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THE TECTONIC EVOLUTION OF THE
NORTH CENTRAL CARIBBEAN PLATE MARGIN

by

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Institute of Technology - Woods Hole
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Submitted to the Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography on January 10th. 1981 in partial fulfilment of the requirements for the degree of Doctor of Science.

ABSTRACT

The results of a detailed geophysical survey are used in conjunction with all available information in a study of the tectonic development of the Cayman Trough and the Greater Antilles Ridge. This development is connected with the relative motions of the North and South Americas' and the eastern Pacific plates. Thus, the pre-Tertiary history of the region is one of simple convergence. This contrasts with the complex tectonism of primary translation, with secondary convergence and divergence during the Tertiary. The ancestral Greater Antillean Arc suffered fracturing during collision with the Bahamas stable platform in the Late Cretaceous. Oblique convergence re-established itself across the remnant fragments of the ancestral arc in the Tertiary, producing a sheared welt partially decoupled from both the North American and Caribbean plates. Pronounced temporal and structural heterogeneity occurs within this Plate Boundary Zone. Along its northern margin secondary convergence with the North American plate formed the massive subduction complex of the Cuchillas Uplift and the Sierra Septentrional. Convergence between the Plate Boundary Zone and the Caribbean plate resulted in the triple virgation of the fold belts extending westward from the Los Muertos Trough to Oriente Province (Cuba), the Cayman Trough and the Nicaraguan Rise. Tectonism along these fold belts youngs southwestward preserving the stratigraphy of the Caribbean Basin at the time of their formation during the early, middle, and late Tertiary. The Caribbean/North American Plate boundary occured along the zones of major strain accomodation within the Plate Boundary Zone. The Cayman Trough was produced during a period of divergence between the Nicaraguan Rise and the North American plates during the Miocene. Since the Pliocene, the shear boundary within the Cayman Trough occurs along the Oriente Deep proceeding via the

Windward Passage Deep and the Valle del Cibao to the Puerto Rico Trench. Convergence and shear predominate the present tectonic framework of the Plate Boundary Zone.

Thesis Supervisor: Dr. Elazar Uchupi
Title: Senior Scientist

ACKNOWLEDGEMENTS

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The relationships of all those people and events that influenced me during this period appear to be like a spiders web in the early morning dew. They are too delicate to capture. By acknowledging only the complexity and recursion of the structure can I hope to thank all those who helped and hindered me. These include ships, computers, labourers, teachers, friends, artists, authors, poets, philosophers, arguments, oceans, emptiness and silence.

Elazar Uchupi, John Sclater, Henry Dick, Hans Schouten, Kevin Burke and Hartley Hoskins require special mention. I humbly thank them. Henry will long be remembered for his honesty.

In so much that life is a footnote in the evolution of the volatiles of the Universe, I acknowledge those organic components, and the paths that energy, space-time and chance took to assemble them.

My final thanks go to my family. Their quality and intelligence burn brightly in a dark world.

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CHAPTER 1

INTRODUCTION

This study is intended to resolve the present and past geometry of the northern Caribbean plate boundary in the region extending roughly from Jamaica to the Puerto Rico Trench (Figure 1). Comparitively little subaerial exposure of the major geologic and structural elements occurs in this region. Elements along this boundary include the Old Bahama Channel, the Caicos Basin, the Greater Antillean Ridge, the Cayman Ridge, the Cayman Trough, the Nicaraguan Rise, the Colombian Basin, the Beata Ridge, the Venezuelan Basin, and the Puerto Rico Trench (Figures 1, 5). The marine geophysical data base gathered during this study was specifically located to allow the mapping of the inter-relationships occuring between these major structural and stratigraphic entities.

The Caribbean Plate

The Caribbean Plate and adjacent borderlands are shown in Figure 1. The present extent of the Caribbean Plate includes the Colombian and Venezuelan basins, the Beata Ridge, the Aves Swell, the Grenada Trough and the Lesser Antilles. The Nicaraguan Rise, Central America, northwestern South America and portions of the Greater Antilles are commonly included as part of the plate (Figures 1-3; e.g. Molnar and Sykes, 1969; Bowin 1976). The physiography of the Caribbean region is discussed in detail by Uchupi (1975).

Location of the seismicity along the Caribbean borderlands define narrow unambiguous plate margins along the Middle America Trench, the Cayman Trough, the Puerto Rico Trench and the Lesser Antilles (Figures 1-3). The seismicity within the area extending from Jamaica to Puerto Rico, including the island of Hispaniola, is diffuse and fails to identify a unique plate boundary (Figures 1-3). Thus workers in the field have proposed several loci for the northern Caribbean plate boundary in this region including through northern, central or southern Hispaniola (e.g. Molnar and Sykes, 1969; Uchupi, 1975; Bowin, 1976). One of the major quandries surrounding the location of the present plate margin is the apparent dissapearance of the major shear boundary running along the northern Cayman Trough in the region of the Windward Passage (Molnar and Sykes, 1969). The problem is addressed in this study.

Geological evidence from the Caribbean suggests that the dominant tectonic process is translation with subduction with or without volcanism being secondary. Translation and shear.

Figure 1. Principle features in the Caribbean region. Contours on land are at elevations of 200, 1000, 2000, 3000, and 4000 m (Times Atlas of the World, 1957). At sea contours are at depths of 200, 2000, 4000, and 6000 m (Uchupi, 1971; Chase and Menard, 1964). Solid circles are active volcanoes. Inset shows plate boundaries given by Molnar and Sykes (1969, Figure 1). Figure is taken from Bowin (1976, Figure 1).

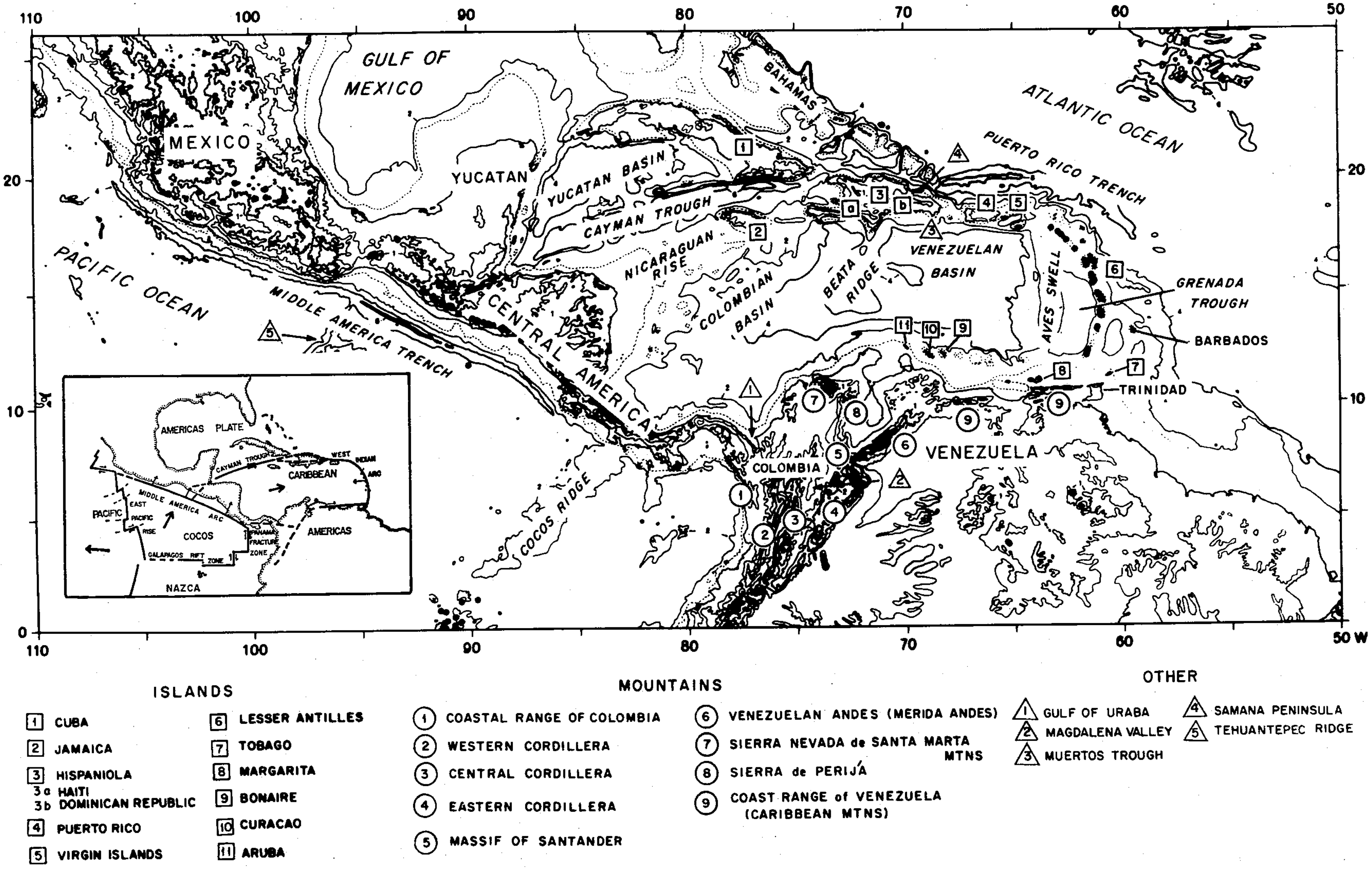

110
100
90
80
70
60
50
50 W
20
10
0
GULF OF MEXICO
MEXICO
YUCATAN
YUCATAN BASIN
CAYMAN TROUGH
BAHAMAS
ATLANTIC OCEAN
PUERTO RICO TRENCH
NICARAGUAN RISE
COLOMBIAN BASIN
BEATA RIDGE
VENEZUELAN BASIN
AVES SWELL
GRENADA TROUGH
BARBADOS
TRINIDAD
PACIFIC OCEAN
MIDDLE AMERICA TRENCH
CENTRAL AMERICA
COCOS RIDGE
COLOMBIA
VENEZUELA
AMERICAS PLATE
CAYMAN TROUGH
WEST INDIAN ARC
CARIBBEAN
MIDDLE AMERICA ARC
EAST PACIFIC RISE
PACIFIC
COCOS
PANAMA FRACTURE ZONE
GALAPAGOS RIFT ZONE
AMERICAS
NAZCA
ISLANDS
1 CUBA
2 JAMAICA
3 HISPANIOLA
3a HAITI
3b DOMINICAN REPUBLIC
4 PUERTO RICO
5 VIRGIN ISLANDS
6 LESSER ANTILLES
7 TOBAGO
8 MARGARITA
9 BONAIRE
10 CURACAO
11 ARUBA
MOUNTAINS
1 COASTAL RANGE OF COLOMBIA
2 WESTERN CORDILLERA
3 CENTRAL CORDILLERA
4 EASTERN CORDILLERA
5 MASSIF OF SANTANDER
6 VENEZUELAN ANDES (MERIDA ANDES)
7 SIERRA NEVADA de SANTA MARTA MTNS
8 SIERRA de PERIJÁ
9 COAST RANGE of VENEZUELA (CARIBBEAN MTNS)
OTHER
1 GULF OF URABA
2 MAGDALENA VALLEY
3 MUERTOS TROUGH
4 SAMANA PENINSULA
5 TEHUANTEPEC RIDGE

Figure 2. Earthquake epicenters in the Caribbean region from 1961 to 1970 as compiled by the U.S. Coast and Geodetic Survey. Figure taken from Bowin (1976, Figure 13)

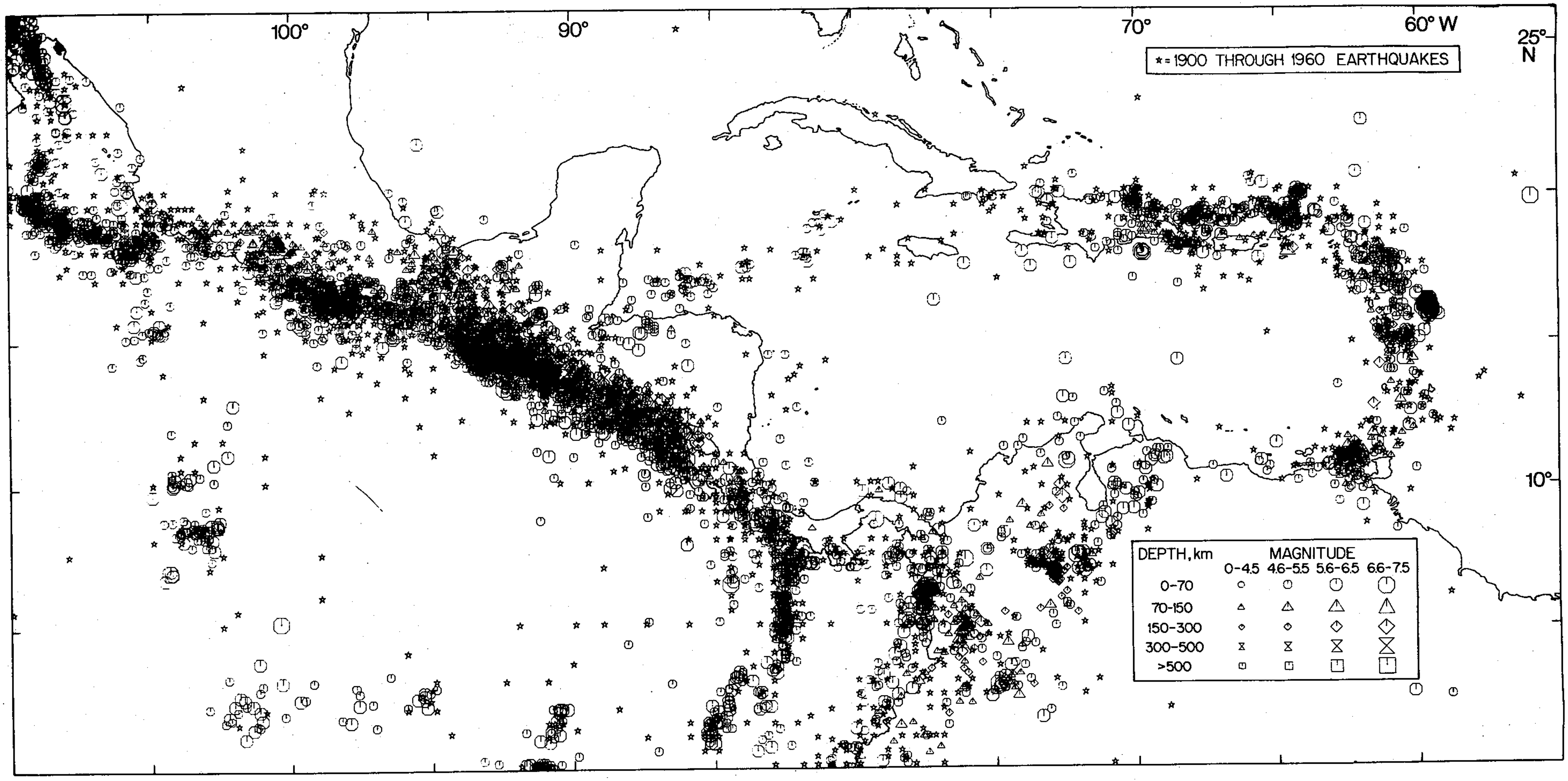
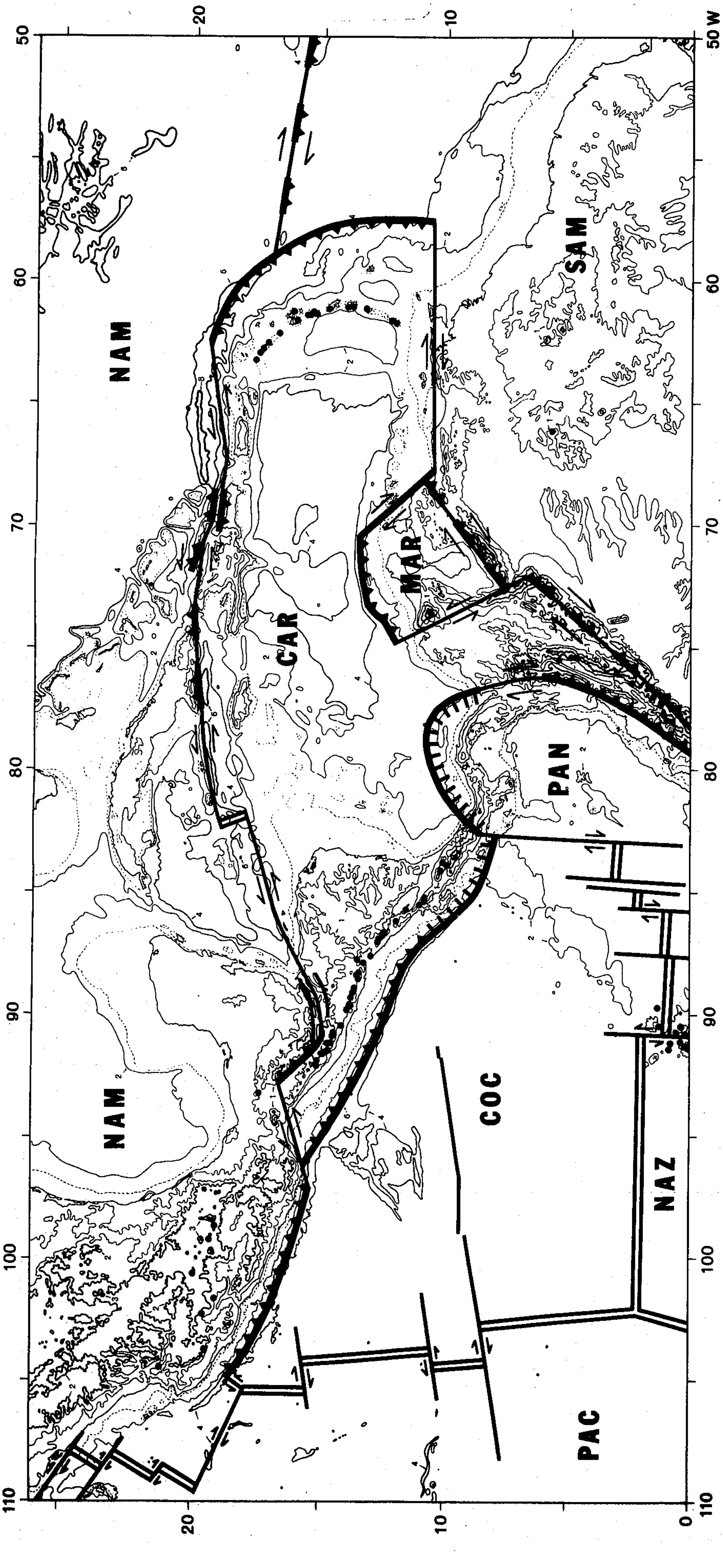

100°
90°
70°
60° W
25°
N
10°
★= 1900 THROUGH 1960 EARTHQUAKES
DEPTH, km
MAGNITUDE
0-4.5 4.6-5.5 5.6-6.5 6.6-7.5
0-70
70-150
150-300
300-500
>500

Figure 3. Inferred present plate boundaries in the Caribbean region. Double lines: extensional tectonics. Single thin lines: strike-slip tectonics. Single heavy lines with hatchure: sites of compression. Heavy lines with solid triangles: subductive tectonism. Plates are labled: NAM, North America; SAM, South America; CAR, Caribbean; COC, Cocos; PAC, Pacific; NAZ, Nazca; PAN, Panama block; MAR, Maricaibo block. Contours and solid dots as in Figure 1. Figure taken from Bowin (1976, Figure 16).


NAM
NAM
CAR
MAR
PAN
SAM
COC
NAZ
PAC
110
100
90
80
70
60
50
50 W
20
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0

Data Base

Approximately 3,000 line kms of geophysical data were collected in the Jamaican and Windward Passages during cruise 97, leg 1, of the R/V ATLANTIS II in January and February 1978. The ships tracks are shown in Figure 5. Navigation was by satellite, Omega, Radar (near shore), and dead reckoning.

Bathymetry was measured primarily with a hull mounted twelve element broad-beam, 3.5 kHz transducer, using pulse lengths ranging from 0.2 - 5.0 milliseconds, and recorded on a Hydro Products graphic recorder. The records were digitized at five minute intervals and at every slope break. Depths were corrected for sound velocity using Matthews (1939) tables. These data, supplemented by all other available data from the region, were used to compile the chart in Figure 4. The total geomagnetic field intensity was measured with a Varian proton precession magnetometer towed 250 meters behind the ship. The magnetic anomaly was calculated by subtracting the International Geomagnetic Reference Field (Leaton, 1976).

Gravity measurements were made with a vibrating string accelerometer mounted on a gyro-stabalized table (Bowin, Aldrich, and Folinsbee, 1972). Corrections were applied for the Etvos effect and instrument drift, and free air and Bouguer anomalies were calculated.

Seismic reflection profiles on lines 1 through 3 were made with a 12-channel array, and lines 6 through 28, with two signal summed single channel hydrophone arrays. The sound source consisted of combinations of a 1000 in^3, a 300 in^3, a 120 in^3, an 80 in^3, and a 40 in^3 Bolt air guns. They were fired every 34.0 seconds at an air pressure of 1500 lbs/in^2. Towing speeds varied between 4.5-5.5 knots depending upon the sea state. Signals from the arrays were recorded in real-time analog format on Hewlett Packard X-Y recorders at a 5.0 and 10.0 second sweep. Channel 3 was monitored during the multi-channel profiling. The data also were recorded on magnetic tape in digital format, using a 4.0 millisecond interval, and predominantly a 5.0 second record length. Both single-channel and 12-channel records were deconvolved in single channel format for all water depths of less than 1.0 sec. Interpretation of the records was done by using acetate overlays to trace reflectors. These reflectors were then reduced with proportional dividers and grid onto the bathymetric profiles.

Figure 4. Topography of study area . The contour interval is 200m, (offshore contours are corrected for sound velocity). Solid dots: AII 97/1 track lines; Open circles Ch 47 tracks. Additional bathymetric data were obtained from the Preliminary Bathymetric Map of the Caribbean compiled by Case and Holcombe (1976). The contours for Cuba and Hispaniola were taken from maps compiled by the American Geographical Office (1955).

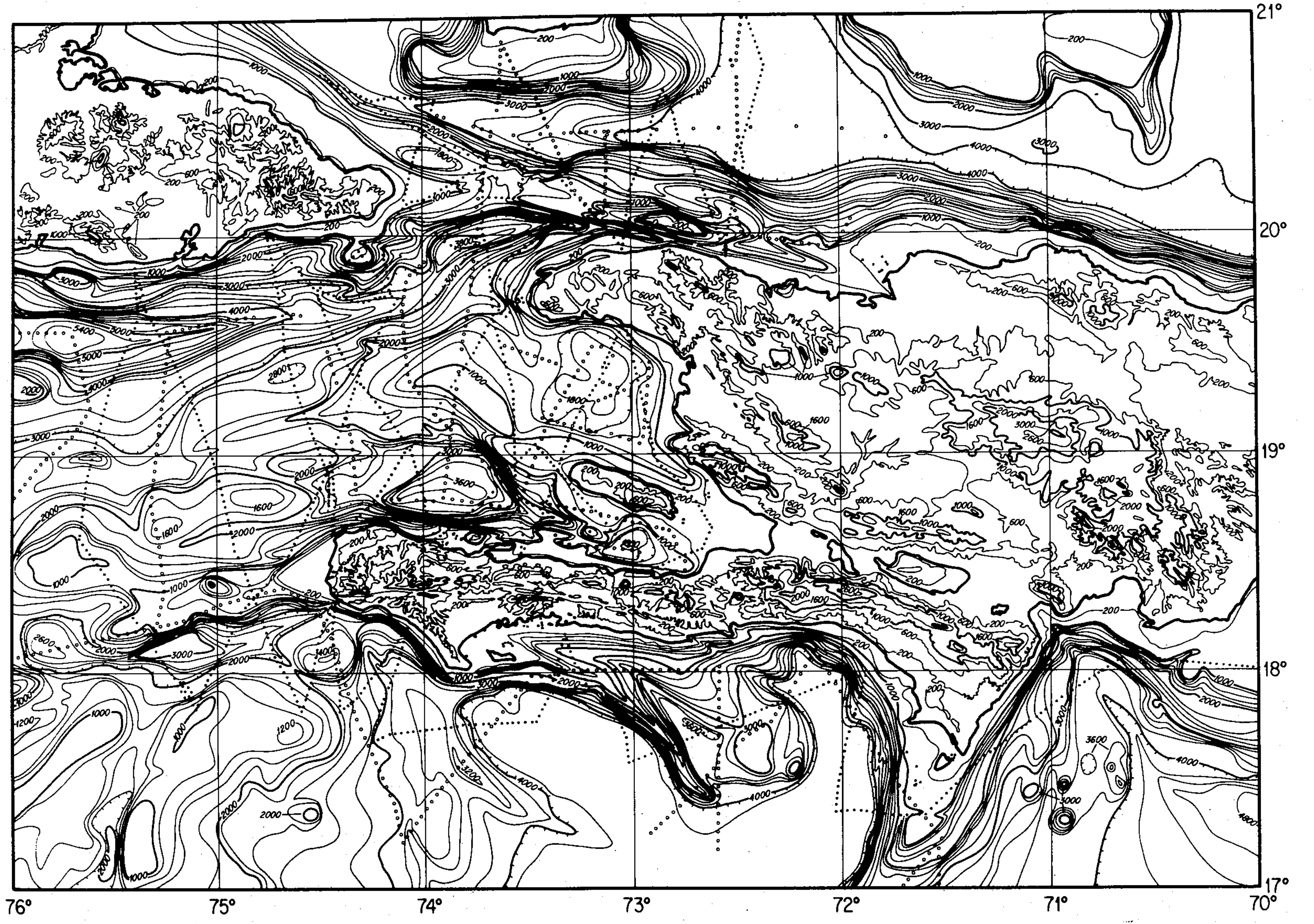
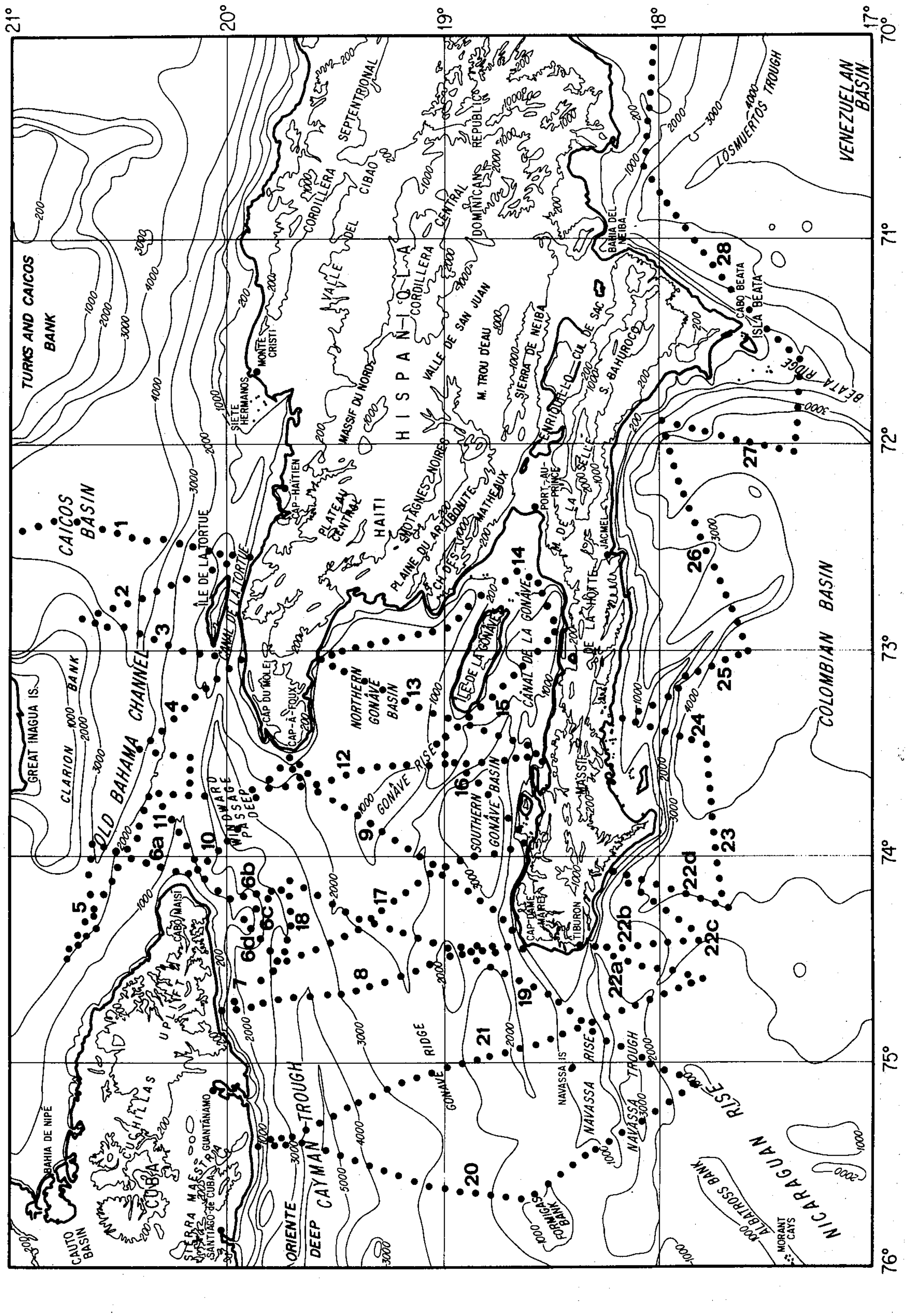

21°
20°
19°
18°
17°
76°
75°
74°
73°
72°
71°
70°

Figure 5. Major Physiographic units in the study area. Contours are in meters. Numbered and dotted lines are ATLANTIS II Cruise 97/leg 1 profiles.


21°
20°
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18°
17°
76°
75°
74°
73°
72°
71°
70°
TURKS AND CAICOS BANK
CAICOS BASIN
GREAT INAGUA IS.
CLARION BANK
OLD BAHAMA CHANNEL
ILE DE LA TORTUE
CANAL DE LA TORTUE
WINDWARD PASSAGE DEEP
SIETE HERMANOS
MONTE CRISTI
CORDILLERA SEPTENTRIONAL
VALLE DEL CIBAO
CORDILLERA CENTRAL
REPUBLICA DOMINICANA
HISPANIOLA
MASSIF DU NORD
VALLE DE SAN JUAN
M. TROU D'EAU
SIERRA DE NEIBA
ENRIQUILLO
CUL DE SAC
S. BAHURUCO
BAHIA DEL NEIBA
CABO BEATA
ISLA BEATA
BEATA RIDGE
LOS MUERTOS TROUGH
VENEZUELAN BASIN
CAP-HAITIEN
PLATEAU CENTRAL
HAITI
MONTAGNES NOIRES
PLAINE DU ARTIBONITE
CHAÎNE DES MATHEUX
PORT-AU-PRINCE
M. DE LA SELLE
JACMEL
MASSIF DE LA HOTTE
CAP DU MOLE
CAP-À-FOUX
NORTHERN GONÂVE BASIN
ÎLE DE LA GONÂVE
CANAL DE LA GONÂVE
GONÂVE RISE
SOUTHERN GONÂVE BASIN
CAP DAME MARIE
TIBURON
COLOMBIAN BASIN
CABO MAISI
UPLIFT
CUCHILLAS
CUBA
SIERRA MAESTRA
GUANTÁNAMO
SANTIAGO de CUBA
BAHIA DE NIPÉ
CAUTO BASIN
ORIENTE DEEP
CAYMAN TROUGH
GONÂVE RIDGE
NAVASSA IS.
NAVASSA RISE
NAVASSA TROUGH
FORMIGAS BANK
NICARAGUAN RISE
ALBATROSS BANK
MORANT CAYS
200
1000
2000
3000
4000
5000
1
2
3
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5
6a
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6d
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22b
22c
22d
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28

CHAPTER II

GEOLOGIC SETTING

It is apparent from the bathymetric map that the study area is marked by considerable physiographic complexity (Figure 4). For simplicity I subdivide the area into a series of morphologically and genetically related basin and rise systems (Figures 5-7). These divisions are based on physiography, stratigraphy and structural relationships.

Old Bahama Channel/Caicos Basin System.

The Caicos Basin is an irregularily shaped depression between the Clarion Bank, the Turks and Caicos Bank, and Hispaniola (Figure 5). Elongated on an east north east trend it has a secondary north south elongation in the central portion (Figure 5). It is continuous with the Puerto Rico Trench to the east, and the Old Bahama Channel to the west. The main portion of the basin lies at depths greater than 4000m, rising to 2900m in the Old Bahama Channel to the west (Figures 4, 5).

Ball et al. (1968), Uchupi et al. (1971), Uchupi (1975), and E. Richardson (personal communication) have described

Figure 6. Major geological units in the region. S = Samana peninsula; SB = Bahia de Samana.

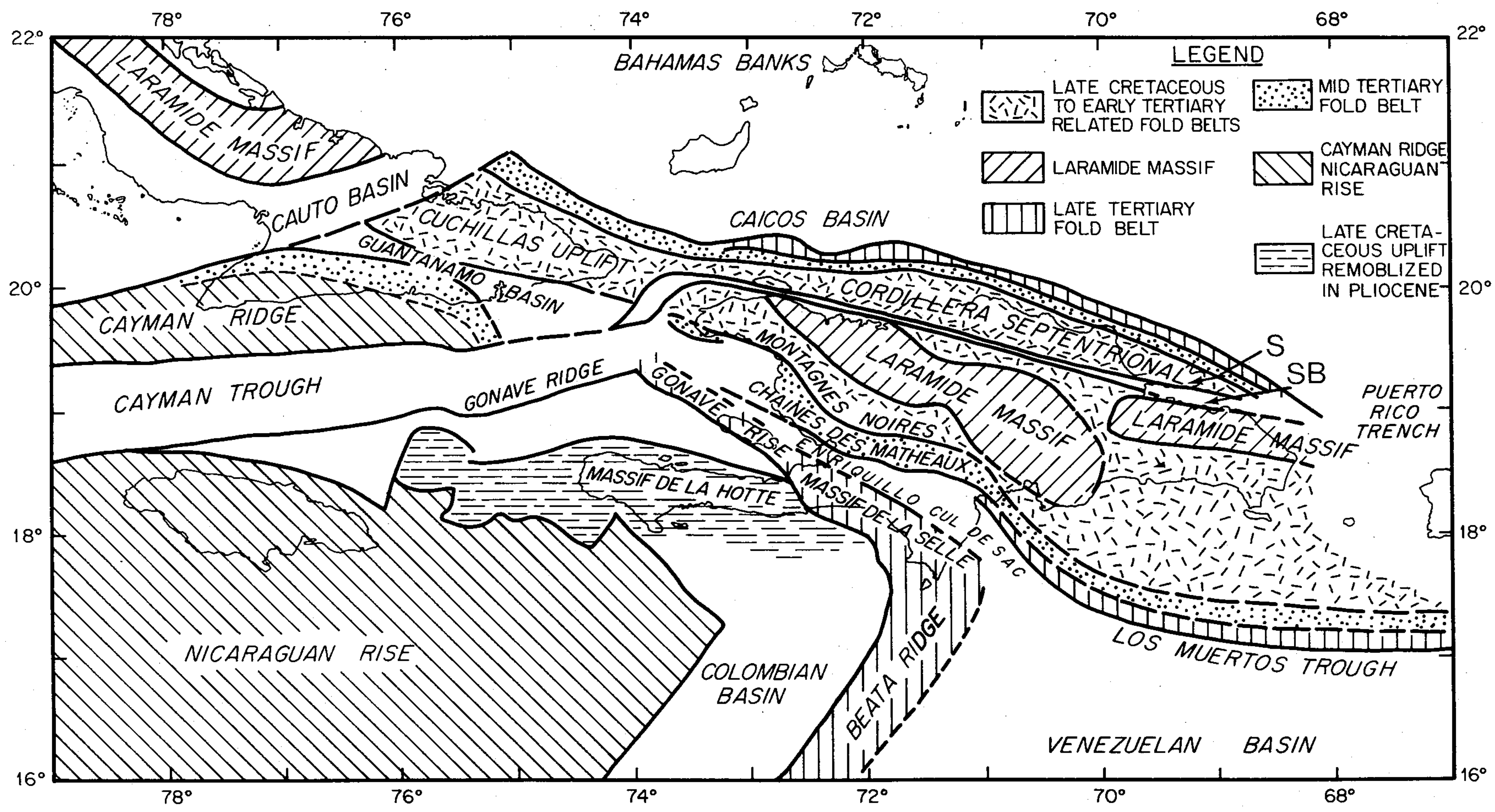
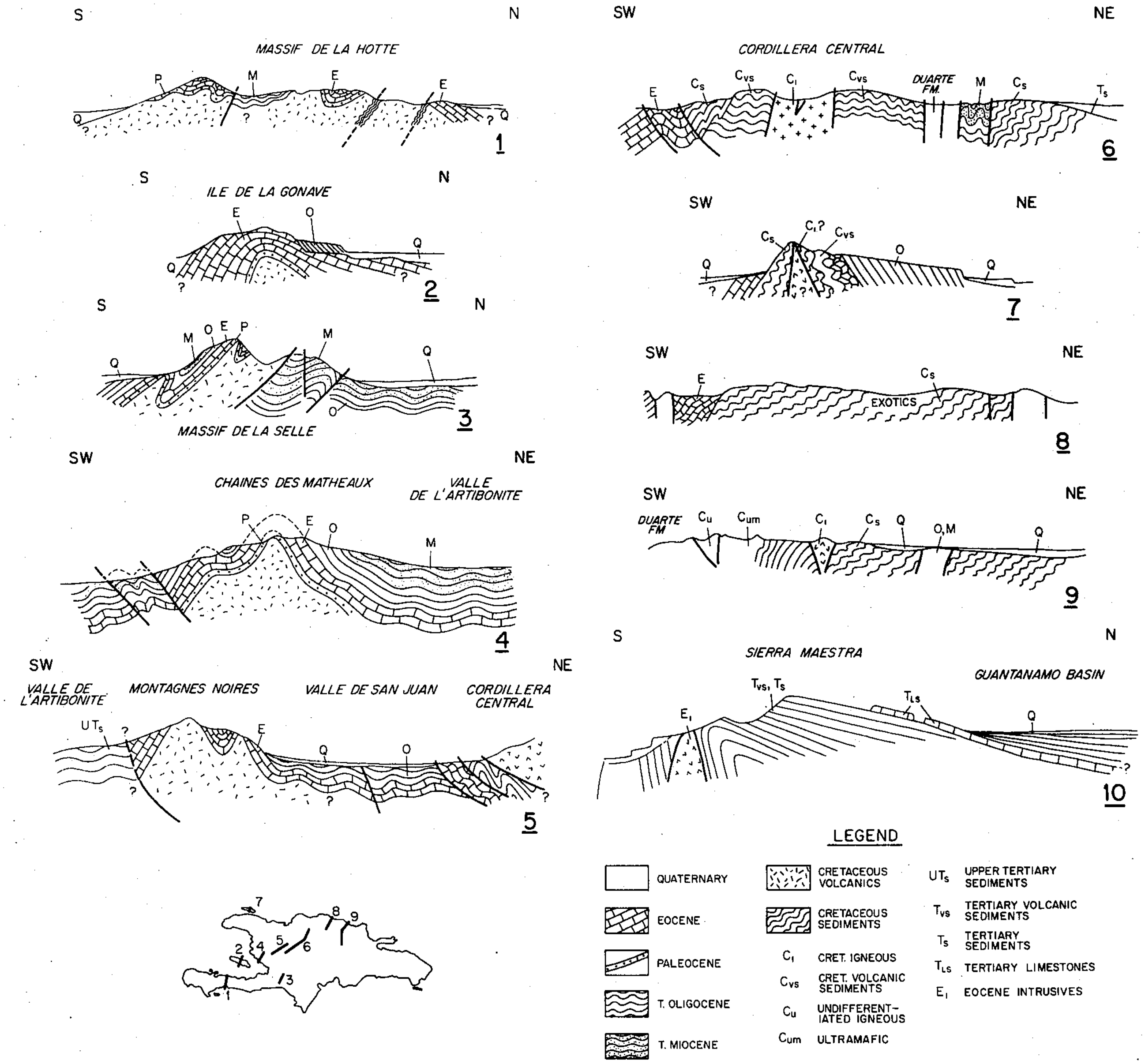

LEGEND
LATE CRETACEOUS TO EARLY TERTIARY RELATED FOLD BELTS
LARAMIDE MASSIF
LATE TERTIARY FOLD BELT
MID TERTIARY FOLD BELT
CAYMAN RIDGE NICARAGUAN RISE
LATE CRETACEOUS UPLIFT REMOBLIZED IN PLIOCENE
78°
76°
74°
72°
70°
68°
22°
20°
18°
16°
BAHAMAS BANKS
LARAMIDE MASSIF
CAUTO BASIN
CUCHILLAS UPLIFT
GUANTANAMO BASIN
CAICOS BASIN
CORDILLERA SEPTENTRIONAL
S
SB
PUERTO RICO TRENCH
CAYMAN RIDGE
CAYMAN TROUGH
GONAVE RIDGE
GONAVE RISE
MONTAGNES NOIRES
CHAINES DES MATHEAUX
LARAMIDE MASSIF
LARAMIDE MASSIF
ENRIQUILLO CUL DE SAC
MASSIF DE LA HOTTE
MASSIF DE LA SELLE
NICARAGUAN RISE
COLOMBIAN BASIN
BEATA RIDGE
LOS MUERTOS TROUGH
VENEZUELAN BASIN

Figure 7. Diagrammatic cross sections over the major physiographic provinces within the study area. Sections 1 through 9 from Weyl (1966) and Bowin (1975). Section 10 is a generalized cross section in south central Oriente Province, Cuba, adapted from Lewis and Straczeck (1955).


S
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MASSIF DE LA HOTTE
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Q
O
MASSIF DE LA SELLE
3
SW
NE
CHAINES DES MATHEAUX
VALLE DE L'ARTIBONITE
P
E
O
M
4
SW
NE
VALLE DE L'ARTIBONITE
MONTAGNES NOIRES
VALLE DE SAN JUAN
CORDILLERA CENTRAL
UTs
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?
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SW
NE
CORDILLERA CENTRAL
E
Cs
Cvs
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Cvs
DUARTE FM.
M
Cs
Ts
6
SW
NE
Cs
Ci?
Cvs
Q
O
Q
?
7
SW
NE
E
Cs
EXOTICS
8
SW
NE
DUARTE FM
Cu
Cum
Ci
Cs
Q
O,M
Q
9
S
N
SIERRA MAESTRA
GUANTANAMO BASIN
Tvs, Ts
TLs
Ei
Q
?
10
LEGEND
QUATERNARY
EOCENE
PALEOCENE
T. OLIGOCENE
T. MIOCENE
CRETACEOUS VOLCANICS
CRETACEOUS SEDIMENTS
Ci CRET. IGNEOUS
Cvs CRET. VOLCANIC SEDIMENTS
Cu UNDIFFERENTIATED IGNEOUS
Cum ULTRAMAFIC
UTs UPPER TERTIARY SEDIMENTS
Tvs TERTIARY VOLCANIC SEDIMENTS
Ts TERTIARY SEDIMENTS
TLs TERTIARY LIMESTONES
Ei EOCENE INTRUSIVES
7
8
9
2
4
5
6
3
1

seismic profiles from the basin. A zone of salt diapirs extends from northern Cuba (Khudoley and Meyerhoff, 1971) down the axis of the Old Bahama Channel, sub-paralleling the southern margin of the Caicos Basin (Uchupi, 1975; Richardson, personal communication). No direct stratigraphic information exists within the basin. However where diapirs have been sampled on the northern coast of Cuba they are cored with Portlandian evaporites and are overlain by massive Cretaceous to Eocene carbonates (Khudoley and Meyerhoff, 1971; Pardo, 1975). Structurally uneventful, the basin has a turbiditic character with minor faulting associated with the evaporite stocks. In the southern portion of the basin the strata are involved in folding along the Greater Antilles Ridge. The basin is aseismic (Molnar and Sykes, 1969; Bowin, 1976). Free air gravity anomalies range from -125 mgals to -225 mgals, indicating a nonisostatic regime (Bowin, 1976).

Cuchillas Uplift/Windward Passage Sill/Ile de la Tortue Rise/Cordillera Septentrional System

The Cuchillas Uplift--Cordillera Septentrional System is physiographically continuous from the Cauto Basin to the Samana peninsula (Figure 7). It is bound to the north by the Old Bahama Channel and the Caicos Basin, to the west by the Cauto Basin and to the south by the Guantanamo Basin, the Windward Passage Deep, the Canal de la Tortue, the Valle de Cibao, and the Bahia de Samana (Figure 6). Along the northern margin depths range from 4000 m to 2800 m below sea level . The crest of the System lies on a W 15° N trend, with elevations ranging from 1300 m below sea level to 1000 m above sea level. At the southern margin elevations vary from 3000 m below sea level to 200 m above sea level (Figure 4). The topography is rugged with a short wave length component subparalleling the major axis.

The Cuchillas Uplift--Cordillera Septentrional System is geologically heterogeneous, containing all the elements associated with a mature subduction complex (Bowin, 1975). Mapping in the Cordillera Septentrional and Peninsula de Samana by Nagle (1966, 1971, 1974), reveal the presence of highly deformed clastics, pyroclastics, and serpentinites (presumed to be of ophiolitic origin) (Sections 7-9, Figure 7). These rocks are typical of accretionary sediment prisms associated with convergent tectonic margins. On Isle de la Tortue, Butterlin (1960), Bowin (1975), and Nagle (personal communication) report the existence of heavily folded and sheared calcareous schists of Eocene/Miocene age. They contain some well rounded cobbles of quartz diorite, dacite, and andesite of Late Cretaceous(?) age (Nagle, personal communication).

Mapping coverage on the Cuchillas Uplift is poor (see

Appendix 1 for discussion of the geology of the uplift). Presumably it is this lack of data which has allowed the Cuchillas Uplift and the Sierra Maestra to be considered as portions of a single geologic entity (e.g. Khudoley and Meyerhoff,1971; Appendix 1).

The stratigraphic units of the Cuchillas Uplift include a basal overturned ophiolitic fragment (Kumpera, 1968), pillow lavas (Lewis and Strazeck, 1955; Boiteau et al, 1972), followed by a thick succession of interbedded clastic, pyroclastic, and bioclastic sediments (Lewis and Strazeck, 1955; Appendix 1). Boiteau et al. (1972a,b) described eclogitic and amphibolitic metamorphic assemblages within the pillow lava sequence along the southern margin of the Uplift (Appendix 1). The stratigraphy of the Chuchillas Uplift suggests a similar age, deformational sequence, and structural trend to that of the Cordillera Septentrional and the Montagnes Noires (Appendix 1).

Free air gravity anomalies over the entire length of the Cuchillas Uplift/Cordillera Septentrional System are roughly +50 mgal (Bowin, 1976). On the order of ten earthquakes of magnitude 5.0-7.0 have occurred along the rise at depths of less than 70 kms (Bowin, 1975; Figure 2). Molnar and Sykes (1969) have calculated an oblique slip thrusting vector from first motion studies of some of these seismic events.

The Windward Passage Deep/Canal de la Tortue/ Valle de Cibao/Bahia de Samana System.

The Windward Passage Deep/Bahia de Samana System is a narrow low extending from the eastern tip of the Cayman Trough through the Canal de la Tortue, the Valle de Cibao, and the Bahia de Samana into the Puerto Rico Trench (Figure 4-6). It is bound to the north by the Cuchillas Uplift/Cordillera Septentrional System, and by the Northwest Haitian peninsula/Massif du Nord/Cordillera Central System and the Sierra del Seibo to the south. Striking predominantly N 75^{o}W from the Bahia de Samana to the northern margin of the Windward Passage Deep it widens into a sigmoidal basin in the deep and joins the eastern Cayman Trough (Figures 4-6). Its width varies from 5 kms in the Canal de la Tortue to 40 kms in the Valle del Cibao. Elevations range from 3800m below sea level in the Windward Passage Deep to 200 m above sea level in the Valle del Cibao.

Bowin (1975) believes the northern and southern flanks of the Valle del Cibao are strike slip fault controlled (Figures 4, 5, 35). The Valle del Cibao itself is a Pliocene feature containing up to 3600m of sediments (Bowin 1975). Bowin (1975) suggests that prior to the Pliocene only gentle down warping occured along the system. By inference the Bahia de Samana and the Canal de la Tortue have a similar tectonic history. It seems reasonable to assume the existence of a Late Cretaceous to Holocene fore arc basin in this region which was dammed by the subduction complex of the Cordillera Septentrional (Figures 4, 35; Bowin, 1975; Nagle, personal communication).

Bowin (1976) found free air gravity anomalies ranging from -175 mgals in the Windward Passage Deep to 0 mgals for the Valle de Cibao. Seismicity appears to be related to underthrusting of the Atlantic Basin (Molnar and Sykes, 1969; Figure 2). Klitgord (personal communication) considers the seismicity along the northern Hispaniolan margin to define a inclined strike slip fault plane dipping south.

The Cordillera Central System.

The Cordillera Central strikes N 70^{o}W and extends as a rugged mountainous terrain from the northwestern tip of the Massif du Nord, to the Coastal Plain of central Hispaniola (Figures 4-6). It varies in width from 30 kms to 60 kms, with elevations ranging from 200 m to over 3000 m above sea level (Figure 4). The highest peaks in the Caribbean exist in this Cordillera. It is bound to the north by the Canal de la Tortue/Valle de Cibao and to the south by the Plateau Central/Valle de San Juan, and varies in width from 30 kms to 60 kms.

The oldest rocks of the Massif du Nord/Cordillera Central System consist of metamorphosed basic volcanics including quartz keratophyres, keratophyres, and waterlain pyroclastics (Bowin, 1960, 1966, 1975; Palmer, 1963; Roobol, personal communication). These are assigned a minimum age of 127 MYBP, the radiometric age of an intrusive body within the basal units (Bowin, 1975). Donnelly (1964) considers similar rock suites on the Virgin Islands to be oceanic in origin, and indicative of the earliest stages of island arc volcanic activity. A fault zone within the basal formations on Hispaniola is interpreted as the trace of a northward dipping subduction zone by Bowin (1975) (Section 6, Figure 7). This implies that the initial stages of island arc volcanism of the ancestral Greater Antilles Ridge were caused by the Pacific (Farallon) plate thrust beneath the North Atlantic plate, a phase lasting only from 160-130 MYBP (Mattson, 1979).

During the Late Mesozoic the direction of subduction reversed (Mattson, 1979; Bowin 1975). The geology of the Cordillera Central indicates prolonged subduction of the North Atlantic basin beneath the Farallon plate along this portion of the ancestral Greater Antilles Ridge at this time (Bowin, 1975; Nagle, 1972). This reversal heralded the rise of the mature island arc volcanic/plutonic complex and associated sedimentary sequences which make up the bulk of the Greater Antilles Ridge

(Bowin, 1975; Mattson, 1979; section 6, Figure 7). Major uplift, deformation and implacement of the major plutonic series throughout the Cordillera Central in the Maastrichtian resulted in large pyroclastic deposits. Concurrent with the uplift, major deposition occured along the northeast and southwest flanks of the Cordillera (Bowin, 1975; Weyl, 1966).

A curious feature of the Cordillera Central, is its abrupt termination against the Tertiary to Quaternary deformed sediments of the Ile de la Tortue high in the northwest and those north of the Los Muertos Trough to the southeast (Bowin, 1975; Ladd and Watkins, 1978; Ladd, personal communication). Clearly mature island arc systems have much greater lateral continuity than is evidenced in this region. Thus these discordant relations indicate:

i) that the ancestral Greater Antilles Ridge was fragmented prior to the establishment of the flanking Tertiary basins.

ii) that the present location and geometry of the Cordillera Central are probably not the same as for the ancestral Greater Antilles Ridge.

iii) that, once disrupted, the present Cordillera Central acted as a "nucleus" for further basin and range formation on its flanks.

Free air gravity anomalies over the Cordillera Central are generally above +100 mgals and range up to +175 mgals (Bowin, 1975). A Bouguer Gravity anomaly high exists in the region with values ranging from +50 mgals to +75 mgals and is flanked by lows of -25 mgals in the basins to the northeast and southwest (Bowin, 1975).

The Cuchillas Uplift/Montagnes Noires/Massif Trou d'Eau, and Plateau Central/ San Juan Basin System.

The Cuchillas/San Juan Basin System includes both the Montagnes Noires highlands and the related Valle de San Juan sedimentary basin to the north east (Figures 4-6). It extends southeastward from the Cuchillas Uplift via the northwestern Haitian peninsula, the Montagnes Noires, the Massif Trou d'Eau to the Coastal Plain of the southwestern Dominican Republic. The associated basin includes the Plateau Central and Valle de San Juan (Figure 4, 5, 6). The Plain de l'Artibonite and Sierra de Neiba flank this System to the southwest and south respectively. Elevations of 600 to 1000 m are common on this province, while those of the Plateau Central and the Valle de San Juan vary from 200 m to sea level. The basin and rise system strikes roughly N 70°W subparalleling the Cordillera Central.

The geology of the southern Cuchillas Uplift is discussed in Appendix 1. Elsewhere along the system the basal unit consists of undifferentiated Cretaceous basalts and dolerites (Butterlin 1954). Their affinity is unknown, but Butterlin (1954) included them with the Cretaceous basalts found in the Chaines des Matheaux, the Massif de la Selle and the Massif de la Hotte. They represent the only recognized volcanics southwest of the Cordillera Central (Butterlin, 1954; Weyl, 1966).

Initial deposition in the region started in the Maastrichtian with the uplift of the Cordillera Central (Bowin, 1975). Sedimentation consisted of pyroclastic material and massive lower Tertiary limestones overlaying the Cretaceous dolerites (Bowin, 1975; Weyl, 1966). These sediments are the youngest deformed units exposed and thus give a maximum age of early Tertiary for the uplift of the Montagnes Noires highland (Section 5, Figure 7). Both lower and upper Tertiary sediments are exposed within the Valle de San Juan basin (Bowin, 1975). Bowin (1975) suggests that there was a progressive emergence of the Cuchillas Uplift/San Juan Basin System until the early to middle Eocene when it became fully emergent and terrestrial deposition became dominant within the Valle de San Juan basin.

Reverse faulting occurs along the contact between the Valle de San Juan basin and the Cordillera Central (Bowin, 1975;

Weyl, 1966) (Section 5, Figure 7). Sediments in the Valle de San Juan basin have been subjected to low amplitude folding affecting even the most recent strata, evidence that diffuse compression continues in the region to the present date (Section 5, Figure 7). The Montagnes Noires highlands are strongly folded and probably overthrust the Plain de l'Artibonite to the southwest (Section 5, Figure 7).

Free air gravity anomalies range from +100 mgals over the highlands to +25 mgals over the Valle de San Juan basin (Bowin, 1975, 1976).

The Cayman Ridge/Sierra Maestra/ Cauto Basin/Guantanamo Basin System.

The Cayman Ridge is one of the major pysiographic features of the northern Caribbean, extending in a broad arc from Central America to the eastern tip of the Sierra Maestra, a distance of roughly 1500 kms (Figures 1, 5, 6). Within the study area only the Sierra Maestra segment of the Ridge is present. This segment is bound by the Cauto and Guantanamo basins to the north and northeast respectively, and by the axial Oriente Deep of the Cayman Trough to the south (Figure 5). Topography of the Sierra is rugged with depths ranging from 5400 m below sea level in the Oriente deep to elevations of greater than 1000 m above sea level on the subaerial portions of the Rise (Figure 4). The topography of the Guantanamo Basin to the north is smooth and has an elevation of roughly 200m above sea level (Figures 4, 5).

Structurally the Sierra Maestra is a sharply assymmetrical homocline (Section 10, Figure 7; Lewis and Strazeck, 1955). Strata are tightly folded along the crest of the Sierra just north of the Cayman Trough. Inland of the topographic divide, the strata dip gently northward plunging under the Tertiary and Quaternary fill of the Cauto and Guantanamo Basins (Section 10, Figure 7). Several major reverse faults lie along the E-W trend of the fold axes. In the eastern section of the Sierra Maestra, structures and outcrops swing to the southwest intersecting the coastline just west of Guantanamo Bay (Figures 4, 5, 35).

Perfit and Heezen (1979) collected seven dredge hauls from the southern flank of the Sierra Maestra. Their samples were predominantly granodiorites, tonolites and basalts showing varying degrees of metamorphism, with some highly sheared and possibly cataclastic samples among the metaplutonic assemblages. A K/Ar^{40} date of 83 ± 2 m.y. was derived from one of the tonalites.

According to Perfit and Heezen (1979), the lithology and stratigraphy of the Cayman Ridge and the Nicaraguan Rise are broadly similar and are composed typically of sedimentary, volcanic and plutonic associations of calc-alkali affinity. These rocks are indicative of an island arc/subductive province that probably dates from the Cretaceous to the mid-Eocene (Appendix 1.).

The Cauto and Guantanamo Basins are broadly synclinal with the strata weakly folded to flat laying. Small domes which may be indicative of deeper structural elements affect the upper strata (Lewis and Straczek, 1955). The nature of the basin and its sedimentary fill is not known. Middle and upper Eocene exposures are largely clastic with biohermal and bedded limestones. The Oligocene and Miocene consists of sandstones, shales, chalks and minor bioclastics. Quaternary deposits are alluvial gravels, sands and silts (Lewis and Straczek, 1955) (Section 10, Figure 7).

Bowin (1976) reports free air gravity anomaly values of approximately +150 over the Sierra Maestra. Pardo (1975) indicates numerous, shallow magnetic sources in the Sierra Maestra and the Cuchillas Uplift, with very deep sources in the Cauto and Guantanamo basins.

The Cayman Trough/Northern Gonave Basin/Plain de l'Artibonite/Chaines des Matheaux/ Sierra Neiba System.

From west to east the Cayman Trough--Sierra Neiba System is bound to the north by the Cayman Ridge, the Sierra Maestra, the Guantanamo Basin, the Cuchillas Uplift, the Windward Passage Deep, the northwestern Haitian peninsula, and the Montagnes Noires System. To the south it is bordered by the Nicaraguan Rise, the Gonave Ridge, Gonave Rise, and the Enriquillo Cul de Sac (Figures 1, 4, 5, 6).

The entire system is a major physiographic and geological feature of the northern Caribbean and extends from Central America to the Los Muertos Trough, a distance of approximately 2000 kms. Within the study area (Figures 4, 5) the Cayman Trough ranges in depth from 5400 m in the Oriente Deep, to 1800 m in the northern Gonave Basin. On Hispaniola elevations in the Plaine du Artibonite tend to be less than 200 m, while those of Chaines des Matheaux, Sierra de Neiba range up to 1600 m above sea level (Figure 4). The topography is rugged on the Chaines des Matheaux and smooth on the Plaine de l'Artibonite and in the Cayman Trough. The Trough is assymetric, deepening to the north (Uchupi, 1975). The strike of this physiographic province changes from east-west in the west of the study area to N 70°W in the east (Figure 1, 2, 3). The Cayman Trough trend is reflected in the structure on the adjacent flanks of the Cayman Ridge and the Nicaraguan Rise (Ballard et al, 1978; Fox and Burke, 1977; Horsfield, 1974; Burke et al, 1980) (Figures 1, 2, 29). These effects are probably due to the sinistral shear strain proposed for the origin of the trough (Molnar and Sykes, 1969; Case, 1975; Case and Holcombe, 1976).

The floor of the Cayman Trough is composed predominantly of the ultramafic suites typical of normal oceanic crust (Perfit and Heezen, 1979). Fresh basaltic rock suites have been recovered from the Mid-Cayman Rise (Holcombe et al., 1971; Ballard et al, 1978).

Perfit and Heezen (1979), describe dredge hauls recovered from the central Cayman Trough midway between Cuba and Jamaica which contain a fine-grain chloritic schist. Land (1979) describes a brown siltstone recovered from a basement high in the mid Cayman Trough which resembles the lower and mid-Eocene pyroclastic unit (the Richmond formation) of Jamaica (Robinson, personal communication). However no stratigraphic information exists for this sample, and carbonates overlaying it are of late Miocene age (Land 1979). Thus the minimum age for this strata is late Miocene. This siltstone horizon represents acoustic basement in seismic profiles taken by Land (1979) and by us (lines 8, 9, 17, 19, 20, 21; Figures 18-21, 24, 25).

No geological information exists for the northern Gonave Basin. The structure of the Plaine de l'Artibonite/Chaines des Matheaux/Sierra de Neiba is similar to that of the Montagnes Noires/Valle de San Juan System (Butterlin, 1954; Bowin, 1956) (Sections 4 and 5, Figure 7). The Chaines des Matheaux and the Sierra Neiba are strongly folded and overthrust to the south and southwest (H. Meyerhoff, personal communication; Weyl, 1966). The Plaine de l'Artibonite is structurally analagous to the Valle de San Juan, being a subsidiary basin developed on the northeast flank of an upthrust foldbelt. Both display the broad deformation affecting the most recent stratigraphic horizons that is indicative of diffuse present day compression (Sections 4 and 5, Figure 7).

Important differences however, occur in the stratigraphic character of either system. Undifferentiated Cretaceous basalts and dolerites occur as the basement in the Chaines des Matheaux (Butterlin, 1954; Bowin, 1975). Overlaying the dolerites are Paleocene and Eocene chalks and limestones, and Oligocene chalky limestones with cherts. These strata are involved in the folded structure of the highlands and give a minimum mid-Tertiary age for tectogenesis of the Chaines des Matheaux/Plaine de l'Artibonite. In contrast, the tectogenesis of the Montagnes Noires/Valle de San Juan is early Tertiary. As has been pointed out by Bowin (1975), there was a progressive emergence of western Hispaniola from the northeast to the southwest over the Tertiary.

A relatively large amount of geophysical data exists in the Cayman Trough (Case, 1975). Over much of the floor of the Trough free air gravity anomaly values indicate it to be near isostatic equilibrium. On the basis of gross similarity, Bowin (1976) suggested that similar tectonic processes were at play in the Cayman Trough, the Red Sea and Gulf of California, with oceanic basement being formed during a rifting episode. However a major narrow low of less than -200 mgals coincides with the Oriente Deep, which led Bowin (1976) to suggest a present day compressive regime across the Trough. Free air gravity anomaly values in the northern Gonave Basin range around 0 mgals increasing to +50 mgals and +100 mgals over the Plaine de l'Artibonite and Chaines des Matheaux/Sierra Neiba respectively.

Seismic refraction measurements reveal a seismic velocity structure typical of oceanic basins in the Cayman Trough, a crustal thickness of approximately 6 kms, and mantle velocities range from 8.0 to 8.3 km/sec (Ewing et al., 1970; Edgar et al., 1971a).

Magnetic anomalies over the eastern Cayman Trough have low amplitudes, and do not have recognizable trends (Case, 1975). However, Gough and Heirtzler (1969) indicate the presence of linear east-west magnetic anomalies paralleling the fracture zone in the Oriente Deep (Figure 3). They have interpreted these anomalies to be due to massive strike slip displacements associated with the Oriente fracture zone.

The Cayman Trough is seismically active along the Oriente Deep (Molnar and Sykes, 1969). On the basis of fault plane solutions which indicate left lateral strike slip tectonics, Molnar and Sykes (1969) have classified the Oriente Deep as a fracture zone forming the present day plate boundary between the North American and Caribbean plates (Figures 1-3).

Heat flow measurements in the Cayman trough are high in the mid-Cayman Rise area ranging from 1.0-3.0 H.F.U. (Ericson et al., 1971; J. Crowe, personal communication). In the eastern portion of the basin a reading of 1.3 H.F.U. has been recorded (Case, 1975).

The Gonave Ridge/Gonave Rise/Massif de la Selle/Sierra Bahoruco/Beata Ridge/ Enriquillo Cul de Sac System.

The Gonave Ridge--Enriquillo cul de Sac System extends from the north-central Nicaraguan Rise via the Gonave Ridge, the Massif de la Selle, the Sierra Bahoruco to the Beata Ridge (Figure 4-6). The Enriquillo Cul de Sac occurs between this system and the Chaines des Matheaux/Sierra Neiba (Figures 4-6). Physiographically variable, depths range from 2000m below sea level along the Gonave and Beata ridges to elevations in excess of 2000m above sea level (Figure 1). The system undergoes a strike change from W 15°S to W 40°N between the Gonave Ridge and Gonave Rise, and again to N 15°E between the Massif de la Selle and the Beata Ridge (Figures 4-6). These various units are interpreted to be parts of a continuous system.

The geology of the Gonave Ridge and Rise west of the Ile de la Gonave is unknown. The Ile de la Gonave is a broadly anticlinal structure of Eocene to Holocene limestones with a presumed core of Cretaceous dolerites (Butterlin, 1956; Weyl, 1966; Bowin, 1975; Section 2, Figure 7). A basement arch of high velocity and high magnetic susceptibility extends from the Ile de la Gonave to the Massif de la Selle (Crux International Inc., personal communication). The Massif de la Selle itself is a complex antiform overthrusting both the Enriquillo Cul de Sac and the Colombian Basin (Weyl, 1966; Section 3, Figure 7).

The basal Cretaceous basalts in western Hispaniola have been correlated by Maurasse et al (1979) with the B" unit in the Venezuelan Basin (Saunders et al, 1973). As discussed in a later section, the stratigraphy of the northern Colombian Basin is assumed to be similar to that of the Venezuelan Basin. Thus the stratigraphy of material preserved within the Gonave Ridge--Enriquillo cul de Sac System is interpreted to be derived from the northern Colombian Basin. On this basis the Cretaceous dolerites mapped by Butterlin (1956) throughout western Hispaniola, which includes those investigated by Maurrasse et al (1979), may either be comparable to, or identical with the dolerites of the sampled in the Venezuelan Basin and also assumed to exist in the Colombian Basin.

Structures in the Massif de la Selle and Sierra de Bahuroco are complex, with block faulting in the west (Maurasse et al., 1979) and extensive compression and thrusting in the central and eastern portions (Weyl, 1966; H. Meyerhoff, personal communication). Where the Massif de la Selle/Sierra de Bahuroco overthrusts the Enriquillo Cul de Sac, deep water upper Miocene marine strata are involved in the folding (H. Meyerhoff, personal communication). The upper Tertiary to Quaternary strata of the Enriquillo Cul de Sac are involved in basinwide folding (H. Meyerhoff, personal communication; K. Burke, personal communication). Thus, the basin is under present day compression, being overthrust along both margins.

The Beata Ridge has a stratigraphy similar to the Venezuelan and Colombian basins (Fox and Heezen, 1975; Case, 1975; Donnelly, 1975). The deformational event giving rise to the Beata Ridge postdates the timing of the Horizon A" event during the mid-Tertiary. The antiquity and tectonic development of the Ridge is debatable. Duque-Caro (1978) suggests it is continuous with a Mesozoic lineament of western South America, while Fox and Heezen (1975) suggest both uplift and subsidence in the Eocene. I suggest that the formation of the Beata Ridge must post-date the mid-Tertiary and pre-date the late Miocene tectonic events that gave rise to the Enriquillo Cul de Sac.

The Beata Ridge is inferred by some workers to reflect a fundamental break in the stratigraphy and structural style of the Venezuelan and Colombian basins (Houtz and Ludwig, 1977; Ludwig et al, 1975; Uchupi, personal communication). Horizon B" forms a planar acoustic basement in the Venezuelan Basin (Case, 1975). In the northern Colombian Basin acoustic basement is a topographically variable and discontinuous surface (Ludwig et al, 1975; Houtz and Ludwig, 1977). However, the supra B" stratigraphy of the Colombian Basin is similar to that of the Venezuelan Basin, with the development of the Carib Beds and Horizon A". Similar seismic velocities for the sub B" units occur within both basins. The debate upon the continuity of the B" horizon and its existance in the Colombian Basin rests entirely upon the difference of structural style in that surface on either side of the Beata Ridge. Clearly the Colombian Basin has represented the interface between the

Caribbean and the Nicaraguan Rise plates in the Cretaceous and mid-Tertiary (Gose and Schwarz 1978). On that basis the difference in structural style is hardly surprising. The distribution of the Cretaceous dolerites on the Massif del la Selle (Maurasse et al, 1978) and the Massif de la Hotte (Butterlin, 1954) indicate derivation from the Colombian Basin (Figure 2). Therefore, it is assumed that the stratigraphic succession of the Colombian and Venezuelan basins are similar, the only variation between them being in structural style.

The Enriquillo Cul de Sac is a late Tertiary to Holocene Basin, with a complex history of sediment accumulation (Bowin, 1975). An enigmatic basin it has been attributed properties from plate margin (Uchupi, 1975) to extensional back arc spreading. It is continuous with the Los Muertos Trough in the east and the northern Gonave Basin in the west. Drilling off the western shore indicated massive carbonate deposits with a Miocene reef occurring at 3000 m (Crux Intl.,personal communication). Marine conditions existed within the basin during the Pleistocene, with coral reefs occurring along the margins of Lago Enriquillo (Bowin, 1975).

Free air gravity anomalies range from +100 mgals over the Gonave Rise to +175 mgals for the Massif de la Selle and Sierra Bahoruco, to +100 mgals for the northern part and 0 mgals for the rest of the Beata Ridge (Bowin, 1975). Bowin (1975) suggests present day isostatic equilibrium over most of the Beata Ridge. Free air gravity anomalies are around 0 mgals for the Enriquillo cul de sac.

Crustal thickness over the Beata Ridge appears to be approximately 15 kms (Edgar et al., 1971; Heezen and Fox, 1975; Ewing, et al., 1960).

The Southern Gonave Basin/Jacmel Basin

The southern Gonave Basin is a triangular low bound by the Gonave Ridge to the west, and Gonave Rise to the northeast, and the Massif de la Hotte, Navassa Rise and Formigas Bank to the south (Figure 5). The eastern basin terminates adjacent to the Jacmel Basin a topographic low marking the juncture between the Massif de la Hotte and the Massif de la Selle (Figure 4, 5). A marked constriction of the basin occurs southwest of the Isle de la Gonave at which point the bottom topography becomes undulatory (Figure 4). In general the basin goes from a depth of 1800 m in the east, to 3600 m in the center, shallowing to 2000 m in the west (Figures 4, 5). At its western end, the basin bifurcates with the southern arm abuting the Formigas Bank, and the northern arm losing its bathymetric identity north of the bank. The region between the bifurcations is a platform less than 1600 m deep (Figure 1, 2). The basin margin against the Massif de la Hotte is marked by laterally continuous undulations associated with folding at the base of the scarp (Figure 1). No geological information exists for the basin to date.

Mercier de Lepinay et al (1979) report compressive tectonism in the valley seperating the Massif de la Hotte and Massif de la Selle with the Massif de la Hotte underthrusting the Massif de la Selle. The youngest rocks involved in the thrusting give a maximum Oligo-Miocene age for the tectonism. A free air gravity anomaly low of approximately -100 mgals occurs over central and eastern portions of the basin (Bowin, 1975).

Formigas Bank/Navassa Rise/Massif de la Hotte System

The Formigas Bank--Massif de la Hotte System extends from Formigas Bank via the Navassa Rise to the subaerial Massif de la Hotte on the Massif du Sud of Haiti (Figures 4-6). Laying on an east-west axis it averages 50 kms in width and 350 kms in length. The system extends into the Colombia Basin southeast of the Massif de la Hotte (Figure 5). Depths range from 1000 m in the west to 3000 m in the southeast and elevations on the Massif de la Hotte exceed 1000 m (Figure 4). An elongate valley extends the length of the Massif de la Hotte from the southern flank of the Navassa Rise to the juncture with the Massif de la Selle (Figure 4). The topography on the Formigas Bank and Navassa Rise is subdued and platform like (Figure 4). Navassa Island is located on the central portion of the Navassa Rise (Figure 5).

Apart from the recent carbonate cover evidenced by the raised modern coral reefs of Navassa Island nothing is known of the geology of the Formigas Bank or the Navassa Rise . Physiographic and inferred geologic continuity with the Massif de la Hotte allows the stratigraphy of the system to be inferred. Unfortunately the Massif de la Hotte also is not thoroughly mapped. The only information available is from the reconnaissance mapping by Butterlin (1956) and (Bowin, 1975).

Upper Cretaceous basaltic and doleritic rocks interbedded with pelagic limestones and radiolarites form the basal unit on the Massif de la Hotte (Section 1, Figure 7). This is a similar unit to that interpreted by Maurasse et al (1979) on the Massif de la Selle to be equivalent to the B" unit. Unconformably above the igneous rocks are massive Upper Cretaceous shallow water limestones (Bowin, 1975). Shallow marine and terrestrial deposition continued to the Holocene. Thus, the system has been a high since the Cretaceous (Bowin, 1975). The post B" stratigraphic succession of the Massif de la Hotte is different to that of the Colombian Basin or the

Massif de la Selle (Section 1, Figure 7). Therein lies an important distinction which will be dealt with in a later section.

Free air gravity anomalies vary from 0 mgals over the Navassa Rise to +150 mgals over the Massif de la Hotte (Bowin, 1975, 1976). Magnetic anomalies from marine portions of the system have the high amplitude short wavelength character common of island arc type areas (Horsfield and Robinson, 1974; Robinson, 1975). A seismic refraction profile by Edgar et al. (1971a) indicated a 10 km crustal thickness for the Navassa Rise.

The Nicaraguan Rise

The Nicaraguan Rise is a broad swell extending northeastward from Central America (Figures 1 and 5). The Cayman Trough, and the Colombian Basin border it to the north and southeast respectively (Figure 1, 4, 5, 6). Topographically the Nicaraguan Rise is extremely variable with elevations ranging from 2500m above sea level to 4200m below (Figure 1, 4, 5). Presently Jamaica marks its uplifted northern margin. Within the study area, the main trend on the Nicaraguan Rise is N45°E, along which several elongate basins and rises are aligned (Figure 4). The Nicaraguan Rise is