South America. Questions are 1) the age range and degree of breakup vs. position, and 2) the kinematics of breakup — how much extension was accommodated and whether motions were streamline or locally rotational.

The objectives are the oldest Mesozoic strata, Jurassic or Early Cretaceous, that are probably native to the Caribbean region — that is, not exotic and a product of large tectonic transport, and shal-

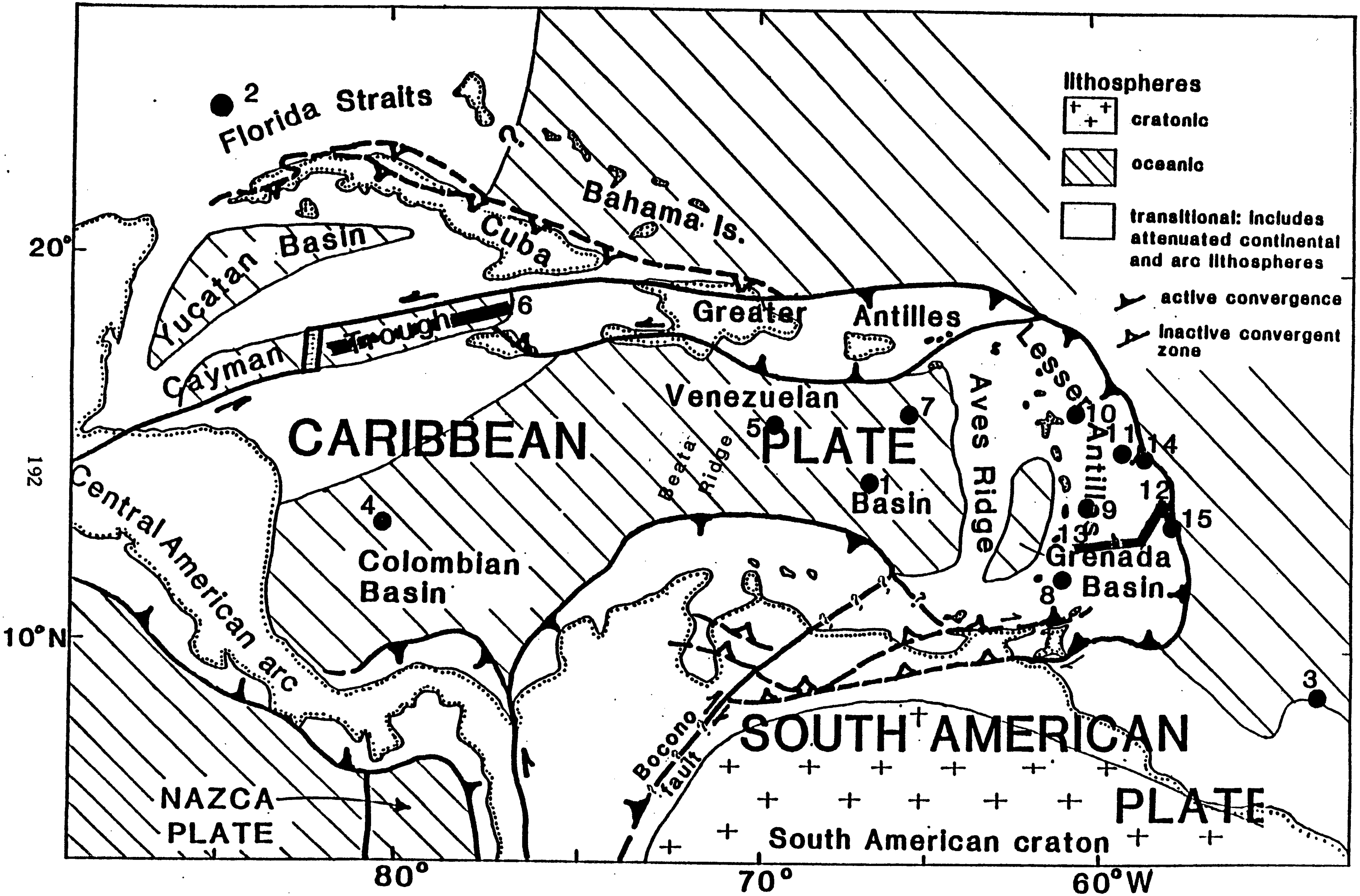

Figure IX-1: Recommended sites for ODP drilling.

low sampling of subjacent basement. Information sought is subsidence and sediment provenance histories, seismic horizon identification, basement affiliation, and paleomagnetic directions.

Primary sites, discussed in section III, are southeastern Venezuelan Basin (Fig. IX-1-1), southeastern Gulf of Mexico (Fix IX-1-2), and Demerara Rise (Fig IX-1-3).

• **Paleoceanography of the Caribbean:** This problem embraces the Jurassic and Cretaceous histories of Atlantic-Pacific interexchanges across the Caribbean region and their influence on global oceanographic and climatic histories, diagenesis, and biotic evolution. Questions are the position and ages of first shallow and deep water seaways and the durations and watermass history (flow direction, chemistry, temperature) of such seaways.

The objectives are, as with paleogateways, the oldest Mesozoic strata as well as succeeding full Cretaceous sections that are probably or potentially native to the Caribbean. Information sought is a complete sediment and pore fluid record, to be obtained with maximum recovery possible.

Primary sites, discussed in section IV, are 1) southeastern Gulf of Mexico (Fig. IX-1-2), 2) Demerara Rise (Fig. IX-1-3), 3) southeastern Venezuelan Basin (Fig. IX-1-1), and 4) Colombian (Fig. IX-1-4) and northwestern Venezuelan (Fig. IX-1-5) Basins.

• **Origin of the Caribbean Plate:** The question is whether the principal oceanic lithospheres of the Caribbean plate, those of the Venezuelan and Colombian Basins, are native or exotic to the Caribbean region. If exotic, a further question is the history of large transport, whether principally mid- and late Cenozoic and at the modern Caribbean-North American plate boundary or principally Late Cretaceous and early Cenozoic. An exotic origin of the Caribbean plate includes important thematic problems: 1) the mechanisms and causes of insertion tectonics wherein a small plate (Ca) is driven into a gap between large plates (NA and SA), and 2) the only preserved fragment of Mesozoic Farallon plate.

Primary sites, discussed in section III, are: 1) Cayman Trough (Fig. IX-6), 2) southeastern Venezuelan Basin (Fig IX-1), 3) western Colombian Basin (Fig. IX-4), and 4) Beata Ridge or eastern Venezuelan Basin (Fig. IX-7). Each of these sites includes investigations for one or more of the other seven major problems.

• **Cayman Trough:** The Cayman Trough includes four thematic problems, as follows: 1) mechanics of formation and deformation (ridge jumping, rotations, faulting) of oceanic lithosphere under very highly oblique spreading; 2) test of theory of thermal subsidence of oceanic lithosphere with wall (lateral) -cooling effects; 3) basaltic magma composition as function of progressive development of a pullapart basin; and 4) Cenozoic history of the Caribbean-North America plate boundary with emphases on duration and total slip.

The objectives are to drill basement at varied positions from the modern ridge east to the oldest basalt of spreading origin in the Cayman Trough and farther, to basalt on presumably rifted crust. Information sought is the age, depth, composition, and magnetization direction at each hole. It is also a goal to drill through a presumably thin layer 2 into gabbroic crust at one hole.

Prime sites, discussed in section III and VI, are (Fig. IX-6) in the eastern half of the Cayman Trough.

• **Caribbean Oceanic Plateaus:** This problem concerns the nature and origin of widespread Late Cretaceous basaltic volcanism in the Venezuelan and Colombian basins that was plateau-forming and probably of midplate generation. Questions are the processes and duration of formation, tectonic environment, and geographic origin (exotic or native) of the plateau basalts, and whether they are primary crust or lie above older sediments and oceanic crust.

The objectives are to establish the character of the plateau basalt by distributed shallow drilling and a single deep hole. The data to be determined are the ages, chemical and isotopic compositions, proportions of intrusion to extrusion, magnetization directions, and sediment provenance through the upper 200 m of basalt in the shallow holes and through the entire plateau basalt section (between 0.8 and 2 km) in the deep hole. A correlative objective is the Cretaceous sediment column at a site of normal oceanic crust adjacent to oceanic plateaus. Here, the data sought are the sedimentation history from the plateaus and its record of duration and composition of plateau magmas and proportion of extrusion.

Primary sites are in the southwestern Colombian Basin (Fig. IX-1-4) and south of the Dominican Republic (Fig. IX-1-5) for the shallow holes; 2) in the eastern Venezuelan Basin (Fig. IX-1-7) for the deep hole; and 3) in the southeastern Venezuelan Basin (Fig. IX-1-1) for the sediment column above normal crust.

• **Sediment Subduction and Arc Magmatism:** The problem is whether or not sediments and(or) surficial fluids continue with downgoing oceanic slabs to magma generation depths below arcs and, if so, whether or not such sediments and fluids are a significant component of arc magmas. Spatially correlated compositional gradients in Atlantic sediments and Quaternary magmatic rocks of the Lesser Antilles arc suggest sediments and(or) fluids substantially affect magmas, and the nature of this possible relation needs amplification. More information is needed on magma compositions, along the arc (along the gradient) and with age over the Quaternary-Neogene eruptive phase of the arc.

The objectives are to drill a succession of tephra layers that will record the eruptive history at each of three sites along the eastern arc flank that record proximal, intermediate, and distal positions of the Atlantic slab with respect to the outflow of South American continental sediment. The data to be determined are chemical and isotopic compositions and ages of the tephra.

Prime sites are east of Grenada (proximal) (Fig. IX-1-8), east of St. Lucia (intermediate) (Fig. IX-1-9), and east of Guadeloupe (distal) (Fig. IX-1-10).

• **Mechanics of Accretionary Forearc Development:** The kinematics and dynamics of accretionary forearcs, widely recognized to be fundamental among tectonic processes and to bear on the development of mountain belts globally, have a fair theoretical foundation. There are, however, major gaps in understanding which are crucial to a comprehensive theory. These are mechanisms of accretionary wedge thickening between the outer deformation front and the structural high; deformation arcward of the structural high and forearc basin-wedge interactions; and nature and causes of episodicity of accretion. Each of these can be investigated probably as well as anywhere in the world in the Lesser Antilles forearc.

The objectives of wedge thickening investigations are to test for the existence and the geometry, motion, and other characteristics of various mechanisms (section V): underplating, out-of-sequence thrusts, and folding plus incorporation of slope cover, all of which have been interpreted from seismic studies on the Barbados Ridge. The sites for examining sediment thickening include a hole into underthrust sediments 15 km upslope from Leg 110 to test for underplating (Fig. IX-1-11) and a transect up the prism slope at 12°20'N (Fig. IX-1-12).

The objectives of the forearc basin-wedge deformation investigation are to learn the timing and kinematics (distribution of basin strata vs. early wedge elements) in the major deformation belt arcward of the structural high. The sites for this investigation are in a transect across the structural high to the forearc basin (Fig. IX-1-13).

The objectives of the episodicity investigation are to see if there have been periods of rapid and slow growth and if these correlate with other geologic variables such as plate motion changes. Such information can be learned by drilling to the base of slope cover in a number of shallow holes on the first transect (Fig. IX-1-12).

• **Fluids Evolution in Accretionary Wedges:** The hydrologic system of accretionary wedges is a forefront topic among today's major scientific questions. The Barbados accretionary wedge has provided more insight and data to the burgeoning theory of how such systems work than any other forearc, and it is evident that further investigations of this type will accelerate our understanding of them. The principal questions are the actual rates and transience of fluid and heat flows, the nature of fluid sources, conduits, and principal transfer mechanisms, and differences between low and high permeability wedges (mud and sand-rich, respectively).

The objectives are to measure fluid flow, pressure, and composition as a function of depth through the lower wedge slope and through the underthrust strata as deep as top oceanic crust. The objective should also include analysis of rock structures and sediment diagenesis. The sites should also include reference sections outboard of the deformation front and cut a major out-of-sequence thrust and mud diapir within the wedge.

Prime sites for such activities should include 1) a hole near ODP 671 for full penetration of the underthrust section (Fig. IX-1-14); 2) holes just upslope from 671 for flow at an out-of-sequence thrust (Fig. IX-1-11); and 3) a set of holes across the outer deformation front near about 15° N (Fig. IX-1-15) where incoming sediment is probably much sandier than at the Leg 110 latitude.

Drilling Summary

Numbers attached to sites are their locators on Figure IX-1; they are not rankings. Estimated drilling legs are 2 months.

Southeastern Venezuela Basin (1):

problems: paleogateways, paleoceanography, plateaus, Ca plate.

specifications: core full 2 km sediment and penetrate oceanic basement through weathering zone (Fig. III-6).

objectives: age, tectonics, and exotic vs. native origin of normal oceanic basement; bathymetric, sediment and biotic provenance; and paleoceanographic histories of succeeding Jurassic(?), Cretaceous, and Cenozoic strata; particular emphasis on Late Cretaceous volcanogenic sediment succession related to formation of then-adjacent(?) oceanic basaltic plateaus.

duration: 1 leg.

Southeastern Gulf of Mexico (2):

problems: paleogateways, paleoceanography.

specifications: drill at sites with shallow penetration to Lower Cretaceous level of Leg 77 and into layered rocks above basement (Fig. III-4).

objectives: age range, tectonic, and bathymetric history and kinematics of rifting in transitional crust between Cuba and Gulf of Mexico.

duration: 1/2 leg.

Demerara Rise (3):

problems: paleogateways, paleoceanography.

specifications: drill outboard of shelf-slope break for shallow penetration through known Valanginian horizon and to subjacent strata and as far as basement (Fig. III-5); second shallow hole outboard of slope to oceanic basement.

objectives: age range, tectonics, and bathymetric history of rifting at northern passive margin of South America; time of onset of drifting.

duration: 1/2 leg.

Southwest Colombian Basin (4)

problems: paleoceanography, plateaus, Ca plate.

specifications: drill 1000 m sediment section and 200 m into igneous and sedimentary rock of oceanic plateau.

objectives: Cenozoic and Late Cretaceous bathymetric history; sediment provenance history; water mass character; biotic provinciality; age, composition, and magnetic directions of plateau igneous rocks.

duration: 1/4 leg.

Northwest Venezuelan Basin (5)

problems: paleoceanography, plateaus, Ca plate.

specifications; objectives: same as (4); to obtain distributed data on age and composition of plateau magmatism.

duration: 1/4 leg.

Cayman Trough (6)

problems: 1) crustal formation and development of spreading in pullapart basin of a major transform fault; 2) thermal subsidence with lateral transfer; 3) basalt evolution; 4) Ca plate and duration and total displacement on present Ca-NA plate boundary.

specifications: series of 5-6 holes in eastern Cayman Trough (Fig. III-8) between modern ridge and rifted terrane east of oceanic lithosphere through thin pelagic sediments; core basal sediment and top of basement; in one hole, drill thin (200 m) layer 2 into gabbroic crust.

objectives: histories of spreading, deformation, rotation, ridge jumps, and subsidence; basalt compositions and ages.

duration: 1 leg.

Northeast Venezuelan Basin (7)

problems: paleoceanography, plateaus, Ca plate.

specifications: drill through full section of oceanic plateau igneous rock (between 0.8 and 2.0 km thick).

objectives: age range and compositional evolution of basaltic magmatism; proportion of intrusive and extrusive igneous rock; proportion of sediment in plateau; magnetic directions; Late Cretaceous and Cenozoic paleoceanography of strata succeeding plateau and detection of existence, type, and age of sediments just below, Ca plate.

duration: 1 leg.

Lesser Antilles Arc Platform Flank East of Grenada (8)

problem: sediment subduction in arc magmatism.

specifications: core about 1 km of sediment on eastern flank of arc platform or western forearc basin about 50-100 km east of the active volcano (Fig. IV-10).

objectives: compositions and ages of tephra layers for arc magmatic history in Quaternary and

Neogene times at a site where sediments of mainly cratonic provenance are probably being subducted.

duration: 1/3 leg.

Lesser Antilles Arc Platform Flank East of St. Lucia (9)

problems: sediment subduction.

specifications; objectives: same as (8); site east of volcano above slab with intermediate proportions of continental and pelagic sediments.

duration: 1/3 leg.

Lesser Antilles Arc Platform Flank East of Guadeloupe (10)

problem: sediment subduction.

specifications; objectives: same as (8,9); site east of volcano above slab with minimal proportion of continental sediments.

duration: 1/3 leg.

Barbados Wedge: Upslope from Leg 110 (11)

problem: mechanics of accretionary wedges.

specifications: deep hole through accretionary wedge 15 km inboard of outer deformation front drilled to basal detachment.

objectives: test whether underriding sediments have accreted to wedge base (underplating, duplexing) as a major upslope wedge thickening mechanism.

duration: 1/2 leg.

Barbados Wedge: Lower-Upper Slope Transect (12)

problem: mechanics of accretionary wedges.

specifications: series of shallow holes through seismically identified structural features on the lower and upper wedge slope: out-of-sequence thrusts (12a), uplifted slope cover (12b), and deformed slope basins (12b) between latitudes 12° and 15°N.

objectives: mechanisms of upslope thickening of accretionary wedge; bathymetric history of wedge surface; timing of deformation of slope cover vs. position upslope to test episodicity of accretion.

duration: 1/2 leg.

Barbados Wedge: Inner Forearc Transect (13)

problem: mechanics of accretionary wedges

specifications: one km-deep and two shallow holes in inner forearc deformation belt through seismically identified structural features.

objectives: test timing of major structures in belt, whether layered rocks in belt are of forearc basin or other origin, and sense of key faults (repetitive or omissional).

duration: 1/2 leg.

Barbados Wedge: Outer Deformation Front and Atlantic Plain (14, 15)

problem: fluids evolution in accretionary wedges.

specifications: two sets of deep holes to penetrate toe of wedge through detachment and underthrust strata to oceanic crust; each set includes reference hole seaward of wedge toe; holes 14 in low permeability (muddy) wedge; holes 15 in higher permeability (sandy) wedge; deep holes need pressure, flow velocity, and water chemistry measurements with depth.

objectives: accurate measurements of hydrologic system within and below wedge toe and between wedge and undeformed strata seaward of deformation front.

duration: 2 legs.

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