GEOLOGY OF THE FONDO NEGRO REGION, DOMINICAN REPUBLIC

A thesis presented to the Faculty
of the State University of New York
In partial fulfillment of the requirements
for the degree of
Master of Science

School of Arts and Sciences
Department of Geological Sciences

J. Calvin Cooper
1983

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Detailed geologic mapping of the Fondo Negro-Sierra de Martin Garcia region of the Southwestern Dominican Republic establishes that this area is part of a broad and diffuse Northern Caribbean plate boundary zone (PBZ). Faulting in the study area is predominantly left lateral strike-slip, with secondary compression (thrusting) causing both substantial, and rapid, uplift of the region. Folding associated with the wrench faulting affects rocks of all ages in the field area from Paleocene limestones to Quaternary alluvial fans.

New stratigraphic designations are proposed for mappable litho-units in the area, and these are correlated with Hispaniola stratigraphy in general based on biostratigraphic age determinations. Thus a new formation name, the Fondo Negro Formation is proposed for a thick (2650 m. exposed) predominately calcareous siltstone, marl and sandstone sequence which is exposed between the village of Fondo Negro and the Sierra de Martin Garcia where it lies in tectonic contact with Paleocene to early Miocene carbonates. The Fondo Negro Formation contains microfauna belonging to the Tortonian and Messinian intervals. The lowest exposed section of the Fondo Negro Formation contains distinctive, ridge forming, sandy limestones and this unit is described as the Gajo Largo member. The 400m. of predominantly grey calcareous shales apparently conformably overlying the Fondo Negro Formation are redefined as the Bao Formation, also of

Messinian age, and conformably above that the Pliocene, Arroyo Blanco Formation, also more specifically defined than previous studies. The Arroyo Blanco Formation comprises sandy marls, and resedimented carbonate shelf debris, as well as coarse sandstones and conglomerates. In the east it is approximately 100m thick, and it varies as a facies transition into evaporites in the northwest of the field area. The evaporite facies, including massive pure gypsum beds are probably thicker than the facies in the east.

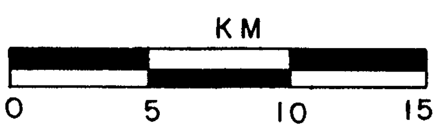
The carbonates of the Sierra de Martin Garcia were not mapped in detail, but paleontological determinations for samples collected indicate a broader age range for the carbonates than suggested on existing maps (Blesch, 1967), from Paleocene to Early Miocene.

In addition to the primary field mapping, reconnaissance studies and paleontological analysis of samples from the Tavera Basin suggest that it is the earliest basin yet identified related to the initiation of the northern Caribbean PBZ. That is that this basin can be related to strike-slip faulting in probably early Oligocene times and this represents movement along the Cayman Trough.

An interpretive cross-section across Hispaniola is presented which suggests that present strike-slip activity is greatest in the Cibao Valley, the Enriquillo Valley and in the northern, offshore areas of Hispaniola, and that the Island is cut by a great number of splay faults. The mountain ranges, the Sierra de Neiba and the Sierra de Bahoruco are compressional structures related to bends in the strike-slip fault system. An attempt is made to integrate this in the perspective of the Cainozoic evolution of the Greater Antilles.

FRONTISPIECE

The Sierra de Martin Garcia – Fondo Negro Region seen from space, as photographed by NASA Skylab false color imaging, courtesy NASA and the Lunar and Planetary Institute. North is approximately parallel with the edge of the photo, and scale 1:310,000



ACKNOWLEDGEMENTS

This thesis has been made possible by the good will and generous support of a great number of people. Kevin Burke suggested the project, further refined it in the field, and proved to be an outstanding teacher of the way the earth works. Bill Kidd patiently explained some of the finer points of geological data collection and interpretation, and encouraged me to "just do it." Tony Eva critically read, and no doubt improved, the manuscript as well as provided much information on Caribbean stratigraphy. Ted Robinson kindly determined paleontological ages for samples that I collected. Jim Pindell provided companionship in the field, motivation, and definitely taught me a great deal about the tectonic evolution of the Caribbean region. Paul Mann educated me on the geology of Hispaniola and was a sounding board for my sometimes crazy ideas, while David Rowley helped me put it all together.

In the Dominican Republic, Dr. Abraham Risk B., his family and friends all made my stay as comfortable as possible and taught me about their country and its peoples. I can't thank them enough. Dr. Victor Beras and the staff of the Minera extended every courtesy, and provided me all necessary documentation to get my work done, and the Instituto Cartographico Universitario was very helpful in obtaining topographic maps and aerial photographs, which were essential to this study.

Ken Wilks proved to be an outstanding field assistant, companion and friend.

Substantial financial support for this study was provided by a grant from Weeks Petroleum Ltd. Their geologists, Mike Nemec, and Doug Klemme taught me about the subsurface geology of the island, while Superior Oil Company and Steve Pierce also showed me subsurface data from the Enriquillo Valley and my field area. The study was also funded by NASA, through Kevin Burke, as well as by the Department of Geological Sciences at SUNYA.

Miss Debra Booker kindly typed the manuscript.

Last, but never least; Mom and Dad, thanks for everything.

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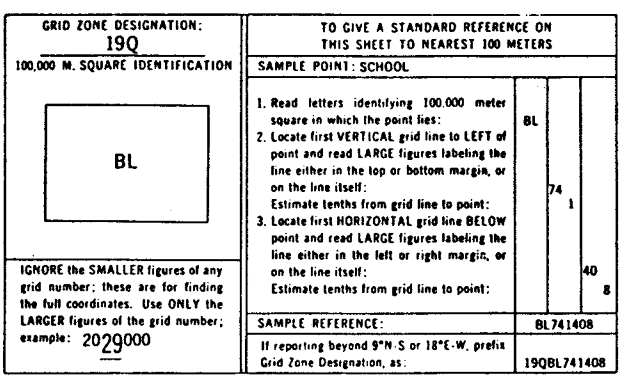
CHAPTER 1 INTRODUCTION

MAP GRID COORDINATES

Locations in the text are referred to using the Universal Transverse Mercator Grid (UTMG) System as designated on the U.S. Army map service topographic maps of the Dominican Republic. This grid system is annotated on the Geologic Map, plate 1. For all locations between 9° N-S and 18° EW the prefix Grid zone designation is: 19Q. This designation will be omitted for brevity, following traditional practice. The 100,000 meter square identification for most of the field area surrounding Fondo Negro is: BL, although the eastern most section includes zone: CL, so all locations referred to in the text begin with the 100,000 m square designation. This is followed by the vertical grid line to the left of a location point given as a two digit number, (these are the larger numbers on maps), followed by an estimate of tenths (one digit) from the grid line to the location point. The vertical coordinate is followed by the horizontal coordinate (two digit by numbers on map) <u>below</u> the location and an estimate of the nearest tenth from the grid to the point. Thus a typical location would be: BL741408. See figure 1.1 below for a summarized explanation.



Regional Setting

The Dominican Republic comprises approximately the eastern two-thirds of the island of Hispaniola which it shares with Haiti. Located between Cuba and Puerto Rico in the Greater Antilles Island Arc, Hispaniola, perhaps to a greater extent than any other island, records geologically (Bowin, 1975; Lewis, 1980), the complex evolution of the northern Caribbean following the Early Cenozoic collision of the Greater Antilles with the Bahamas carbonate shelf. In essence, Hispaniola is a tectonic knot, or focal point where the trends of the Cayman Trough and Ridge, the Nicaragua Rise, the Puerto Rico Trench, the Beata Ridge, the Muertos Trench and Cuba all converge (See Figure 1.2). Modern tectonics of Hispaniola are dominated by strike-slip faulting and secondary compression associated with the North America-Caribbean plate boundary (Burke et al., 1980). Quite predictably the geologic relationships are obscured by anatomizing faults common to any strike-slip dominated plate boundary. Yet surprisingly, given its close proximity to the North American geological communities, the island has been little studied until recently, and large areas have yet to be mapped to modern acceptable standards.

Figure 1.3 shows an interpretation of the types of plate boundaries presently surrounding the Caribbean plate. In Hispaniola the boundary cuts a broad swath across the island and causes complex deformation. The Septentrional fault zone in the Cibao Valley seems to enjoy the greatest

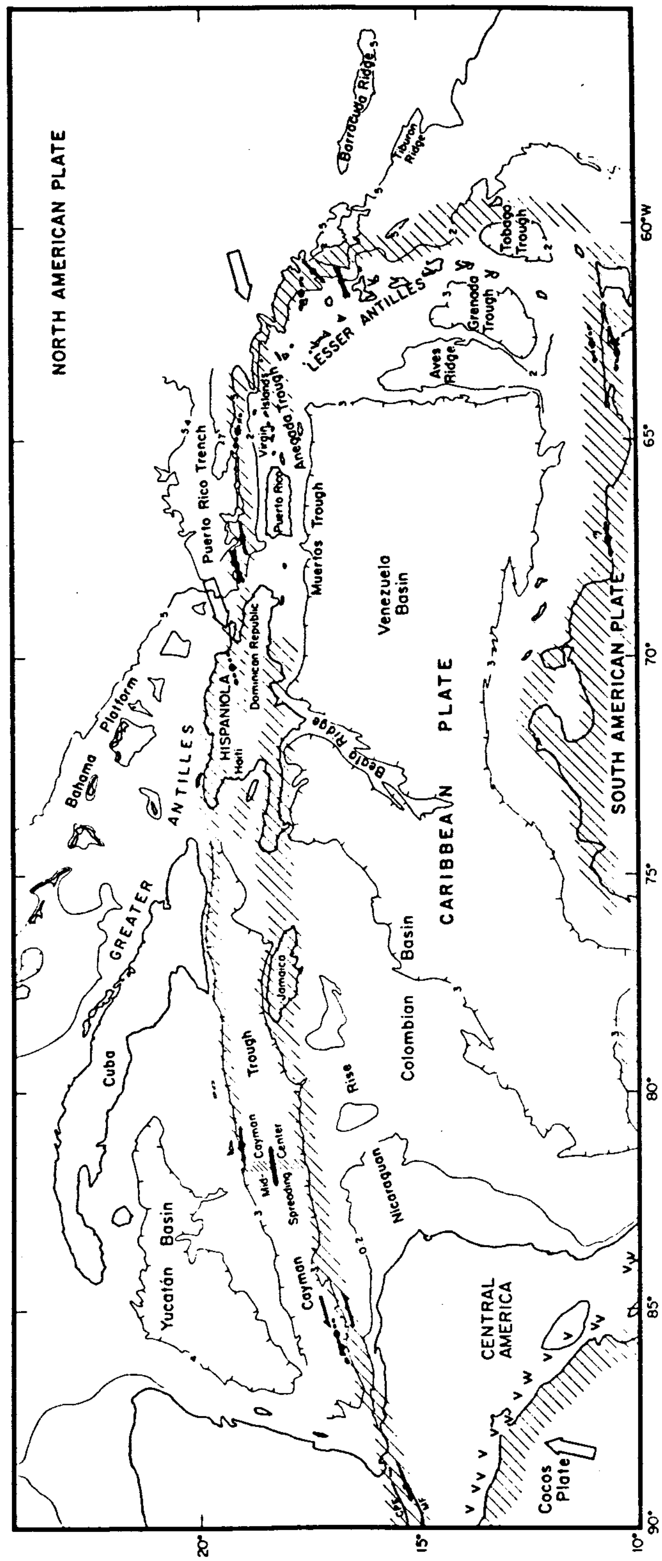


Figure 1.2

Caribbean region major features, from Sykes et al., 1982. Diagonal hatching indicates zones of higher earthquake activity and major interplate motion.

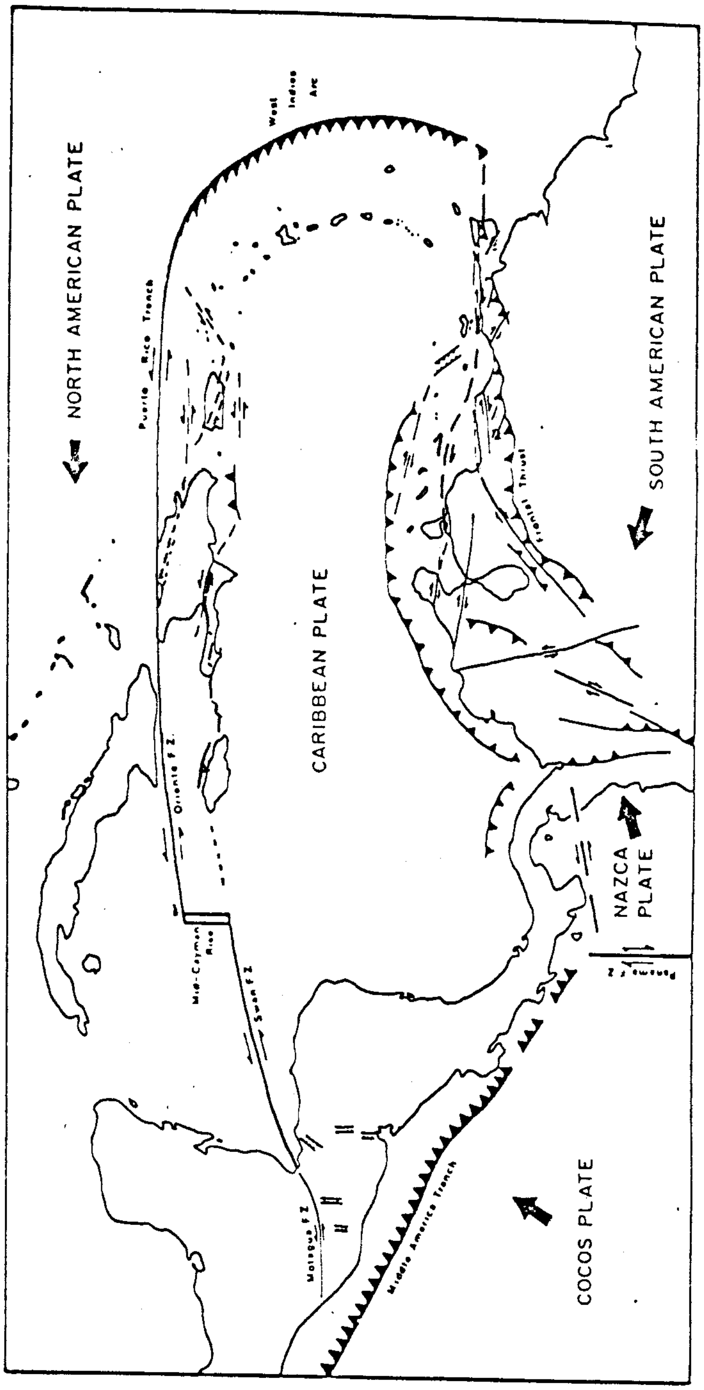


Figure 1.3

Caribbean Plate boundaries, modified after Jordan,1975.

lateral motion presently, although substantial motion and deformation occurs in the Cul de Sac - Enriquillo Valley in the southern tier of the island. Greater lateral motion probably occurred in this latter region in Mio-Pliocene times. The plate boundary relationships are far more complicated and diffuse in the Enriquillo Valley than in the Cibao, and a major splay of the boundary fault system presumably continues offshore through the convergent Muertos trench, continuing eastwards south of Puerto Rico before bending NE in a wrench-fault system through the Virgin Islands. The nature of the plate boundary throughout Hispaniola will be discussed later in the text.

Not unexpectedly, some volcanism is associated with extensional elements in the complicated plate boundary crossing Hispaniola. These include small limburgite flows in the Cordillera Central as well as hornblende-augite-andesite porphyry at the Dos Hermanos eruptive center (71° oo' W, 18° 37' N) in the San Juan Valley. They are all thought to be of late Cenozoic, probably Pleistocene age (MacDonald and Melson, 1969; Vespucci, 1980).

The Field Area

The focus of field studies was a 625 km^2 area of the Fondo Negro-Sierra de Martin Garcia region on the northern side of the Enriquillo Valley, as outlined in Figure 1.4. In addition, reconnaissance mapping in the Tavera region in the foothills on the southwest flank of the Cibao Valley was conducted principally to resolve stratigraphic problems, and to better constrain the timing of initiation of the Cayman spreading center.

The Fondo Negro-Sierra de Martin Garcia region was chosen primarily because it was practically unknown geologically and because it had the potential to provide clues to the early Tertiary evolution of Southern Hispaniola, as well as the development of Neogene strike-slip activity. In addition the mapping tested the hypothesis that a Neogene subduction system crossed the Enriquillo Valley and veered through the field area at Fondo Negro between the Sierra de Neiba and the Sierra de Martin Garcia. The fieldwork complements a larger field study to the immediate west conducted by Paul Mann as part of his Ph.D. research aimed at understanding major Plio-Pleistocene faulting in the Enriquillo region.

Figure 1.4.

Location map identifying the principal topographic features and cities of Hispaniola, as well as the Fondo Negro - Sierra de Martin Garcia field area. From Weyl, (1966, Fig. 36).

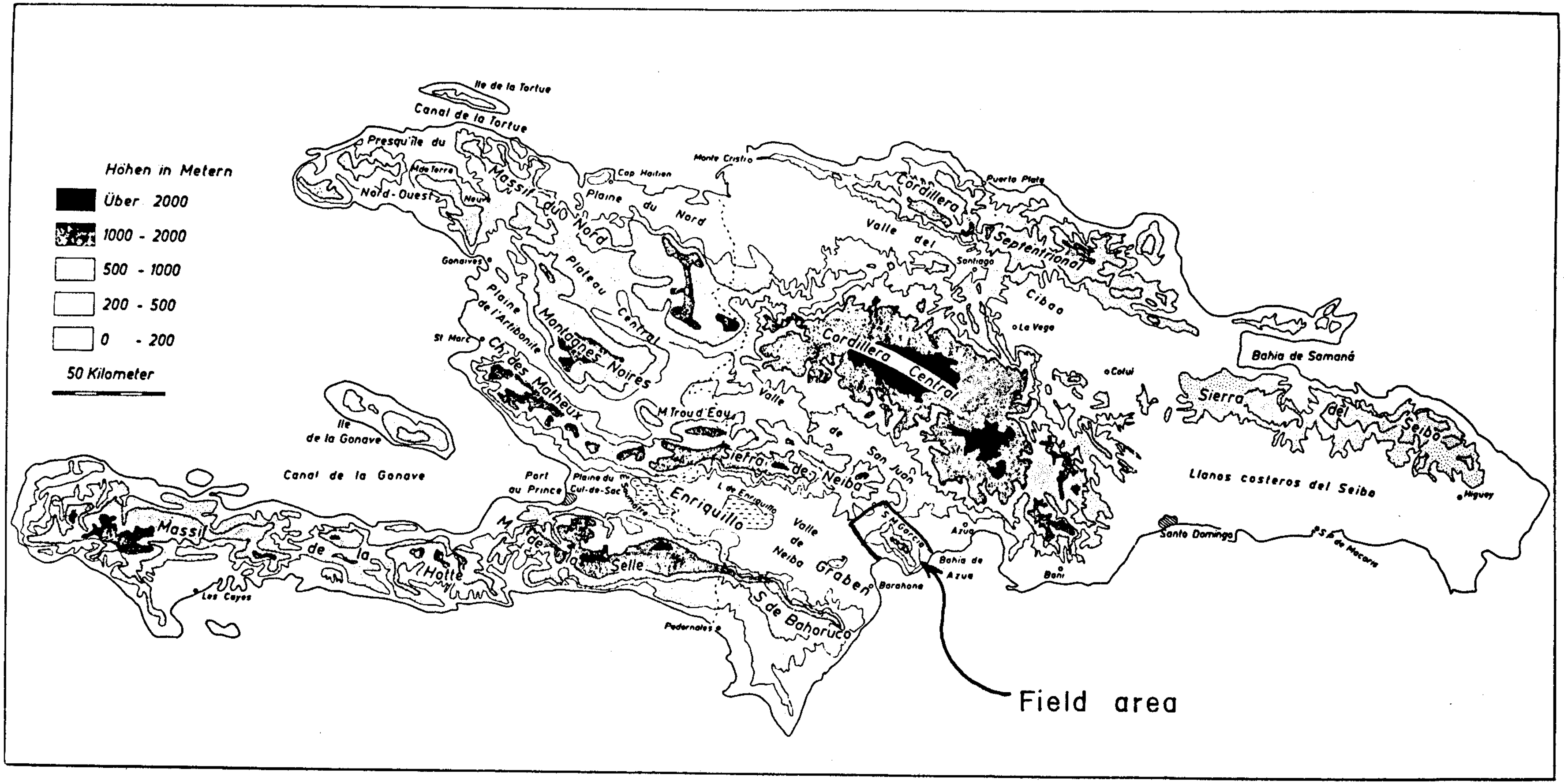


Figure 1.4 Hispaniola, showing field area

Field work

Approximately five months field work was conducted in the Dominican Republic as part of this study. Of that time approximately three and a half months was spent in the Fondo Negro-Martin Garcia Region, two and a half weeks in the Tavera region and the remainder of the time examining the regional geology of the island, and relationships in other field areas. The work spanned three field seasons, January - February 1981 and 1982, and July - early October 1981. Stereo pair Aerial photographs at scales of 1:20,00, and 1:60,000 were used to assist interpretations wherever possible, as well as NASA Skylab and Landsat images.

The terrane, vegetation and exposure vary substantially in the main Fondo Negro-Martin Garcia Region. The Sierra de Martin Garcia rises from the sea to altitudes in excess of 1300 meters and upper elevations are thickly vegetated, nearly jungle, while the Fondo Negro region is a desert covered with cactus and mesquite yet having abundant cuesta outcrops. Only one paved road crosses the field area so access is generally only practicable on foot, burro, or motorcycle on the widespread arroyos and extensive trail network in the desert regions.

Previous work

The first modern geological investigation of the map area in Barahona and Azua provinces was conducted in 1919 as part of a reconnaissance of the country by the U.S. Geological Survey under the direction of T. W. Vaughan. D. D. Condit and C. P. Ross summarized the field party's scientific findings which included maps, formation designations, measured sections and some geochemistry in 1921 (Vaughan, et al., 1921, Ch. 9). Their work was largely of a reconnaissance nature and varies greatly in quality from one area to another depending on the detail of their work. Along the carefully mapped river exposures of the Rio Yaque del Sur between Vicente Noble and Vuelta Grande, (BL830472) the rocks were designated the Miocene Yaque group, and carefully delineated into accurately defined lithologic members. On the other hand they also claimed to find metamorphic basement in the Loma el Magote and Los Gatos north of the main highway, approximately midway between Quita Coraza and Azua at BL911451. The only metamorphic rocks in the area are boulders transported by the Rio Yaque presumably from well known metamorphic basement exposed in the Cordillera Central to the north and east. Generally the report did not focus on structural relationships, and with the exception of bedding attitudes only those structural features observable along the river are noted.

Very little additional geological work was done in this part of the Dominican Republic until the late 1930's, when Dominican Seaboard Oil acquired an interest in the area. In 1939 they drilled a dry hole 1311 m deep on the Quita Coraza anticline (Approx. BL803410). Unfortunately any studies they conducted have been lost except for the generalized well data (Bowin, 1975). In the early 1940's Standard Oil of New Jersey began to focus on the shallow oil seeps in the Azua-San Juan and Enriquillo basins, and sent out field parties to map a large portion of the southwestern Dominican Republic. In addition they commissioned detailed biostratigraphic, especially foraminiferal studies, and aerial photography. The resulting maps comprised the only comprehensive study of the region, and were used as a basis for the Blesch (1967) compilation map. Unfortunately internal inconsistencies tended to render the geology obscure.

In spite of the renewed interest in the northern and central Dominican Republic in the 1960's, including dissertations and subsequent papers by Bowin (1960), Nagle (1966), and Palmer (1963), except for studies of the Sierra de Bahoruco by Weyl (1966) and Llinas (1972), the southwestern part of the country especially the region between Azua and Barahona was largely neglected by the geological community until 1979 when an international group organized by the Institute Francais du Petrol and the Naturhistorisches Museum of Basel (Switzerland) conducted a detailed stratigraphic study of the easily accessible outcrops in the region. Their work included measured sections, micropaleontology and regional interpretations which were summarized in the field guide book, abstracts and proceedings of the 9th Caribbean Geological Conference, (Mascle, *et al.*, 1980, and Biju-Duval, *et al.*, 1980) as well as in a forthcoming AAPG

Memoir 34 on the continental margin (Biju-Duval, et al., in press).

This work established that the section exposed near the village of Fondo Negro was an especially thick deep water unit almost entirely deposited during nannoplankton zone NN11 (Late Miocene), grading upward into a shallow water Pliocene (?) section. The hypothesis was advanced that the section represented the frontal part of an accretionary prism and that the Enriquillo Valley is a landward continuation of the Muertos Trench south of Hispaniola (figure 1.2) (Biju-Duval, et al., 1980). However no structural geology was done to substantiate the claim of the region's accretionary character. In other words the area begged for detailed fieldwork to put it into the proper context, and to determine the genetic and tectonic significance of compression on the margin of the Enriquillo Valley.

CHAPTER 2 STRATIGRAPHY

Previous Stratigraphic Designations for Litho-units of the Field Area.

Stratigraphic nomenclature for the southwestern part of the Dominican Republic (refer to figure 2.1) is mired in confusion, resulting largely from the abuses of biostratigraphers. They ignored lithofacies relationships and attempted to correlate lithologic units based on the unfortunate assumption that the presence or absence of specific microfossils could be used to erect a meaningful stratigraphy in resedimented units. To compound the confusion a group of unpublished oil company private reports (e.g.Dohm, 1942) supposedly supported the biostratigraphic relationships with field evidence. In fact, several of these reports questioned the reliability and applicability of the biostratigraphy, but their doubts were apparently in vain. The field reports were even used by the biostratigrapher Bermudez (1949) to support his designations.

All the oil company reports, including the biostratigraphers' neglected the earlier lithologic designations of the U.S. Geological Survey (Vaughan et al., 1921), and used their own inaccurate assumptions supporting stratigraphic designations both in the field and in the laboratory. Cloaked in secrecy these reports were unquestioned for their accuracy, accepted blindly and firmly entrenched in the geological literature of the region in spite of the

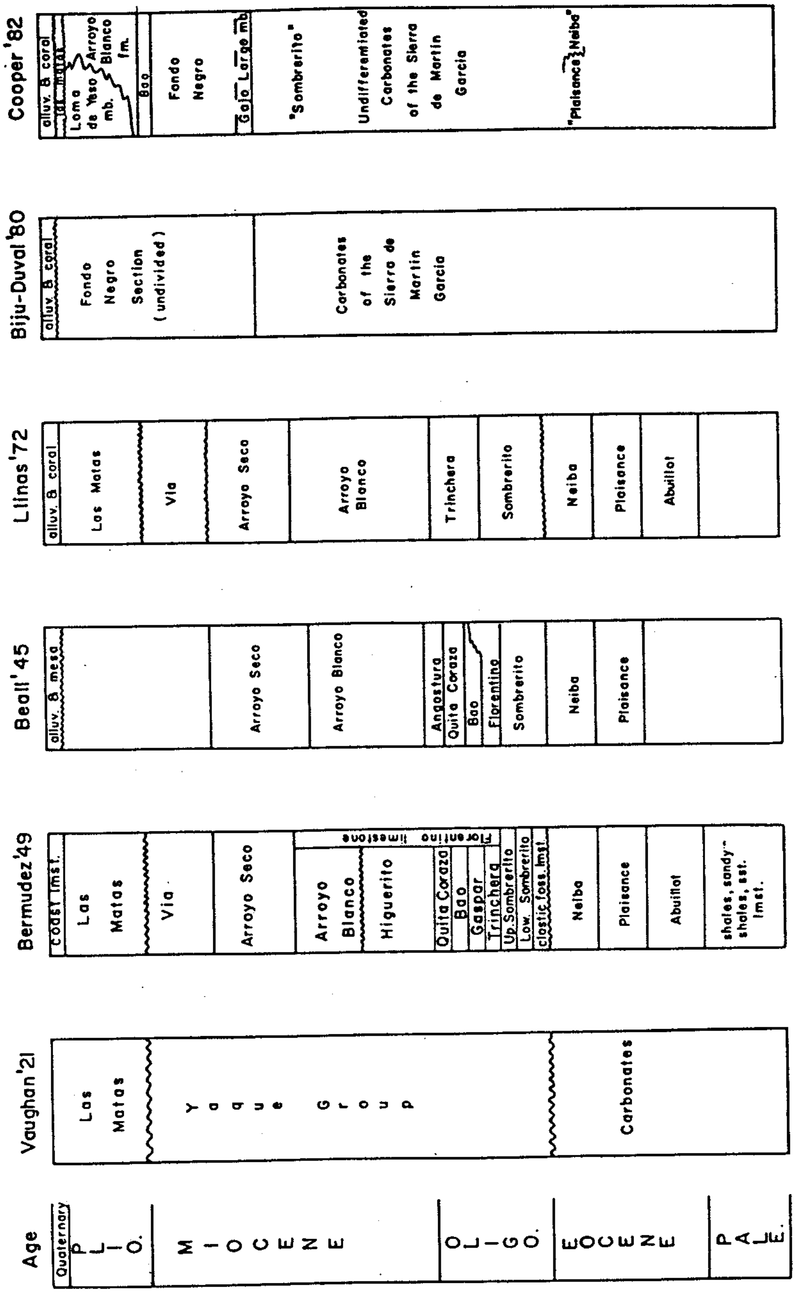


Figure 2.1

Stratigraphic correlations of the field area difficulty in applying them.

Clearly in field studies and even in well-logs, geologists attempted to force correlations based on the prejudices of the biostratigrapher instead of looking at the mappable relationships which show that the biostratigraphy is useless. Apparently the credibility of the biostratigraphy was difficult to challenge. Later field workers as well as industry workers seemed confused by the obvious problems with the nomenclature, and chose, apparently arbitrarily, to use some parts of the biostratigraphy and to ignore other parts. Unfortunately many of these workers mistakenly assumed that a formation with a geographical location as part of its name could be found at or near that geographical location. While that assumption is usually valid when one operates under the international stratigraphic code, by his own admission (see p. 42) the biostratigrapher Bermudez chose names arbitrarily without regard for actual geography. The result has been near chaos in stratigraphic nomenclature.

As an illustration of the stratigraphic nomenclature problem consider, for example, the Fondo Negro Formation in my map area. It consists of approximately 2650 meters of sandy limestones and marls at its base, monotonously alternating siltstones and sandstones gradually coarsening upward to conglomerates (a more detailed description can be found later in the text). Vaughan _et_ _al_. (1921), of the U.S. Geological Survey, in the first published study of the region referred to this section as the basal member of the Yaque group which can be seen along the river of that name. They believed that the basal member of the Yaque group rested on limestones of the Sierra de Martin Garcia and was overlain by a bluish shale unit, another member of the Yaque group. My lithologic designations follow similar divisions up to this point, and I refer to the bluish-grey shale unit as the Bao Formation.

Vaughan's pioneering work was neglected, cast aside by Bermudez (1949) and surplanted by a stratigraphy based on the presence or absence of particular microfossils. Bermudez (p.23) introduced the name Bao zone for the bluish grey shales with thin sandstones described by Vaughan. (Bermudez's type locality, #H-5044, was two kilometers northeast of Quita Coraza in the Arroyo Bao south of the highway approx. BL845440.) He termed the sandstones, shales and marls the Upper Oligocene Trinchera Formation and sub-divided it into Basal, Gaspar, Bao, and Quita Coraza zones based strictly on fossils without geologic mapping. To further complicate matters he confused geologists familiar with the local geography by claiming that the Bao zone was overlain by the soft shales of the Quita Coraza zone. The villages of Quita Coraza and Bao are scarcely separated by two kilometers, and both lie atop rocks of what I call the Bao Formation in Bermudez's type locality. Bermudez chose the name Quita Coraza apparently because he liked it, not because the Quita Coraza shales are anywhere nearby. In fact, sample localities that Bermudez (p.42) identifies as the Quita Coraza zone are located some 40 kilometers to the east in the Rio Via near the city of Azua. Many a geologist came to the village of Quita Coraza, saw the fantastic exposures of blue-grey shales across the river from the village and assumed that these must be the Quita Coraza shales, and thus the obvious unit below them would be the Bao. Confusion also ensued concerning the status of a zone as opposed to a formation or member and consequently the flysch unit became known as the Bao Formation which was somehow divided into the Gaspar and Trinchera formations (not members!). Troubled by too many "formations", geologists generally dropped the Gaspar formation altogether and assumed that far off the road, somewhere in the desert the basal Trinchera zone (member ?) could be distinguished.

Even Bermudez's co-workers for the Standard Oil Company of New Jersey and their Creole Petroleum subsidiary were confused by his stratigraphy and could not correlate mappable units with it. Apparently they were in no position to challenge Bermudez and the validity of his subdivisions, so they forced the names onto rocks where lithologies were plausible equivalents. Two of the more active Standard Oil field geologists--C. F. Dohm, and R. Beall would simply report that rocks varied considerably from the type sections. In the case of what I call the Fondo Negro formation, both considered the entire "flysch" section to be the Bao Formation because they were confused by the Quita Coraza definition and the zone distinction. Beall (1945, p. 9) writes, "There are no good lithologic breaks on which field separations could be made and since the name Bao is more commonly used in this part of the island (i.e., in Dohm's report), no attempt is made to divide the formation into Trinchera, Gaspar and Bao formations as does Dr. Bermudez. The entire section is mapped as Bao."

Beall's confusion between the identities of the Bao and Quita Coraza zones, or formations as he considered them, is easy to appreciate. Apparently, he did not realize that Bermudez's type locality for the Bao zone, in the Arroyo Bao, happens to be stratigraphically above the massive conglomerate that Beall thought (incorrectly) to be the top of the Bao formation. Beall did have well correlations available, and in the Higuerito wells northwest of Azua (See figure 2.2) thick (500m?) massive grey calcareous shales were encountered above a sandstone-conglomerate horizon. There, as Beall, knew, the shales were called the Quita Coraza formation, and so correlated on the well logs. Beall simply extended the lithologic correlation and put the Bao below what he interpreted to be the Quita Coraza. It is quite possible that Beall was correct in his identification of a lateral equivalent of the Quita Coraza and that Bermudez constructed an unnecessary formation. In other

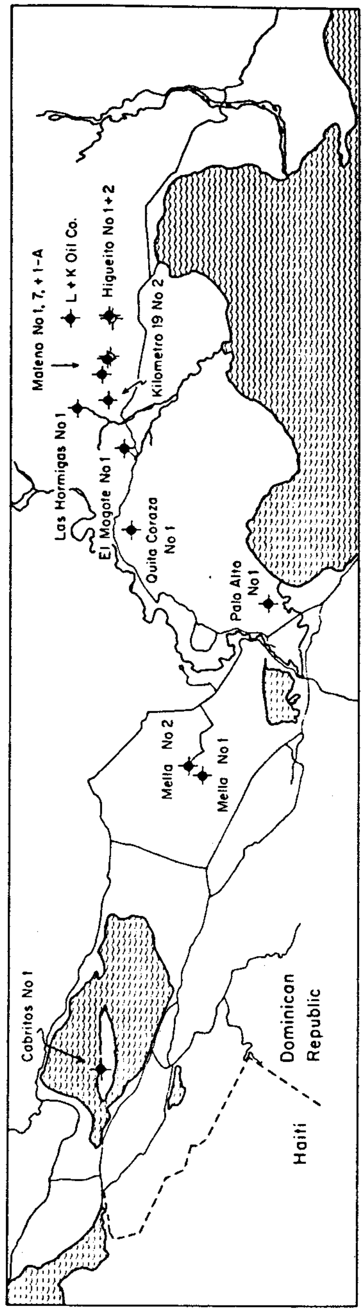


Figure 2.2

Well locations in the southwestern Dominican Republic, from Bowin, (1975).

words, in my mapping, the Bao shales are blanketed by the Arroyo Blanco Formation as one follows them along strike to the east. These same shales may be found in the Higuerito wells, and crop-out in the Rio Via Azua identified by Bermudez as the Quita Coraza zone. It would indeed be an amusing coincidence for the Bao zone (Bermudez) and the Quita Coraza zone so often mistaken for it to be actually the same formation.

Instead of continuing to attack previous stratigraphic subdivisions I now attempt to systematically discuss the stratigraphy of the region, pointing out the limitations of some correlations, beginning with the basal part of the section.

Formation Descriptions

The description of formations in the southwestern Dominican Republic begins with basement complex and works upward stratigraphically through the carbonates to the recent. Not all formations described in the text are found in the field area. A comparison of stratigraphic designations is shown in figure 2.1, and a stratigraphic column for the field area is shown in Figure 2.3

Basement Complex

No rocks of the basement are known to crop out in the Sierra de Martin Garcia-Fondo Negro region although they are know to occur in the Sierra de Neiba to the west and the

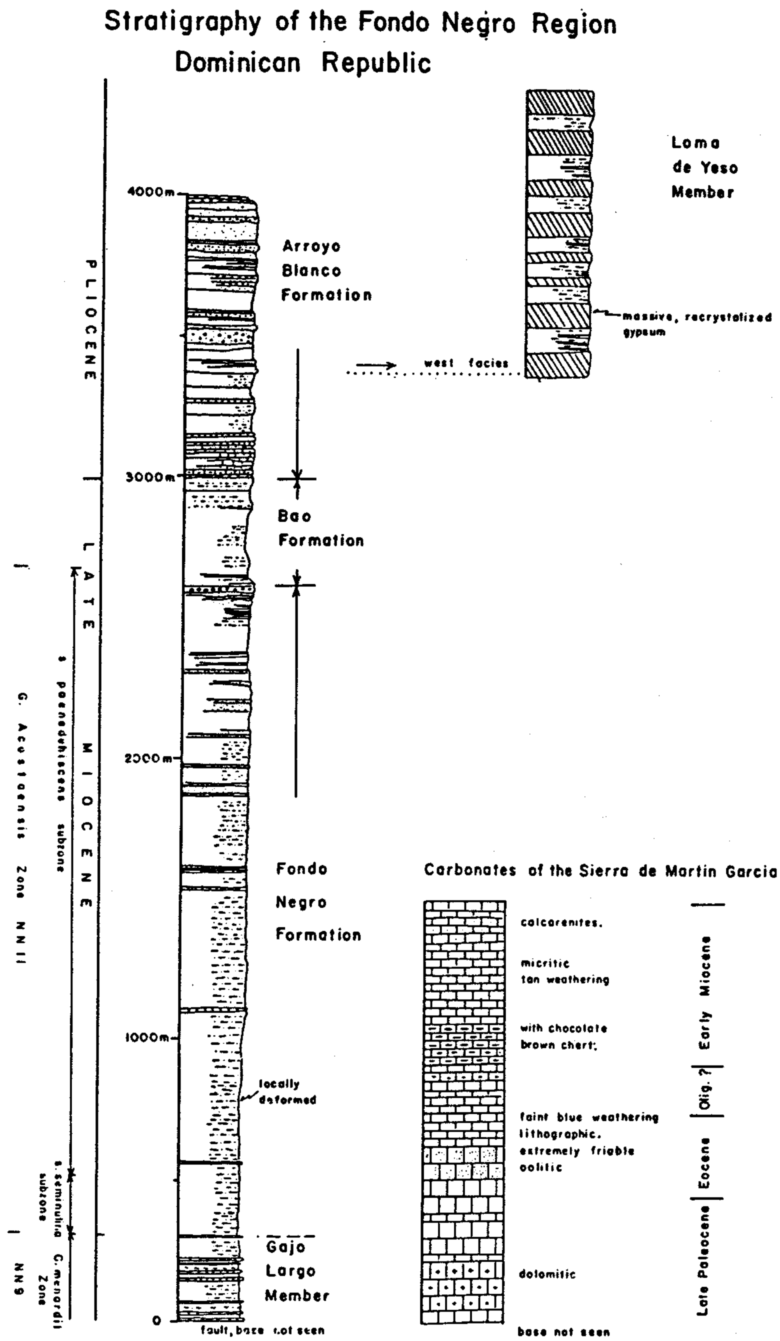


Figure 2.3 Stratigraphic column for the field area.

southern Dominican Republic as well. However, these formations are not known to exist in the Sierra de Martin Garcia region.

Clearly a great deal of detailed work needs to be completed in the Dominican Republic in order to establish the carbonate stratigraphy. Although the original formation names implied restricted stratigraphical ranges, they are now used loosely, more as lithofacies indicators.

Plaisance Formation

In its original definition (Vaughan, 1921) the Plaisance formation with its type locality in the Massif du Nord of Haiti consists of thick beds of coffee colored hard limestones with nodules of chert. Llinas (1972) describes exposures of the formation in the Sierra de Bahoruco as 1.0-2.5m beds of biogenetic calcilutites, biomicrites and calcilutites colored light coffee, yellow and grey, with some interbedding of oolitic limestone, and a largely recrystallized matrix.

The Plaisance formation (*sensu stricto*) contains shallow water faunas and is certainly not older than the middle part of the Middle Eocene and may extend upwards into part of the Upper Eocene (Tony Eva, personal communication 1982).

Neiba Formation

The Neiba formation, (Figure 2.4) originally thought

Figure 2.4

The Neiba limestone formation, exposed along the road north of Neiba to Guacate in the Sierra de Neiba (BL445482). Alternating deep and shallow water foraminiferal horizons combined with sharp bedding contacts, apparent channels, slight grading and laterally varying bed thicknesses (few cms. To a meter) suggest deposition as carbonate turbidites. Note the chocolate colored chert layer near the top of the picture.

These rocks are generally believed to be of late Eocene age.

(Dohm, in Bermudez, 1949) to be stratigraphically above the Plaisance formation, consists of thin (10-20cm) well bedded, hard lithographic limestones, with chocolate colored chert and gray marls. No thickness has been established for the formation. The rock weathers a dull grey color but on fresh surfaces appears as a white micritic limestone. Outcrops in the Sierra de Neiba show distinctive-yellow orange specks on the weathered surface. Microfossil studies show alternating shallow and deep-water fauna definitely indicating deposition as turbidites (Tony Eva, personal communication).

As a formation, the Neiba is one of the time equivalents of the Plaisance. The Plaisance represents the shallow water shelf, the Neiba the transition to deeper water with many turbidite flows and something similar to the Jeremie formation (Maurrasse, 1982) of eupelagic foraminiferal limestones represents the deepest parts of the basin where purely pelagic materials accumulated (See Figure 2.5). Careful mapping would probably reveal intermediate facies which may be worthy of formational status. It is presumed that this style of deposition existed throughout the Paleogene, and that strictly speaking new formation names are necessary to describe a similar situation below the Plaisance-Neiba formations if one restricts them to Eocene ages.

Sombrerito Formation

The Sombrerito formation is lithologically similar to

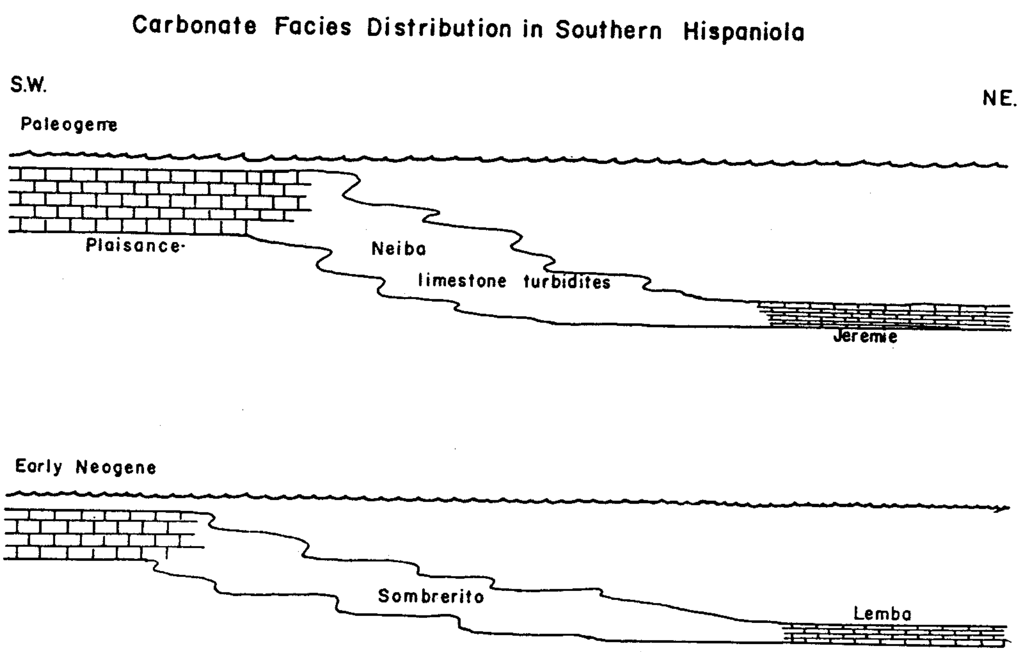


Figure 2.5

Carbonate facies variation and distribution in southern Hispaniola.

the Neiba-Plaisance formations only younger extending well into the early Miocene in the field area. Llinas (1972) claims that it lies with erosional unconformity above the Neiba formation in the Sierra de Bahoruco based on the presence of a basal conglomerate. No such unconformity has been noted in the Sierra de Neiba or in the Martin Garcia region.

Olsson (in Bermudez, 1949) defined the Sombrerito formation in its type locality on the northeast slope on the eastern end of the Sierra de Neiba where it consists of alternating thin to thick beds of grey to buff, chalky to crystalline, locally porous and micro-fossiliferous limestone with thin to thick beds of light-to-dark grey marl or calcareous shale containing numerous pelagic Foraminifera. In places the shale is silty to very finely sandy. In the San Juan Valley, exposures near the base of the formation contain thin beds of indurated limestone conglomerate. In general, the proportion of limestone to shale increases downward in the formation but even at the top some beds of limestone, apparently with materials of reef origin, attain thicknesses of several meters.

Is the Lemba equilavent to the Sombrerito?

Lateral variations in carbonate units are naturally quite pronounced and it is perhaps a philosophical question what to designate a formation or a member (See Figure 2.5). The Dominican literature generally distinguishes formations where good exposures are easily accessible, and in this way the Lemba formation of middle Miocene age (Llinas, 1972) is described as beds of chalky limestone exposed in the hills east of Lemba on the southern flank of the Enriquillo Valley. Bed thickness usually ranges between 20-60 cm, although some beds are up to a meter thick (Llinas, 1972, and Dohm in Bermudez, 1949). Microfauna are rare although the formation may be 750m thick, lying unconformably above what is called the Sombrerito formation. The only observed upper contacts with this unit are tectonic, and its lateral extent is unknown. It seems probable that the Lemba is a facies variation of the upper Sombrerito in the Martin Garcia region.

Carbonates of the Sierra de Martin Garcia

In the preceeding section the difficult and imprecise state of carbonate stratigraphy in the southwestern Dominican Republic was emphasized. My mapping was unable to distinguish formations or mappable litho-units for the carbonates in the Sierra de Martin Garcia, although individual outcrops resembled descriptions of formations known in other areas.

The carbonates of the Sierra de Martin Garcia range in age from late Paleocene through early Miocene based on index fossil determinations (See chapter 3), and are at least 1500 meters thick. Their base is not exposed, and structural complexities make it difficult to be more precise about thickness with any confidence. Generally, the lower carbonates are more massive, and regularly bedded than the upper ones. Two samples dated as late Paleocene contains only shallow water fossil forms, but one appears resedimented, and one (BL893273) contains dolomite rhombs. From a lithologic standpoint there are chalky, faint blue weathering lithographic limestones, tan weathering granular and especially near the upper third of the carbonate stratigraphy limestones with layers of chocolate colored chert (See Figure 2.6) similar to the Neiba formation (Figure 2.4) are found. No Oligocene carbonates have been identified, and this may be due to the low sea level stand at that time, due to ice formation, and the generally resedimented carbonate turbidite character of the upper carbonates in the S. de Martin Garcia region. Early to early medial Miocene carbonates have been identified and these are thought to correlate with the "sombrerito" formation. They are at least 250 meters thick, contain quartz grains (<10%), and their upper contact is almost always fault bounded. Bedding has a distinctly hummocky appearance, and individual beds are rarely greater than one-half meter thick. However, as noted by Beall (1945), the Sombrerito equivalents on Martin Garcia are almost entirely limestone differing greatly from the type section which has thick beds of grey marl, although, the Canoa Dome carbonates do have thin (cm.) marl layers between some beds of limestone. I found no unconformity within the carbonate units, and this supports a similar

Figure 2.6

Undifferentiated carbonates from the north flank of the Sierra de Martin Garcia (Right = B1793335, Left = B1792338) appear similiar to the Neiba formation of the Sierra de Neiba. The outcrop on the right (top) contains layers of chocolate colored chert near the base.

Paleontological dating constrains these to the Early to Early medial Miocene.

Figure 2.6

Undifferentiated carbonates from the north flank of the Sierra de Martin Garcia (Right = B1793335, Left = B1792338) appear similar to the Neiba formation of the Sierra de Neiba. The outcrop on the right contains layers of chocolate colored chert near the base.

Paleontological dating constrains these to the Early to Early medial Miocene.

Figure 2.7

Outcrop location BL822373 on the Loma la Pelada illustrates the pronounced effect of “case hardening” on carbonate exposures. The soft, friable chalky limestone exposed on the right is hardened, presumably by groundwater circulation. Paleontological dating of a sample from this location reveals it to be of Late Eocene age, providing evidence for a local unconformity between the carbonate succession and the late Miocene Fondo Negro formation, which lies above the carbonates, on this block.

finding by Beall (1945). Unconformities are known within carbonate successions to the south and north. To say the least, a lot more could be done with the carbonates.

The Clastic Succession

A thick Medial Miocene through Pliocene clastic succession lies stratigraphically above the carbonates. The contact with the carbonates is tectonic (see plate 1.), but the facies transition suggests conformity on a broad scale with the exception of an area on the Loma la Pelada. The section has been called the Yaque group by Vaughan, et al. (1921) and the Fondo Negro section by Biju-Duval, et al. (1980). The later have dated the 4000m section as entirely Tortonian-Messinian age except for the upper 1000m, which is probably Pliocene age. I distinguish three mappably distinct formations (see plate 1) and two members of this group as follows: the base of the section is the Gajo Largo Member of the Fondo Negro Formation, followed by the rest of the Fondo Negro formation, the Bao Formation and the Arroyo Blanco Formation with the Loma de Yeso Member. Each is described separately.

The Fondo Negro Formation

I propose the name Fondo Negro Formation for the Tortonian-Messianian sequence (See Chapter 3 for fossil lists) which crops out mostly to the south of the village of Fondo Negro in the foothills of the Sierra de Martin Garcia (see plate 1). The type section can be considered the Arroyo Fondo Negro (El Puerto). The formation is conformably overlain by the Bao formation, while its lower contact is tectonic with the limestones of the Sierra de Martin Garcia. The formation is characterized by sandy limestones (maximum bed 2m.) and calcareous siltstones at its base (the Gajo Largo Member), followed by medium to fine calcareous sandstones, siltstones, conglomerates and marls. Fresh samples of calcareous sandstones are medium tan to light grey, and the calcareous siltstone is dark grey in fresh samples, but weathers rust to tan. The section becomes coarser and coarser toward the top which is marked by a prominent cuesta-forming conglomerate unit seen along the highway (e.g. BL825437) near Quita Coraza which contains pebbles up to several centimeters in diameter. In nearly all cases the unit displays regularly fining upward beds, and sedimentary structures including sole marks and flute casts indicative of turbidite deposition. The total minimum thickness of the formation is approximately 2650 meters based on my measurements, confirming Biju-Duval et al., (1980). Note that the base is not exposed.

A typical calcareous sandstone from the Fondo Negro Formation such as one from BL747336, and shown in figure 2.8 has little real matrix other than crushed lithic grains and is generally well sorted without much clay. Calcite has obviously grown in the matrix and the mineralogy includes unstable volcanic and subvolcanic assemblages of biotite and

Figure 2.8

A freshly bulldozed outcrop of the lower Fondo Negro formation (BL747336) showing alternating calcareous shales or siltstones and sandstones. The grey color seen on fresh surfaces weathers rapidly to a milky coffee brown.

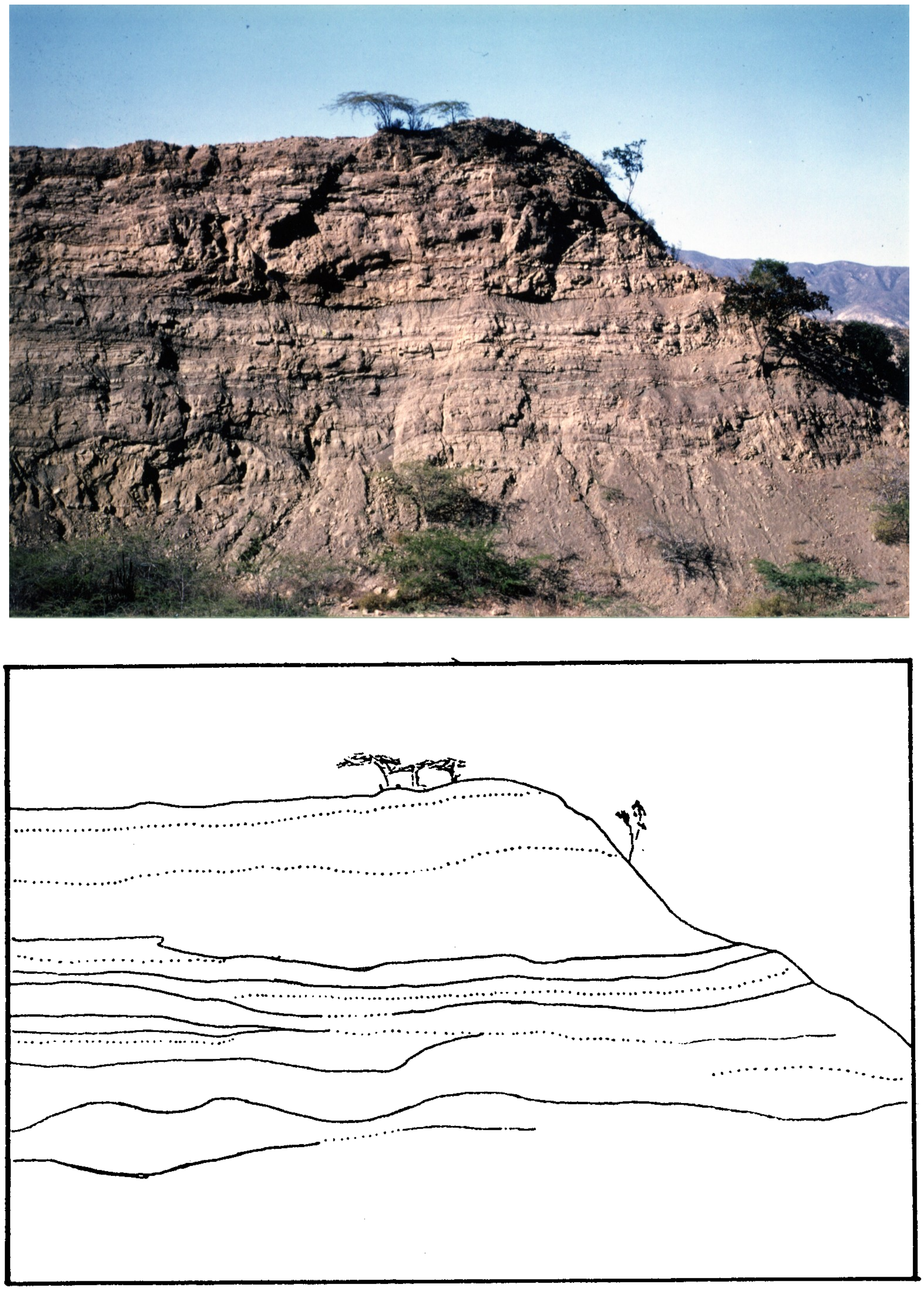


Figure 2.9

The top of the Fondo Negro formation (BL832438) is characterized by massive sandstones and shales capped by a conglomerate unit. Deposition was presumably by a channel fan system.

chlorite, with quartz and smaller amounts of detrital epidote, altered hornblende, altered sphene, rutile and zircons. Somewhat hexagonal rock fragments are common and while altered they appear to be andesitic. The sandstone has little or no porosity due to extensive calcite filling, and recrystallization.

Biju-Duval et al. (1980) reported that the faunas indicate a relatively deep environment of deposition (shallowing with time), exclusively in the Late Miocene nannoplankton zone NN11 (Discoaster quinqueramus zone) with Sphaeroidinellopis Seminulina s., and S. paenedehiscens s.

The Fondo Negro unit has been referred to as the Bao, Trinchera and zones or Higuerito formations by geologists confused by the biostratigraphic nomenclature of Bermudez (1949).

The Gajo Largo Member

The Gajo Largo member of the Fondo Negro formation (Figure 2.10) forms a prominent set of ridges or hogbacks, (BL755335) to the northeast of Canoa for which it is named. It is composed of alternating sandy limestones, marls and siltstones with slope microfauna of the S. Seminulina subzone (G. acostaensis zone) (Biju-Duval, et al., 1980), and includes the uppermost part of nannoplankton zone NN9, as well as lower zone NN11. The nannoplankton zone NN10 has not yet been recognized in this area.

In outcrop, at its type location (BL755335), seven

Figure 2.10

The Gajo Largo member of the Fondo Negro Formation, as seen at location BL754337 approx. 1.5km east of the intersection (Cruce) of the road to Vincente Noble from the main highway. This is the upper resedimented sandy limestone and marly siltstone, a combination which repeats at least seven times although the carbonate is typically less massive lower in the section. The sandy limestone is interpreted as a debris flow deposit.

distinctive beds of chalky grey weathering (but tan in freshly cut samples), sandy limestone are each separated by as much as 15 to 20 meters or as little as 2 meters of siltstone. These are overlain by approximately 30 meters of siltstone and another meter thick sandy limestone. The total thickness of the member is approximately 200 meters. The proportion of sand varies considerably in the limestones from bed to bed as observed in hand sample although no quantitative study has been undertaken. Fresh surfaces characteristically show mottled orange specks similar to samples of the Neiba formation. The uppermost, best exposed sandy limestone displays a well developed rhombehedral joint pattern perpendicular to bedding. The sandy limestone beds are continuous for several kilometers, and form distinctive triangular facets readily mappable on aerial photographs.

The base of the Gajo Largo member is in tectonic contact with the carbonates of the Sierra de Martin Garcia, while the top of the member is considered to be the uppermost distinct sandy limestone which forms a triangular shaped facet on the spur of the mountain. This feature is quite obvious in the field and an on aerial photographs, see map plate 1. As the Gajo Largo is considered a member of the Fondo Negro Formation, it is completely conformable with the overlying massive siltstones and carboneceous sandstones of the rest of the undivided Fondo Negro Formation. Much higher in the section other laterally extensive sandy carbonate layers occur, but they are singular "pulses" or

Figure 2.11

On the southern flank of Martin Garcia, (BL760311) rocks interpreted as the Gajo Largo Member are massive sandy limestones in contrast to the location shown in Figure 2.10. Siltstones crop out to the north (left) of this picture, and figure 2.12 illustrates the interpreted facies variation.

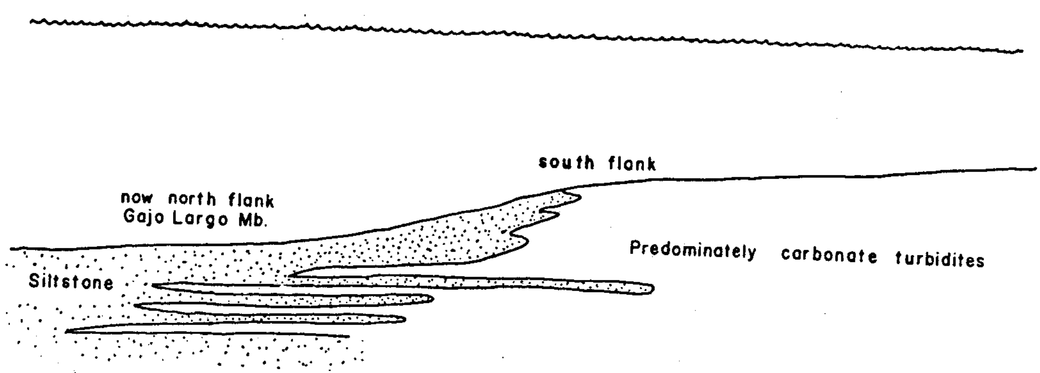


Figure 2.12

Interpreted facies variation

layers, and do not form such an obvious topographic expression as the Gajo Largo member.

On the southern flank of the Sierra de Martin Garcia exposures (Figure 2.11) are interpreted to be a facies variation of the Gajo Largo Member described above. There sandy limestones are more massive (up to 5m.), and are interbedded with thick sandy siltstones. It is easy to palinspastically position them five kilometers apart at the time of deposition, which is more than enough to account for thickness variations (See figure 2.12). One must keep in mind that this suggestion is only an interpretation, and no fossil control has been established to support it.

Bao Formation

The Bao formation, as I define it, comprises some 400 meters of bluish grey calcareous shale and siltstone with thin laminar sandstones lying apparently comformably above the uppermost massive conglomerate of the Fondo Negro formation. The top of the formation is the sandy shale below a bioclastic limestone bed. The type section is show in figure 2.13. Its age is the same as the Fondo Negro, with fossils from zone NN11. The unit is distinctly mappable, and erodes to form the populated river valley.

The Bao Formation was noted as a distinctive member of the Yaque group by Vaughan, et al. (1921) and misunderstood to be the Quita Coraza formation by Beall (1945). The name Bao zone was given to this section by Bermudez (1949) and is

Figure 2.13

The Bao shale formation exposed along the river loop approximately 2.5 kilometers west of Fondo Negro (BL751383) consists of massive bluish grey calcareous shale with some graded, fining upwards laminar sandstones.

one of the few localities where he describes a type locality in outcrop. Unfortunately he identified microfauna similar to that present in Bao shale in numerous other localities in Southern Hispaniola and incorrectly considered those to be Bao zone as well. Understandably this caused confusion. However I chose to retain the name Bao formation to describe the rocks of its original type locality sensu stricto. The Bao Formation in its type locality may be disconformable (erosionally unconformable) above the Fondo Negro Formation, although that is not clearly established. I prefer to interpret it as the result of the migration of deposition in a fan system, probably related to a sea level rise and/or tectonic activity eliminating the supply of pebbles and sand.

Arroyo Blanco Formation

The Arroyo Blanco Formation was first described by Dohm (1942) as a mappable unit, then later obscured by Bermudez (1949) who defined a veritable maze of stratigraphic relationships from samples that are lateral extensions, along strike, of from the very beds that Dohm described as Arroyo Blanco. Dohm considered the Arroyo Blanco formation to consist of two distinct "zones" or "facies". The upper facies includes coralline limestone, sandstone and conglomerates of shallow water origin and a lower facies comprised of compact grey, calcareous shale, weathering ochre-colored believed to be of deeper-water origin (Bermudez, 1949). Bermudez termed this facies the Higuerito member (later formation) apparently without noticing that some of the localities he identified as Bao shales were the same beds that he identified as Higuerito. There is some question, but it seems that Bermudez considered the same rocks two members, and even interjected a third between them.

I prefer to consider the lower facies as defined by Dohm (1942), the Bao formation and restrict the Arroyo Blanco to what Dohm considered the upper facies as used by Llinas (1972). It should also be noted that Bermudez studied various samples from Dohm's upper facies, and identified them as Gaspar, Higuerito, and Bao zones as well. Biostratigraphy in resedimented units is clearly a tricky business.

The Arroyo Blanco Formation as I define it is at least 1000 meters thick. It lies conformably above the Bao Formation, and is overlain by alluvium. The contact with the Bao is a bioclastic carbonate bed with large fossil fragments, and sandy marl. Its precise age is unknown, but is thought to be Pliocene (Mascle et al., 1980). The type section is along the Arroyo following the Yaque de Sur river, north of La Sierrecita (BL840445 and north). The lower 250 meters (Figure 2.14) contains bioclastic and coral limestone debris, marls and calcareous sandstones.

Figure 2.14

The lower Arroyo Blanco formation includes prominent horizons of resedimented carbonate shelf debris, and not unlike conglomerates in the Fondo Negro formation, they form the top of cuestas. The outcrop shown here occurs at BL 792435.

Fragmented coralline microfauna and Mollusks are abundant including *Porites* sp., *Siderastrea* sp. *Montastrea* sp., and *Diploria* sp., as well as *Ostrea haitenses* *Orthalaz aguadillensis* *Larkinia* *patricia* *Siphocypraea* sp., and *Conus* sp., (Biju Duval, *et al*., 1980). In some massive lower beds large coral fragments, somewhat aligned, comprise most of the rock. Exposures are not continuous, but the upper two-thirds to three-fourths of the section (Figure 2.15 and 2.16) is distinctly more sandy and conglomeratic than the lower portion. On an individual basis these beds are very similar to the uppermost Fondo Negro unit, however, in general the beds of the Arroyo Blanco Formation are much thicker and more massive than the Fondo Negro, with distinctly less massive shale or siltstone, and fewer indications of fining upward. Some beds weather reddish and contain millimeter size fragments of igneous rock types, especially basalt and mafic intermediate rocks, and have a calcareous matrix. Most beds weather tan to grey and repeated cycles of shale or siltstone, sandstone and sometimes conglomerate are common. Massive conglomerate is particularly well developed in a major synclinal axis (BL855462) which is essentially the top of the exposed section, although an unknown amount may have been cut off and lost. Vaughan, *et al*. (1921) assigned the conglomerate to the Las Matas formation, and believed that it lay with angular unconformity above what I refer to as the Arroyo Blanco Formation. While conglomerates and unconsolidated gravels

Figure 2.15

The middle Arroyo Blanco formation comprises massive, coarse, poorly sorted immature sandstones and siltstones, shown here at BL 840499, above the marine debris flows.

Figure 2.16

This outcrop, BL 804839, near the axis of a major syncline shows the upper (upper middle?) Arroyo Blanco formation, with coarse, immature calcareous sandstones, and marls covered at the top left by recent river gravel deposits. To the east the recent gravels are better developed.

do lie with angular unconformity over large areas of the field area including along the river to the north, in this case the conglomerates show no sign of unconformity.

The water depth at the time of deposition could not have been great due to the large volume of resedimented shallow water corals, and the entire section is presumed to have been deposited in shallow water. No obvious transition exists which would indicated a beach environment, and plant materials do not exist, except in the Loma de Yeso Member, so the Arroyo Blanco described above is interpreted as entirely marine.

Loma de Yeso Member

The Loma de Yeso member is a lateral equivalent, facies within the Arroyo Blanco Formation described above. Unlike the Arroyo Blanco, sensu stricto, which comprises, presumably, shallow water marine rocks, the Loma de Yeso consists of evaporitic facies, intertidal deposits, and possibly lacustrine immature sandstones. The contact with the Arroyo Blanco is entirely transitional or gradational and its upper contact is tectonic. West of Arroyo Seco, across the Rio Yaque del Sur from Fondo Negro the lower Loma de Yeso is well exposed and comprises massive gypsum beds with some interbedded grey clays and coarse friable sandstones (See Figure 2.17). This should not be confused with the Arroyo Seco Formation named for a group of lithologically distinct rocks in the foothills south of the city of San

Figure 2.17

The Loma de Yeso member is a lateral facies variation of the Arroyo Blanco Formation, and comprises massive gypsum as well as limy clay (shown above at BL 656450), with plant remains, leaf prints, and mudcracks.

Juan. The Loma de Yeso member gypsum beds are of commercial quality, extremely fine crystalline white gypsum with only sparse argillaceous materials. Beds are massive, typically 4-5 meters thick. Some are highly recrystallized, especially in the upper part of the section. To the west the gypsum beds are less massive, and the proportion of limey clay is greater, while plant remains, leaf prints and mud cracks become common. The total thickness of unit was not measured but is estimated trigonometrically to be more than 1000m, and greater than the Arroyo Blanco type section, indicating a thickening basin to the south and west.

Correlation With Other Evaporites

The stratigraphic relationship between what I call the Loma de Yeso member and the Angostura formation found along the southern margin of the Enriquillo Valley has perplexed many a geologist. My study suggests that there exists at least two major evaporite sequences, the upper sequence being the Loma de Yeso of Pliocene (?Pleistocene?) age, and an earlier, more developed, Middle Miocene - pre Fondo Negro evaporitic sequence. The later is known to be thousands of meters thick in the Mella wells (Bowin, 1975) of the Enriquillo Valley, although some have contested the validity of the Middle Miocene correlation for the evaporites in the wells. Aware of the correlation problem, the group from the Institute Francis du Petrol collected samples of marls and siltstones from the Loma de sal y Yeso on the southern flank of the Enriquillo Valley stratigraphically (and conformably?) above evaporite facies, and found them to belong to the nannoplankton Zone NN11, (*Discoaster quingueramus* zone) identical to the Fondo Negro Formation (Biju-Duval personal communication, 1982). In other words, the massive evaporites of middle Mocene age are covered by Upper Miocene Fondo Negro Formation (or equivalents) which is in turn overlain by shallow water marine and evaporite facies of Pliocene age. The massive gypsum deposits north of the Yaque de Sur river are younger therefore than those on the southern margin of the Enriquillo Valley (*Agnostura Formation*).

Here it should be noted that the gypsum deposits on the south flank of the Sierra de Martin Garcia (e.g. BL740300) are mapped as Arroyo Blanco formation of Pliocene age, although no paleontological work has been done to definitively establish that correlation. The designation is based on a preferred geometrical and structural argument presented in Chapter 4.

The formations or rock types that lie above the Loma de Yeso and Arroyo Blanco formations are all considered Quaternary without the benefit of precise fossil control.

Quaternary Limestone

Presumed Quaternary reef materials, including fossiliferous limestones, coquinas and calcareous shales that weather brown and yellow are found on southern margin of the Sierra de Martin Garcia, and probably occur along its northern coast as well. These raised reefs resemble the Jimani Formation described on the southern flank of the Enriquillo Valley (Arick, in Bermudez, 1949). In the gypsum mining area east of Canoa (BL740300) the reefal materials, including shell hash debris, seem almost a diapir amid the gypsum. Precise thickness of the Quaternary limestone was not determined, but with the exception of one location where 60 meters is a reasonable maximum estimate (BL827272), the exposures suggest an average thickness of under 5 meters.

Two pieces of float were found at an elevation of approximately 650m at BL 949250 on the north flank of the Sierra de Martin Garcia, above Barrero, consisting of latest Neogene, or more probably Pleistocene reefal debris once part of a former fringing reef. Assuming that these rocks were not carried up the mountain (for some unknown reason), then the uplift of the Sierra de Martin Garcia has been rapid and recent, and a much greater amount of Quaternary reef material may be exposed on the mountain than is shown on the map, plate 1.

Figure 2.18

Quaternary raised reef overlying Arroyo Blanco formation near the coast on the south side of the Sierra de Martin Garcia at approximately BL 827272. Elevation approximately 10m.

Travertine

Modern travertine occurrences can be found at or near fault zones scattered throughout the field area. Thickness and lateral extent of these deposits are not large. Travertine caps the west-central Canoa dome structure, (BL711324) where it is commercially mined and can also be found near a hot sulphurous spring south of the dome (BL708319). Small travertine deposits are commonly found at springs in the area and in the semi-arid foothills of the Sierra de Martin Garcia, palm groves are almost sure indications of springs. At the head of the Arroyo Quita Coraza a high volume spring (BL820377) studied geochemically by Condit and Ross (in Vaughan et al., 1921) irrigates a substantial area to the northwest of Loma la Pelada clearly seen on satellite images as an oasis in the desert. Only minor travertine deposits are associated with this spring, although travertine is certainly forming presently.

Alluvial fans

Large well-developed alluvial fans mask the northern and southern flanks of the Sierra de Martin Garcia. For the most part these comprise almost exclusively limestone debris cobbles. The fans are commonly terraced, as can be seen especially well east of the main highway between Canoa and Fondo Negro. The terrace levels may reflect vertical movements associated with the regional faulting and tectonic movements. As seen on the map and in Figure 4.5 these fans occur at various elevations, and their pattern suggest rapid uplift of the region.

Near the river Yaque del Sur, and in the region mapped as Arroyo Blanco formation (north of the highway) on Plate 1 (east) gravel deposits similar to the alluvial fans occur. However these gravels include a wide variety of igneous and metamorphic rock clasts including (as identified in the field) granite, andesite, basalt, dacite, serpentinite and marble. Clasts and large boulders display substantial roundness and sphericity and were apparently well weathered, and transported by the Yaque del Sur River from the Cordillera Central. These deposits, termed the Las Matas formation by Vaughan et al (1921), were not mapped in detail in the study area but could be distinguished by some future detailed mapping project.

CHAPTER 3 PALEONTOLOGICAL DATA, AND DEPOSITIONAL ENVIRONMENTS.

Paleontological Data

Selected rock samples from the field area were studied by Dr. Ted Robinson, of Robertson Research in order to determine ages of strata, if possible. The results are summarized below with the locations given in the UTMG system. The sample localities are plotted on the maps, and most are found on the Sierra de Martin Garcia where little previous paleontological work has been done, in contrast to the Fondo Negro formation which was extensively studied from a paleontological standpoint by Biju-Duval and others (1980). A generalized biostratigraphic zonation chart can be found in Figure 3.1.

Sample: BL973274
Lithology: Sparsely fossiliferous micrite with planktonic foraminifera, some interstital organic matter.
Fauna: No positive identifications.
Age: possible Early Tertiary, no real control.

Sample: BL963275
Lithology: Planktonic foraminiferal micrite
Fauna: no identifications, but similar to sample BL853299
Age: presumably Early Tertiary.

Sample: BL959270
Lithology: sparsely planktonic foraminiferal micrite partly recrystallized.
Fauna: small, sharply keeled Globorotalia (cf. Gr. Fomosa).
Age: Early Tertiary, probably Paleocene to early Eocene.

Sample: BL956262
Lithology: sparsely fossiliferous micrite with planktonic forams, some interstital organic matter.
Fauna: No identifications

Sample: BL955258
Lithology: Larger foraminiferal, bioclastic limestone in

fine skeletal debris and micrite.

Fauna: Abundant *Ranikothalia*, nodular coralline algae, rare *Discocyclina* sp. and common "*Amphistegina*" probably a variant of "Tremastegina *lopeztrigoi*.

Environment: All shallow water forms, but possibly resedimented.

Age: Late Paleocene

Sample: BL949250 Float

Lithology: framework limestone - biomicrite

Fauna: algae (*Halimeda* encrusting and branching *Lithothamnium*), poritid and aeroporid coral branches, *Amphistegina* cf. *gibbosa* (flattened Form), *Cyclorbiculina* sp., *Archaias* sp., *Gypsina*, sp.

Age: Latest Neogene, possibly a Pleistocene raised reef, especially a fringing reef. Not a platform reef.

Sample: BL893273

Lithology: recrystallized limestone with dolomite rhombs

Fauna: *Ranikothalia* *catenula*, encrusting coralline algae

Environment: Possibly shallow water, probably resedimented deposit into basinal, pelagic limestones.

Age: definitely Late Paleocene

Sample: BL853299

Lithology: planktonic foraminiferal micrite

fauna: small *Globoratalia*, and other unidentified fossils similar to those seen in float found near BL893273

Age: probably Early Tertiary.

Sample: BL793337

Lithology: Planktonic foraminiferal micrite sapropelic or oily residue trapped in the tops of some of the tests.

Fauna: *Orbulina* sp., *Globigerinoides*, sp.,

Age: Early to Early Middle Miocene

Sample: BL799325

Lithology: Planktonic foraminiferal micrite

Fauna: *Globigerinoides* *quadrilobatus* gp. *Globigerina* cf. *venezuelana*

Age: Early to Early Middle Miocene

Sample: BL822373

Lithology: Planktonic foraminiferal micrite with fine shell hash, possibly graded.

Fauna: Small *Amphistegina*-like forams Planktonics, *Gr. centralis* (= cerroagnlasis) *Globigerina* sp.

	cf. yeguaensis or praefulleides
Age:	Late Eocene
Sample:	BL768317
Lithology:	Micritic biosparitc with calcite veins algal foraminiferal, possibly algal mat with some benthic forams showing algal or sponge borings. Poorly sorted.
Fauna:	encrusting Lithothamnium, possibly Halimeda fragments, Amphistegina, Sphaerogypsina, rare planktonics, small rotaliid benthonics.
Environment:	could be relatively shallow water because of biosparite, but depth difficult to judge. More likely material transported down slope as a talus accumulation instead of turbidite.
Age:	Late Neogene
Sample:	BL734327
Lithology:	Foraminiferal with fine sand size skeletal debris
Fauna:	Planktonics, Operculinoicles rare., Flat Amphistigina, Orbulina rare, Sphaeroidinellapsis or ella, Gq. altispra, No keeled Globorotalia seen
Age:	Neogene, Middle to Late Miocene onward.
Sample:	BL712321
Lithology:	Planktonic foraminferal micrite No fauna or age determined.

Biju-Duval and others (1980, and personal communication 1982) collected and dated well over one hundred samples from near road exposures of the Fondo Negro Formation and several from what I assign to the Bao Formation. Following their data, the lower 200 meters of the exposed Gajo Largo member contains Globoratalia menardi group planktonic forams collected at approximately B7737324, and this section was assigned to the nannoplankton zone NN9 of Tortonian age (approx. 8-12 Ma). Overlying this is approximately 300 meters of section belonging to the Sphaeroidinellopsis seminulina subzone (Globoratalia

FORAMINIFERA

			Absolute Age M.Y.	
NEOGENE	PLEISTOCENE			Globorotalia truncatulinoides truncatulinoides
			1.9	
	PLIOCENE			Globorotalia truncatulinoides cf. tosaensis
				Globorotalia miocenica
			3.2	
				Globorotalia margaritae
			5.5	
	MIOCENE	LATE		Neogloboquadrina dutertrei
				Globorotalia acostaensis (S. Paenedehiscens subzone; S. Seminulina subzone)
		MIDDLE		Globorotalia menardii
				Globorotalia mayeri
				Globigerinoides ruber
				Globorotalia fohsi robusta
				Globorotalia fohsi lobata
				Globorotalia fohsi fohsi
				Globorotalia fohsi peripheroronda
			16.0	
		EARLY		Praeorbulina glomerosa
				Globigerinatella insueta
				Globigerinita stainforthi
				Globigerinita dissimilis
				Globigerinoides primordius
			22.5	

CALCAREOUS NANNOFOSSILS

MARTINI, 1971

NN 19	Pseudoemiliania lacunosa
NN 18	Discoaster brouweri
NN 17	Discoaster pentaradiatus
NN 16	Discoaster surculus
NN 15	Reticulofenestra pseudoumbilicata
NN 14	Discoaster asymmetricus
NN 13	Ceratolithus rugosus
NN 12	Amaurolithus tricorniculatus
NN 11	Discoaster quinqueramus
NN 10	Discoaster calcaris
NN 9	Discoaster hamatus
NN 8	Catinaster coalitus
NN 7	Discoaster kugleri
NN 6	Discoaster exilis
NN 5	Sphenolithus heteromorphus
NN 4	Helicosphaera ampliaperta
NN 3	Sphenolithus belemnos
NN 2	Discoaster druggi
NN 1	Triquetrorhabdulus carinatus

Figure 3.1

Biostratigraphic zonations for the Neogene.

acostaenis zone) and 2150 meters belong to the S. Paenedehiscens subzone (G. Acostaensis zone) (total Fondo Negro = 2650m) all assigned to the nannoplankton zone NN11 (Discoaster quinqueramus) of Messinian age, approximately 5-8Ma. The Bao Formation samples had the faunas like the upper Fondo Negro Formation.

The Biju-Duval group also studied samples from what I call the Arroyo Blanco formations but they were unable to make any definitive age determinations. They presume that the Arroyo Blanco Formation is of Pliocene age.

Environments of Deposition

Paleogene and Early Miocene

Unlike the Sierra de Bahoruco to the South or the Sierra de Neiba to the west, neither arc nor oceanic basement is exposed on the Sierra de Martin Garcia. In spite of the lack of basement, the Paleogene limestones are interpretated as deep water deposits on an oceanic foundation. Shallow water was not far away, and especially in the Late Paleocene, micritic limestone contain shallow water resedimentated foraminifera. Unfortunately neither the sample control nor the mapping permits any detailed subdivisions of the Paleogene carbonate succession, but the general environment seems clear.

By lower Miocene times the limestones are distinctly more sandy, with quartz fragments, and consequently harder. They too contain abundant resedimented shallow water fauna and indications of turbidite deposition. I interpret them as shallower water deposits than the Paleogene carbonates, yet still at depths of more than 100m and certainly not platform carbonates.

Fondo Negro Fm.

As mentioned in Chapter 2, the lower Fondo Negro Formation, Gajo Largo Member, comprises sandy limestones deposited as carbonate turbidites flows in moderately deep water and these are overlain by a predominantly siltstone and marl section of the Fondo Negro with all the indications of turbidite deposition, presumably in a lower fan environment. It is not known whether the source of carbonate material was different from the source of clastic material, however even in the Middle Fondo Negro Formation, single sandy limestone beds are quite extensive laterally-up to 6km - and are indicative of deposition as a carbonate turbidite. (See Figure 3.2).

According to my map interpretation of the Gajo Largo member the sandy carbonates become thicker and more massive, with less interbedded siltstone to the south, which suggests that the source of carbonate material was from that direction.

Paleocurrent Direction

A paleocurrent analysis of the Fondo Negro Formation above the Gajo Largo member is shown in Figure 3.3: clearly at the site of deposition currents from the south and north

Figure 3.2

A sandy limestone found at BL 786376 approximately in the stratigraphic middle of the Fondo Negro Formation where the section is predominantly marls and siltstones. Note the well developed convolute laminae, grading upward, and the intense burrowing (burrows are filled with marl). This is interpreted as a carbonate turbidite debris flow.

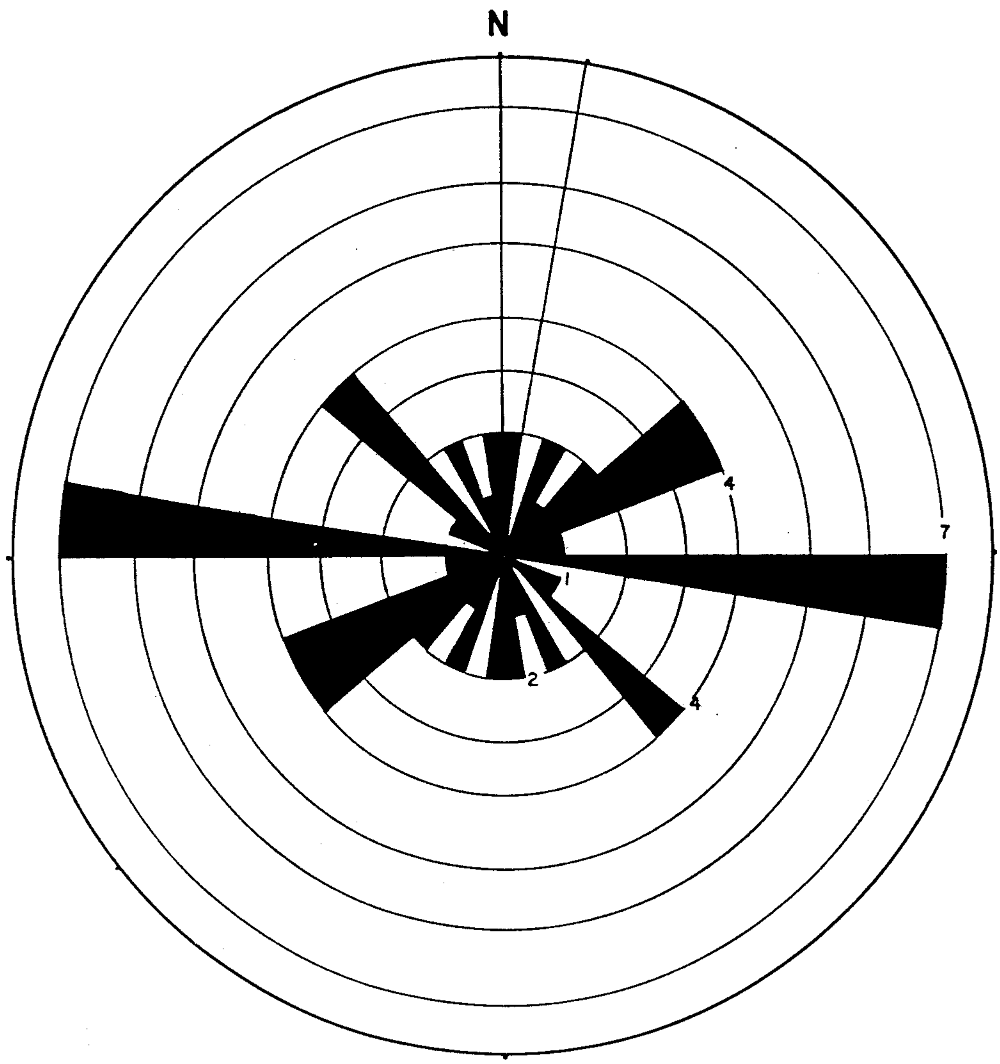


Figure 3.3

A rose diagram showing the distribution of scour, flutes and groves indicating flow directions at the time of deposition, for the Fondo Negro Formation. Data is rounded to the nearest 10 degrees and represents 36 outcrops. The bilaterally symmetric pattern results from no distinction of the vector motion being possible. No corrections have been made for plunge although beds have been rotated to the horizontal.

were substantially less important for sediment transport than those in an east-west direction. The bilaterally symmetric distribution of flow directions is an artifact of the data. Only in rare cases was I able to distinguish the "sense" of transport with certainty, so the diagram represents the "direction" of transport, the linear orientations of flutes and grooves. Unfortunately, an analysis of this kind says nothing about the direction to the source.

Soft Sediment Slumping

In the northwestern foothills of Loma La Pelada the Lower Fondo Negro formation above the Gajo Largo Member is severely deformed by soft sediment slumping. Layers of deformed siltstones and marls alternate with relatively flat lying beds as seen in Figure 3.4 and 3.5. If one accepts a strike-slip origin, or pull apart genesis for a Messinian Fondo Negro basin these would represent the center of deposition and structural down-dropping for the basin. The direction of chaotic "scrunching" is interpreted from NW to SE, based on geometric constraints in these and nearby outcrops. This is also the secondary compression direction for an east-west left-lateral fault system. Nearby thrusting and uplift caused by wrench faulting could cause the deformation seen. In the case of structural down-dropping one would expect to see a lateral thickening, or wedging of sedimentary packages toward the faulted margins and perhaps well developed conglomerates such as in the

Figure 3.4

Just below the alluvial fan emanating from Loma la Pelada and Martin Garcia at BL 799369 the lower Fondo Negro formation is intensely deformed by massive intraformational soft-sediment slumping. The fold in the lower right plunges at 42º in a direction of 68ºE and the deformed beds are uncomformably overlain by relatively flat lying sediments striking 062 dipping 40N. In this region, at the same stratigraphic level, slump structures are widespread and dramatic. Sequences of flat lying beds covered by deformed beds in turn covered by flat lying beds are repeated up to five times in a single outcrop representing approximately 40 to 50 meters of section.

Figure 3.5

A close up of internal deformation shown in figure 3.4, at location BL799369. The deformation is interpreted as a soft sediment slump, presumably near the center of the Fondo Negro basin.

Ridge Basin of California (Crowell and Link, 1982). No such lateral variation was observed in the field, although outcrop control did not permit a detailed analysis, and water depth would not have favor conglomerate deposition.

Sedimentation Rates

One argument in favor of a dynamic tectonic control on the Messinian sedimentation is the high rate of sedimentation. Approximately 2500 meters of section are ascribed strictly to the Messinian zone NN11, in the Fondo Negro Formation not including the Bao Formation. The putative time constraint for the Messinian falls between approximately five and eight million years ago, and the Messinian also includes nannoplankton zone NN12 for half its duration. Thus simple calculations give sedimentation rates averaging 83cm/1000 years strictly for the NN11 interval. These extremely high sedimentation rates on the order of 1m/1000 years are well known for pull-apart basins as documented by Miall (1978), and perhaps an order of magnitude too high for a forearc basin but reasonable for trenchs and trench aprons (See Figure 3.6). Shephard and McMillen (1981) report sedimentation rates from DSDP holes south of Alcapulco in the Middle America Trench of 5000m/million years for uncompacted sedimentation on the trench and slope apron which converts to approximately 2500m/m.y. of compacted sediments in

SEDIMENTATION RATES

LOCATION	COMPACTED RATE	UNCOMPACTED RATE
Fondo Negro Formation	83cm/1000yr	-
Pull apart basins (Miall,1978)	100cm/1000yr.	-
MIDDLE AMERICA TRENCH (Shephard and McMillen,1981)		
Trench and slope apron	2500m/my.	5000m/my.
Middle slope (between contin- ent and forearc)	350m/my.	42-609m/my.
Upper Slope	150m/my.	210m/my.
Stretched continental crust	-	70-139m/my.

Figure 3.6

Sedimentation rates

contrast to uncompacted values of 210m./m.y. along the upper slope, (150 m/m.y. compacted) 42-609m/m.y. uncompacted (350m compacted) on the middle slope between the continent and the accretion zone (forearc) and only 70-139m./m.y. uncompacted for presumably stretched continental crust nearest the continent. They found the sedimentation model of Underwood and Karig (1980) to apply, where large submarine canyons carry coarse terrigenous debris directly toward the trench and apron completely bypassing basins on the landward slope; smaller canyons carry coarse detritus outward, often to blocked tectonic ridges along the trench slope. This is in contrast to simple turbidite fans where coarse detritus is thought to dominate the upper fan and perhaps suprafan channels (e.g. Walker, 1979).

In any case, both pull-apart basins and trench slopes could have high sedimentation rates, slump features and predominately turbidite deposition, as seen in the lower Fondo Negro Formation, and the continuing turbidite deposition for the middle and upper Fondo Negro Formation.

Upper Fondo Negro

The upper 150 meters of the Fondo Negro Formation comprises thick beds of coarse to medium sandstones, with graded bedding, and well developed channels, capped by a prominent conglomerate. (See Figure 2.9). Faunal studies suggest that this represents relatively shallow water compared with the lower Fondo Negro Formation, so its is unlikely to represent a trench deposit. Perhaps a possible interpretation would be a shallow fore-arc basin with a plentiful sediment supply and a well developed small channel fan network.

As seen in figure 2.9, this upper section has undulatory bedding, slightly larger pebbles than lower in the section, and continues laterally for a considerable distance (12km) with little thickness variation. In itself, this might suggest that the section represents a beach bar. However, the complete lack of cross stratification and though cross beds, in addition to the nature of the overlying Bao formation discussed below essentially rule out the possibility of a beach.

Bao

The Bao formation which conformably overlies the Fondo Negro Formation appears to be the result of a major migration of a channel fan system, which cut off the supply of coarse detritus. The formation is distinctly mappable and varies in thickness and percent sand content in a lateral way. Differentiation of units within the Bao is rendered difficult by somewhat intense structural deformation apparently related to recent folding. In other words he predominantly soft shales and siltstones of the Bao formation absorb a good deal of the structural deformation and behave in a less competent manner than the underlying Fondo Negro Formation, or the overlying Arroyo Blanco formation.

Arroyo Blanco

The Arroyo Blanco formation clearly consists of shallow water marine debris flows from a carbonate reef (perhaps fringing) as well as coarse sandstones, probably of very shallow environments and perhaps including beach deposits. These grade laterally into the evaporitic facies of what I call the Loma de Yeso member. Namely very recrystallized massive gypsum beds, interbedded with lagooned or liminal clays with mudcracks, and leaf prints, in an environment suggestive of the modern Lago Enriquillo. These are distinguished from early and middle Miocene evaporites known in the subsurface of the Enriquillo Valley (Bowin, 1975) which are more massive, but suggest that the evaporitic environment of deposition has persisted, intermittently for perhaps the last 20 million years.

CHAPTER 4 STRUCTURE AND MAP DISCUSSION

This chapter discusses the structure of the Fondo Negro - Sierra de Martin Garcia region as well as details and complications of the geologic map. The reader is advised that Plate 1 (west) adjoins Plate 1 (east) to complete the map, and that Plate 2 contains geologic cross-sectional profiles of the mapped area. The level of confidence for the map varies widely depending on the intensity of fieldwork. As noted on the locality map (bottom left, Plate 1 east) the central portion was more carefully scrutinized, due largely to accessibility, than the highland jungle of the Sierra de Martin Garcia which was crossed only by traverses along "burro" trails. The northwestern part of the map area, north of the Rio Yaque del Sur, has recently been mapped in greater detail by Paul Mann (Ph.D. dissertation in preparation, Suny-Albany). A complete set of 1:60,000 stereo pair air photographs for the entire map area was interpreted as a supplemental data base. Skylab and Landsat imagery provided by the NASA Lunar and Planetary Science Institute was used to interpret regional structures wherever possible.

Some regions are undoubtedly more complicated structurally than the map suggests, but without additional detailed fieldwork unique solutions cannot be obtained. These regions and possible solutions are discussed individually.

Folds

At the scale of a few kilometers some regions of the map area such as the Canoa Dome (BL723324) are especially complex, however taken as a whole the map region is remarkable for its structural simplicity. It comprises broadly folded sediments cut by high angle faults which are mostly left lateral strike-slip splays of major plate boundary zone faults to the north, and those have relatively minor offsets, although some have fairly substantial thrust or normal components.

The folds are interpreted as flexural slip or concentric folds riding above a decollement at depth, with essentially parallel fold trends, constant bed thicknesses and slickensides perpendicular to fold axes. The largest of the folds, the Sierra de Martin Garcia anticline, is asymmetric dipping more steeply on its southern limb. The axis essentially follows the ridge crest (BL734325 - 750328 - 765327 - 795326 - 845331 - 883319 - 917303 - 929274 - BL942248) and does not cross the main highway in the west. To both south and north the anticline is bounded by high angle faults with normal and strike-slip components. Aerial photographs and reconnaissance traverses suggest that the eastern lobe of the kidney bean shaped mountain range is cross-cut by an anastomozing network of faults trending NNW-SSE and ENE-WSW. (BL873329 to BL923188 and BL880270 to BL965284 respectively). The latter group of faults more obviously displays or left-lateral offset, while the former

(NNW-SSE) group probably has both a high angle reverse component and some strike-slip motion with offsets less than one kilometer.

Numerous parasitic folds with trends along the predicted secondary compression direction complicate the picture for the southern flank of the mountain, and a veneer of recrystallized, case hardened material usually obscures bedding relationships. Perhaps the most obvious feature of the southernmost third of the range is a well developed pervasive, outcrop-forming joint set with a nearly east-west orientation. Bedding is more subtle, but as observed in the field, and interpreted from aerial photographs bedding for the central core and northern flank of the range wraps around and follows its roughly kidney-shaped pattern turning gradually from almost east-west to nearly north-south at the southern tip. This can be seen on the map (plate 1).

North of the Martin Garcia anticline lies a narrow syncline which trends NE-SW and runs from the main highway at BL758353 to 770353 to BL790352 where a fault truncates it. The fold solely affects rocks of the Fondo Negro Formation, and does not continue through the notch between Loma La Pelada and Martin Garcia as the Blesch (1967) compilation map portrays. Instead the notch is the site of a fault as discussed below.

The Loma la Pelada is another anticline with late Eocene carbonates exposed in its core and it continues westward to affect rocks of the Fondo Negro formation. The axis follows the trend BL862366 - 800359 - 780358 to BL759357 where it comes very close to the axis of the syncline discussed above. Minor thrust faults at an oblique angle to the anticlinal axis complicate the Loma la Pelada structure and well developed alluvial fans obscure the Loma la Pelada anticline to the east along trend, however to the northeast a broad 'V' shaped syncline trends WNW-ESE at BL865406 to BL886398.

Quita Coraza Anticline

Continuing to move northward, up the map, we cross a high angle fault, probably strike slip, trending E-W which veers toward the ENE, (BL850408 to BL880410). Above this fault, to the north, is a major, kidney-shaped, doubly plunging anticline known as the Quita Coraza anticline. The axis continues from BL83410 to 843419 to 862423 to BL884421, and is cut by several faults, including a NW-SE trending fault from BL873410 to 862423 - 853443 perhaps continuing to BL839458 at the river. Near its southern termination field observations suggests a left lateral offset of only one five meters at best. Another fault, this one trending approximately NE-SW from BL833406 to BL850424 warps the axis of the anticline, but apparently most of the offset is accommodated internally by deformation in less competent shale beds.

North of the Barahona - Azua highway, and the Quita Coraza anticline, lies a major syncline which extends somewhat east-westerly for nearly twelve kilometers from B1884459 to 840641 - 790445 to BL766450 where it is lost in the transitional facies change to a predominately gypsum section. Apparently the gypsum behaves differently in a mechanical sense and "flows" instead of bending to form a syncline. North of this major syncline is a minor anticline from BL785471 to BL810473 and another small syncline from BL783478 to BL808478, presumably related to compressional structures in a strike-slip regime.

Secondary Folding

On the northwestern flank of Martin Garcia at least five tight anticlines trend NW in the predicted secondary compressional direction for left lateral strike-slip faulting, and are apparently secondary deformation following the folding of the Sierra de Martin Garcia. One of these can be seen in Figure 4.1. Likewise the anticlinal trend of the southern coastal lobe of the Sierra follows the secondary compression direction.

Figure 4.1

On the northwestern flank of the Sierra de Martin Garcia at least five tight anticlines trend NW in the predicted secondary compressional direction for left lateral strike-slip faults. This one occurs at BL790344 and can be followed along trend to BL803338. Others include BL793342 – 803337, BL793349 – 800345, BL803345 – 810342, and BL806346 – 813344, all shown on the map, plate 1.

Faulting

The most prominent fault zone in the field area is found in the northernmost part of the map area. These east-west trending faults (e.g. BL660494 to BL770480) are interpreted as part of the diffuse Carribbean Plate Boundary Zone, and have substantial thrust components as well as left lateral strike-slip offsets, although no real constraints can be put on the offsets of faults based strictly on my fieldwork. Regional geometric arguments suggest displacements of at least 200 km in the Enriquillo area since Oligocene times. Apparently Paleogene limestones of the Sierra de Neiba are being thrust over Pliocene sediments of the Arroyo Blanco formation, and the folds in the Fondo Negro region discussed above are presumably all related to this compressional component of strike slip faulting. It is not known how the system behaves to the east of the map area, but it seems quite complex, and perhaps the Los Hermanos eruptive volcanic fields are related to local extension as the faults step up (northward).

In the northwestern part of the map area two prominent conjugate faults splay in a NE-SW direction (i.e. BLG53430 - 661450 to BL677473) and offset Quaternary alluvium in the valley in a left lateral sense. These are certainly active faults, although the amount of vertical displacement, if any, is unknown.

Faults and the Canoa Dome

An important fault with a small strike slip offset as

Figure 4.2

The Yaque de Sur river valley looking towards the Sierra de Neiba. The Eocene carbonate mountains in the background are being thrust over the upper Neogene Arroyo Blanco and Bao formations in the foreground.

well as a normal component continues from the Cerros de Cristobal to the immediate west of Lago Rincon in the Enriquillo Valley south of the field area (seen in the bottom left of the thesis frontispiece) to the Canoa Dome structure, which it crosses (BL730325 to BL712320), and obviously truncates rotated beds. The Canoa dome structure itself remains one of the most complicated enigmas of the field area. At first inspection, one is tempted to simply continue the anticlinal axis of the Sierra de Martin Garcia, westward to the topographically discrete Canoa Dome, as perhaps a doubly plunging anticline. But that simplification does not work. Instead a tear fault separates the structures, and complicated wrench faulting crosscutting NNW-SSE thrust faults (BL718330 to BL722317) combined with strike-slip faults) cause an elongate dome to form. Paleontological determinations for the age of the Canoa Dome limestones (Miocene) lack the precision to determine with certainty whether the limestones are younger than the extensive evaporites in the Enriquillo Valley subsurface, but the possibility seems likely, and thus the Canoa Dome is probably the complex surface expression of a salt diapir along a fault zone. Hot springs and recent travertine deposits near the crest of the Canoa Dome and on its southern flank are thought to be evidence for active faulting through the structure.

North of the Canoa Dome structure another left-lateral fault splays between the contact of the Fondo Negro

Formation with its Gajo Largo member and the Canoa Carbonates, and this fault may have a thrust component as well. In any case while the fault has an important expression as a surface linear, and demonstrably cuts beds at BL731331, it is difficult to quantify the offset. Based on stratigraphy it seems likely to have a high angle thrust component between Loma la Pelada and the Sierra de Martin Garcia (See cross section plate 2). As shown on the map this fault is cut by three oblique N-S trending strike-slip faults with measured left lateral offsets of 3 to 5 meters in exposures of the Fondo Negro Formation.

Gajo Largo Fault

East of the Canoa Dome, a sinuous fault runs along the boundary of the Gajo Largo member and the carbonates of S. de Martin Garcia (BL738310 to 748325 to BL755332) before heading south where it is truncated by a normal fault north of the gypsum mining area. The nature of this fault remains unknown, although from simple geometric arguments it is clearly older than surrounding faults and probably predates the folding event. This fault, together with a disconformity of the Fondo Negro Formation on carbonates of the Loma la Pelada strongly suggests a prolonged episode of faulting since at least pre-Middle Miocene times.

The Southern Coastal Flank of Martin Garcia

Where not covered by alluvial fan deposits the foothills of the Sierra de Martin Garcia reveal an especially complicated geometry which I interpret as a -V-shaped wedge, bound by strike-slip faults with a substantial normal component in front of the Martin Garcia anticline, all above or cutting a thrust plane (see Figure 4.3). This region includes two prominent anticlines, one involving the Loma de Yeso member in the gypsum mining to the west (BL732296 to BL748300) and another as smaller anticline in the Arroyo Blanco formation (between BL760304 and BL753045).

Beall (1945) interpreted this entire region as a syncline parallel with the axis of the Martin Garcia anticline and chose to ignore the normal and strike-slip faults.

Field data indicates that the region contains numerous small anticlinal structures bounded by faults, without synclines between anticlines. Such a style is well known in strike-slip dominated environments as documented by Wilcox et al. (1973), and the overwhelming dominance of strike-slip wrench faulting seems inescapable here. The distribution of young reef materials at substantial elevations indicates that the wrench faulting is causing rapid uplift, and I infer that the Sierra de Martin Garcia structure results from such a mechanism.

Structural Contacts

The map clearly illustrates structural, tectonic con-

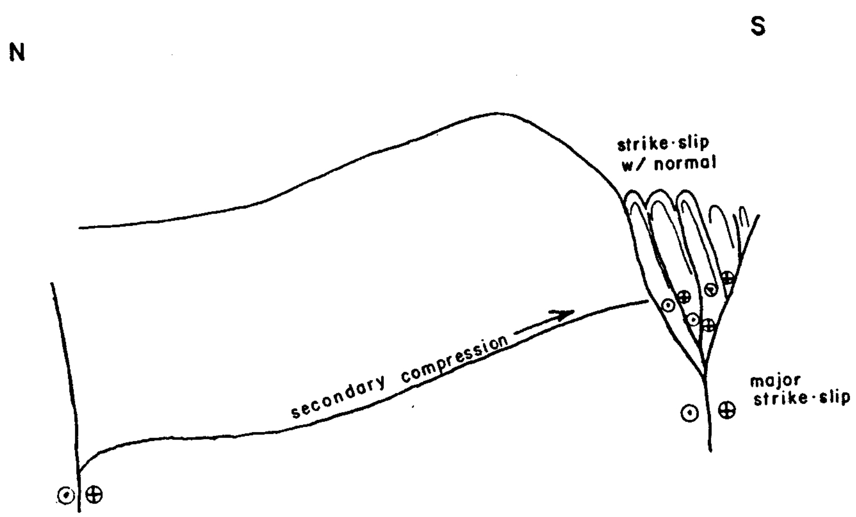


Figure 4.3

A cartoon showing the interpreted relationship of strike-slip faulting, substantial secondary compression and normal faults on the coastal foothills of the Sierra de Martin Garcia.

tacts between the various carbonates and the Fondo Negro Formation.

As already mentioned in previous chapters the contact between the Arroyo Blanco formation and the Loma de Yeso Member is transitional. The serrated sinusoidal shape of the contact shown on the map is a gross approximation of the actual surface expression in the Arroyo Calero (BL770460 to BL758430). Originally I though that the Arroyo represented a fault (and it may be controlled by unidentified faults in the subsurface), but some beds are continuous across it while others terminate there forming an irregular pattern which suggests a depositional facies variation.

As shown near the main highway at BL923418 to BL942407, the Arroyo Blanco formation overlaps the Bao formation which disappears and the Arroyo Blanco is blanketed by alluvial fan deposits. Presumably there is some unknown structural control of this feature.

Secondary Extension

On the southern flank of the Sierra de Martin Garcia the topography includes a large number of short valleys oriented approximately NE-SW, which are interpreted as products of secondary extension in the predicted direction associated with left-lateral strike-slip faulting. In addition significant local extension and rotational slumping was observed in a small valley within the Fondo Negro formation at BL772353, but this is not unequivocably related to specific faults.

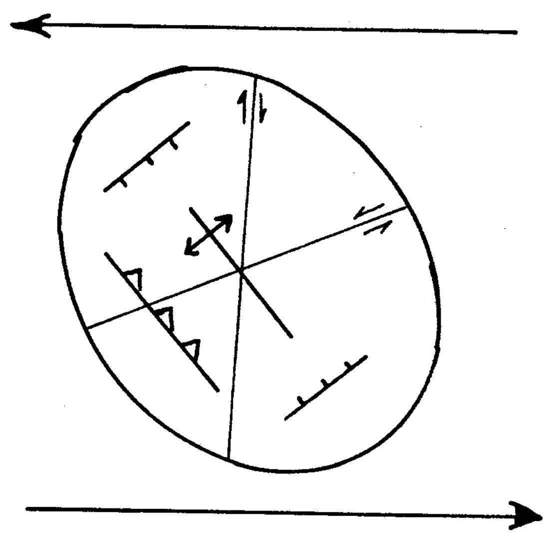


Figure 4.4

The structural pattern resulting from simple shear produced by an E-W sisistral shear couple (modified from Harding, 1974).

Note: Secondary NE-SW extension, and NW-SE compression. Based on Riedel, 1929.

Uplift and Terraces

Figure 4.5 illustrates the extensive terrace development in the central core of the field area on the flanks of S. Martin Garcia. These are particularly noteworthy for their gentle inclines, and the fact that there are five unique terraces suggesting substantial differential uplift, and capturing of slope debris by different distribution systems. The composition of terrace material for all the terraces shown in figure 4.5 comprises almost entirely limestone debris eroded from the Sierra de Martin Garcia. The terraces are up to 5 meters thick, whereas terraces north of the main highway in the Quita Coraza syncline include a wide variety of rock types indicating deposition by the Rio Yaque de Sur system.

As mentioned previously, the identification of Pleistocene reef material at BL949250 at an elevation of 650m on the Sierra de Martin Garcia suggests extremely rapid uplift rates for the region (conservatively 6.5mm/yr) as a consequence of strike-slip faulting.

Structural Interpretation

The structural interpretation of the field area throughout the Cenozoic based on mapping and regional tectonic extrapolations is considered in Chapter 5.

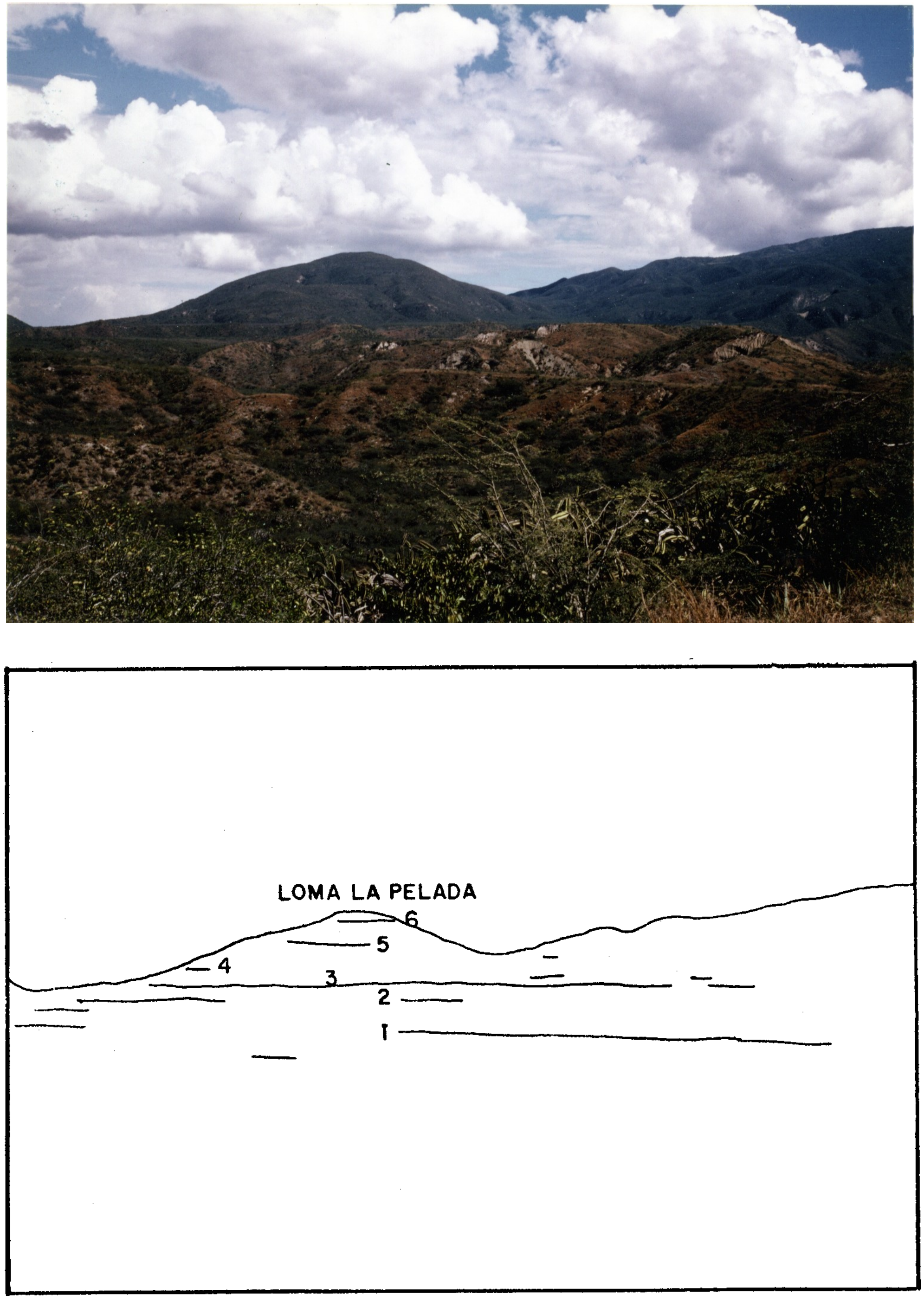


Figure 4.5

The central field area looking west toward Loma la Pelada (foreground) from the main highway. Note the well developed extensive terraces with only a few degrees incline.

CHAPTER 5 REGIONAL SYNTHESIS, AND STRUCTURAL INTERPRETATION

Geologic History of the Map Area

Presently the Fondo Negro-Sierra de Martin Garcia region is dominated by left lateral strike-slip faulting associated with the Northern Caribbean PBZ, with substantial secondary compression. Pleistocene reef materials at 650m. elevation on the Sierra de Martin Garcia suggest that at least locally, this secondary compression has caused rapid uplift. The faulting, although diffuse on the scale of Hispaniola, is concentrated in zones on the scale of the field area. The most obvious of these zones is to the north, in the foothills of the Sierra de Neiba, where essentially east-west strike-slip faults have a substantial thrust component, and Eocene limestones are being thrust over the Pliocene Arroyo Blanco Formation. The southern flank of the Sierra de Martin Garcia is the second most intense zone of strike-slip faulting, and complications of the system have undoubtedly contributed to the uplift of the mountain range. On the southern flank one finds numerous fault bounded, tightly folded anticlines of the Pliocene Arroyo Blanco Formation, overlain with obvious angular unconformity by Quaternary reef materials. No synclines occur between these fault bounded anticlines. Secondary compression, and extension associated with this system deforms rocks of all ages in the field area. Perhaps one of the world's most spectacular normal faults occurs on the eastern coastal limit of the Sierra de Martin Garcia, associated with this secondary extension.

The zone between the Sierra de Martin Garcia and the Sierra de Neiba, namely the Yaque del Sur river valley is only relatively gently deformed with broad anticlines and synclines and secondary faults. Here the thick (2650m) Upper Miocene Fondo Negro and Bao Formations and the Pliocene Arroyo Blanco Formations are exposed, lying in tectonic contact with carbonates of the Sierra de Martin Garcia. I interpret them to have formed in a fault bounded basin similar to the modern San Pedro Basin south of Santo Domingo in the late Neogene as a consequence of the southward migration of the zone of greatest strike-slip faulting from the San Juan Valley in the north in early Miocene (and Oligocene) times to its present position crossing the Enriquillo Valley. Evaporites older than the Fondo Negro Formation are known in the Enriquillo Valley (Biju-Duval personal communication, 1982), and although not yet established to exist beneath the Fondo Negro region, they may play a role as a decoupling surface at depth. In any case the early Miocene section exposed in the field area in tectonic contact, is certainly carbonates. Most appear to be the result of carbonate turbidites, in contrast with the early Miocene clastic section which is lithologically similar to the Fondo Negro Formation known in the San Juan Basin to the north.

Once the strike-slip basin was established in the Fondo Negro region, it quickly filled with sediments, gradually shallowed, until extensive Pliocene evaporites (1km) were deposited north and west of the Yaque del Sur River, and it enjoyed the deformation described above.

The pre-medial Miocene history of the field area is somewhat more interpretive as we do not know the nature of the bottom of the Fondo Negro Formation (it is in tectonic contact with the carbonates, except where in disconformably overlies late Eocene limestones on the Loma la Pelada and we do not know what is missing).

The carbonate stratigraphy needs further detailed study to unravel its complicated past, however one can generalize from my mapping that water depth has varied with time. The early Miocene carbonates are nearly all resedimented carbonate turbidites. No Oligocene carbonates have yet been identified, and this may both be a result of sampling, and the low sea level associated with ice formation. Eocene carbonates have generally relatively deep water affinities, while the late Paleocene was either very close to shallow water or was in fact shallow. The Paleocene beds are more massive than the younger carbonates. On the whole the carbonate sequence in the field area seems very similar to the carbonates known in the Sierra de Bahoruco to the south. All of these rocks have been involved in the northern Caribbean PBZ, whose evolution is discussed below, on a regional scale.

The Northern Caribbean PBZ and the Cayman Trough

Since the pioneering work of Hess and Maxwell (1953) a great magnitude of strike-slip faulting has been recognized as a primary component in the tectonic evolution of the Greater Antilles. The precise amount of offset, its timing and expression in the rock record has been the subject of controversy for decades. It is now widely accepted that spreading in the Cayman Trough (Bowin, 1958; Holcombe et al., 1973) has accompanied a transform fault plate boundary system between the Caribbean plate and the North American plate, and measurements of spreading yield a minimum offset for the fault system. See for instance figure 1 of Molnar and Sykes (1969 p. 1641) for an early version, or Jordan, (1975) for a more recent interpretation.

While Hess and Maxwell (1953) did not quantify "a great magnitude" of displacement across the Cayman Trough their figure suggests a value of approximately 1100km. Scoffing this for lack of supporting data, Meyerhoff (1966) argued that the cumulative sinistral offset since Late Jurassic time has not exceeded 200km and probably is less than 50km. Pinet (1972) on the other hand suggested 1000km of sinistral offset based on the distribution, and proposed continuity of two salt basins or diapir like structures, while Perfit and Heezen (1978) studied dredge samples from the Cayman Ridge, Nicaraguan Plateau, and mid-Cayman spreading center (Trough), and concluded that similar geologic features on the Cayman Ridge and Nicaraguan Plateau are offset left-laterally only 200km, giving a spreading rate of approximately 0.4 cm/yr. They also noted the offset of metamorphic belts from Cuba and northern Hispaniola of only 180 km and like Meyerhoff (1966) considered this a constraint on the motion of the Cayman spreading center. MacDonald and Holcombe (1978) however studied magnetic anomaly patterns and concluded that the record of seafloor spreading yields total opening rates of 20 ± 2mm/yr. for 0-2.4 Ma and 40 ± 2mm/yr for 2.4-6.0, Ma. They further suggest based on west flank data that the half-opening rate of 20mm/yr extends back to 8.3 Ma, and that spreading has been very nearly symmetrical. Simple calculation from this data yields an offset relative to a fixed North America of 380 km in the last 8.3 m.y. Allowing the assumption that the Cayman spreading center has been active since latest Eocene time, (40 m.y.) it is easy to extrapolate and accept a cumulative offset of 1200 km or more. Based on geometrical arguments and the Case and Holcombe (1980) map, Pindell and Dewey (1982) proposed a minimum offset of 1200km, based on the topographic expression of the trough, or twice the distance between the Cayman spreading center and the continental crust of the Yucatan platform.

Simple geometrical arguments for the offset of the Cayman spreading center yield minimum values because the fault system is not a simple line over which the entire offset has taken place, but a diffuse zone, a Plate Boundary Zone (PBZ) with many major splays accommodating offset (Burke et al., 1980). For instance in Hispaniola major splays are found offshore to the north, in the Cibao Valley

(Septentrional fault), the San Juan Valley, and a major system crosses the Enriquillo Valley. Judging a total offset based on measured offsets of only the northern most block (fault bounded silver) with respect to a fixed Cuba as Meyerhoff (1966) and Perfit and Heezen (1978) suggested would give erroneously small values for the total offset. Likewise many smaller-scale strike-slip faults have undergone motion in the same sense to further complicate the picture.

The maximum age of strike-slip faulting in the Cayman Trough is deduced to be Eocene. As noted by Ewing and Ewing, (1960) diorite plutons of Eocene age on the Oriente coast of Cuba have been truncated by later strike-slip faulting associated with the Oriente transform fault. Meyerhoff et al., (1969) report early middle Eocene whole rock K-Ar ages of $49\pm$ 6 Ma and $46\pm$ 6 Ma. for two of these plutons as well as a Paleocene, $58\pm$ 8 Ma. age for a third. In any case the faulting is clearly younger than the youngest of these plutonic events.

A minimum age for spreading is contained by the oldest known sediments on top of seafloor generated at the spreading center. Perfit and Heezen (1978) report that the oldest sample from the floor of the trough is a possible Miocene micritic limestone dated by pelagic forams, and it is certainly possible that older samples exist. Presumably geologic structures around the Cayman Trough should provide data to constrain the initiation of spreading, especially subsidence indicators, and interpretations of the water depths at the time of sedimentation. Several of these studies Emery and Milliman, (1980); Ivey and others; (1980); Land, (1979); Fahlquist and Davies (1971); Steineck, (1981); support movement along the Cayman Trough throughout the Neogene.

The Tavera Basin

The earliest indication of strike-slip faulting known in the Greater Antilles is found in the Tavera basin on the north central flank of the Cordillera Central (Figure 5.1) The narrow, fault bounded character of the basin studied by Palmer (1963, 1979), De Reimer, (1978) and Lewis (1980) led Mann and Burke (personal communication) to interpret it as a pull-apart basin in a major strike-slip PBZ. In my field work I was able to establish, largely due to abundant new road-cut exposures, that the stratigraphy proposed for the basin by Palmer was imprecise, and that the age of the basin is probably early Oligocene. Substantial secondary thrusting complicated the local geology in late Oligocene or early Miocene times. Thus I suggest that the Tavera basin is the oldest pull-apart on land in the Greater Antilles yet identified, and that it provides a constraint on the timing of Cayman Trough spreading. No effort was made to map this area in detail, and my energies were directed at stratigraphic sampling and interpretation especially of the lowermost part of the section. In this respect I found evi-

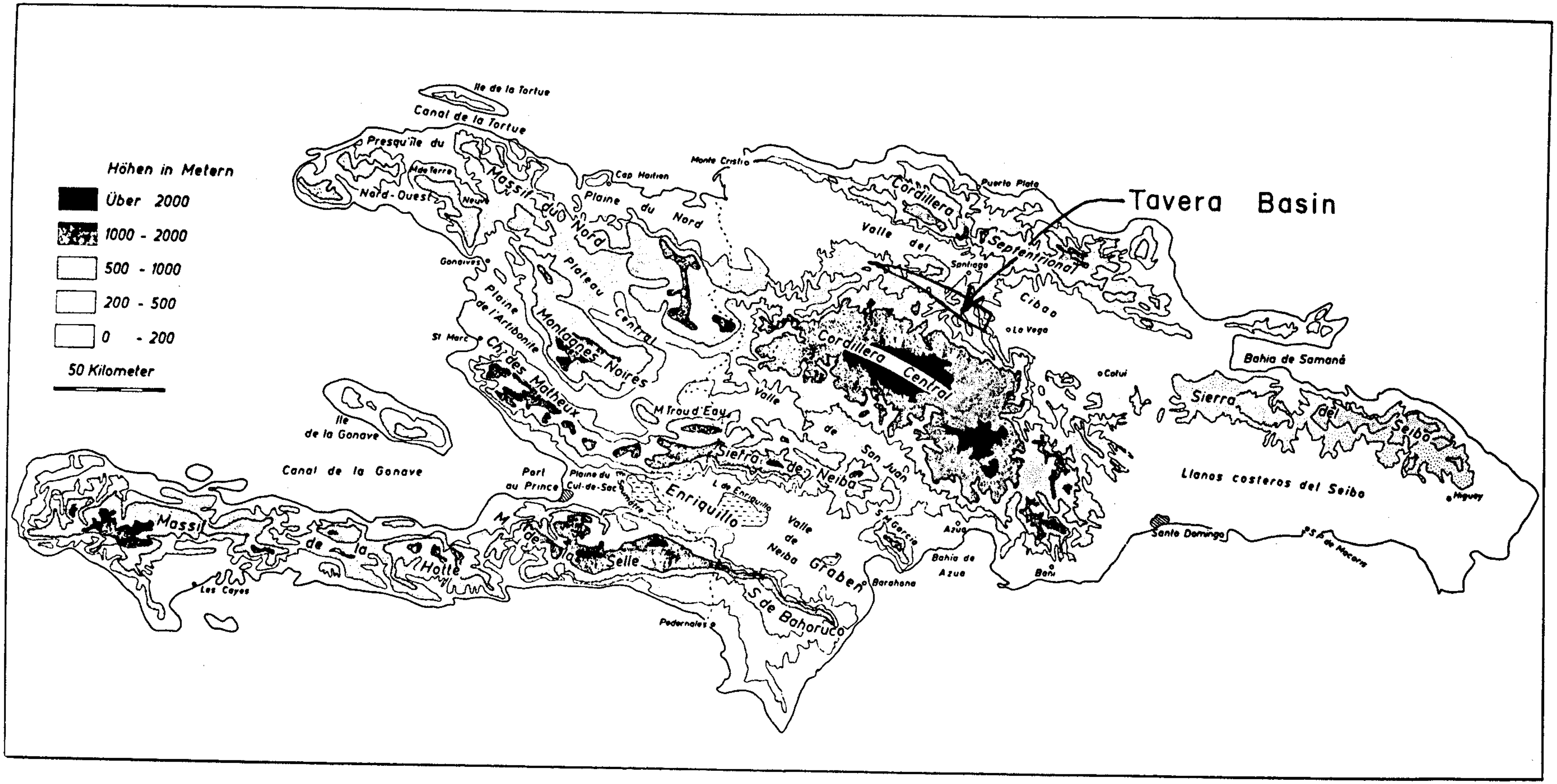


Figure 5.1 Tavera Basin location

dence to support the modified stratigraphic column for the Tavera basin based on Lewis (1980), shown in figure 5.2, compared with Palmer (1963, 1979)

Palmer reported paleontological studies which showed the Inoa, Repressa, and Velazquitos Formations to be the same age, but he chose to consider the Inoa and Repressa conglomerates older than the Velazquitos Formation as shown in Figure 5.2. My field work following Lewis (1980) and Groetsch, (1980), indicated that the massive Repressa and Inoa conglomerates were clearly deposited stratigraphically above the Velazquitos Formation, in spite of the fault contract between them and that as Palmer reported the Velazquitos contains conglomerate members near its base. Aside from stratigraphic precision, the change is significant because Palmer's best foraminiferal data for the Tabera (Tavera) group was an Early Oligocene determination in the Repressa conglomerate. Samples collected by the Institut Francais du Petrole group at coordinates CM196360 indicate an early to medial Oligocene age (ciperoensis zone) for the Repressa conglomerate (Tony Eva, personal communication) some 800-1000 meters stratigraphically above the Velazquitos formation. Bathymetric indicators suggest intermediate marine depths on the order of 100m, and this indicates that the basin was moderately deep in absolute terms as the Early Oligocene had a low sea-level stand. Perhaps the general regression contributed the massive conglomerate materials.

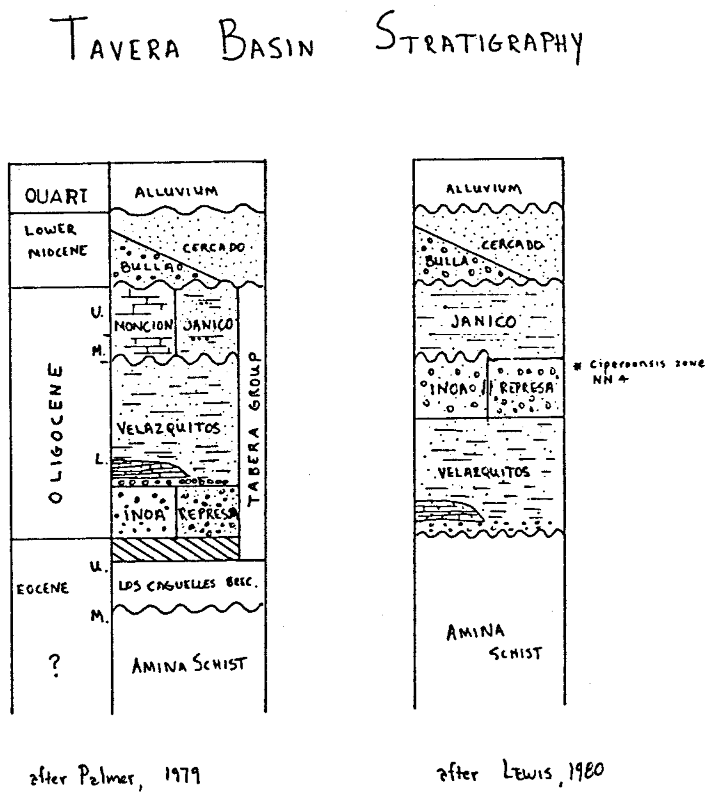


Figure 5.2

Tavera Basin stratigraphy

Sea level rose, then fell again in the late Oligocene before an Early Miocene transgression.

While my field work found that Palmer's (1963, 1979) Velazquitos Formation is stratigraphically lower than what he identified as the Inoa and Repressa Conglomerate Formations, it may be appropriate to consider all three the same formation with abrupt facies variations. These may have resulted from substantial syndepositional strike-slip faulting, in a predominantly bathyal (100m deep) marine environment with rapidly shifting sediment sources. The division of the section into mappable litho-units remains complicated, and detailed mapping in the rough topography south of the town of Janico is needed to solve the problem. In that area the Velazquitos formation is only gently folded, and exposures resemble the monotonously alternating carbonaceous sandstone and siltstone components of the Janico formation. By contrast, in the Tabera-Bao dam connecting channel, near the intersection of the Tabera fault and the Sabana Inglesia fault, exposures of the Velazquitos formation are intensely disharmonically folded while the overlying Repressa conglomerate is only gently folded.

Relationships between the upper members of the stratigraphic column suggest continuing, progressive tectonic disturbance. The Janico Formation of calcareous sandstones and siltstones lies unconformably above the Inoa conglomerate, while it is both apparently conformable above the Repressa conglomerate (in the Rio Yaque) and in fault (thrust) contact in other locations (BM055389, BM174361) or is entirely absent (Groetsch 1980, p. 214, km 10.1). The Moncion limestone appears to be of only local significance and it may be simply a large olistolith. In the Rio Guarbo (BM704492) it is a limestone matrix conglomerate suggesting a carbonate debris flow origin. Other thin carbonates within the Repressa formation (ie at BM214361, BM050387) suggest that carbonate debris flows were not uncommon during deposition of the Tavera (Tabera) Group. The Cercado Formation of early Miocene age and its basal Bulla conglomerate overly the Tavera Group with obvious angular unconformity, and although, interpreted as a tectonic response, its deposition correlates with a world-wide sea level rise at NN4. The Formation appears to have great lateral extent, unlike the Tavera group, and continues in the subsurface across the Cibao Valley to the Septrentrional fault according to interpretations of seismic reflection data (Mike Nemec, personal communication), buried beneath a substantial thickness of late Neogene clastic sediments.

In spite of the lack of detailed mapping in the Tavera region, it is possible to propose an reasonable interpretation of the general geological features. At the time of initiation of strike-slip faulting in the early Oligocene, conglomerates and thin shallow-water carbonates were being deposited in the region. Then, figuratively speaking, the bottom dropped out as the pull-apart formed, and Velazquitos shales were deposited. The orientation of strike-slip faulting changed and the Velazquitos formation was intensely folded. Nearby regions were uplifted as a consequence of compressional strike-slip, providing ample source materials for extensive conglomerate deposition. Continued faulting led to a change in the depositional pattern, and conglomerates no longer reached the Tavera basin. Subsidence led to the deposition of the Janico formation (sandstones and siltstones) in a narrow basin in upper Oligocene times, and before the lower Miocene deposition of the nearby flat lying, northward dipping, Cercado formation, the entire Tavera group was tilted and eroded as the dominant strike-slip faulting moved northward. A thick upper Neogene cover then blanketed the Cubao Valley.

The Tavera basin may be the only early Oligocene pull-apart basin presently exposed at the surface in Hispaniola, but it seems quite possible that other discrete pull-apart basins formed at that time in a broad PBZ, and that they lie buried deeply below the surface of the Cibao Valley.

Does the Fondo Negro Formation represent an accretionary prism and can it be considered an extension of the Muertos Trough?

Hess and Maxwell (1953) and their numerous followers have handed to those making structural interpretations in Hispaniola 1100 + km of offset on the Cayman trough and this motion must be accommodated on the numerous strike-slip strands of PBZ as it passes north and south of the island so that any interpretation must embody an element dominated by strike-slip faulting. This in itself would suggest that it is unlikely that the Fondo Negro Formation would represent the consequences of subduction tectonics. Nevertheless, it has been proposed by Biju-Duval, et al. (1980, 1983 in press) and Mascle et al., 1980) that the Fondo Negro section represents the frontal part of a accretionary prism and that the Muertos trench continues onshore across the Enriquillo Valley so that in effect the Enriquillo represents the zipped shut part of a progressively closing subduction system. Based on my detailed scale mapping of strike-slip and normal faults, and the scale required by regional interpretations of the Cayman Trough, the hypothesis seems unjustified.

It is much more likely that the Fondo Negro formation formed in a consequence of strike-slip faulting either by local extension (a pull-apart) or due to nearby compressional loading similar to the Ridge Basin of

Southern California described by Crowell (1975) Link and Osborne (1978), and Crowell and Link (1982). Thus it is my contention that the Fondo Negro basin was analogous to the present day San Pedro basin offshore, south of Santo Domingo, and, like it, formed as the result of left-lateral strike-slip faulting with localized extension and nearby wrench-fault uplift, both providing the source of sediment and causing large scale slumping and resedimentation. It should be noted that unlike Ladd and others (1981) I do not interpret the San Pedro basin as a forearc basin in an incipient Pacific type subduction zone, but rather I prefer to consider it a consequence of wrench faulting.

The argument for a wrench fault-strike slip origin is bolstered by numerous primary field observations besides the present distribution of strike-slip and normal faults. For instance, as shown in Figure 3.2, there is large scale soft sediment slumping in the restricted center of the basin in addition to the extremely high sedimentation rate and the apparent abrupt thinning of sections of the same age toward both the Enriquillo and San Juan basins as they are known in the subsurface.

It might be argued that the lack of conglomerate fans seen near faults, or for that matter the complete lack of conglomerate material in the lower and middle Fondo Negro Formation would suggest that the basin did not form as a pull-apart, because such conglomerates are present in many better known examples. However in each of these better known examples water depths were presumed shallow (or lacustrine), whereas the Fondo Negro Formation clearly formed in moderately deep water without proximal sources of conglomeratic material.

It is tempting to assert that the lack of structural complexity, such as syndepositional thrusting and folding, in the Fondo Negro formation disqualifies it as an accretionary prism. Such a claim would be based on schematic cross sections of accretionary complexes which portray stacked imbricate thrusts with intense internal deformation such as well studied diagrams by Seeley and others (1974), Karig and Sharman, (1975), Moore and Karig (1976, 1980), Shipley and others (1980) or Moore and others (1982). Perhaps unfortunately these studies de-emphasize the great variability of accretionary prisms, and their fickle dependence on sediment load, duration of existence, and convergence rate.

Biju-Duval and others (1982) have recently shown that in the Lesser Antilles accretionary complex there is great variability along strike in the style of deformation. Especially in the frontal zone of the active Barbados ridge complex there are broad anticlines at the axial culmination of reverse faults with smaller deformed sedimentary wedges between them that are remarkably similar in cross-section to the Fondo Negro region, minus the strike-slip faults. While I am in fact arguing against an accretionary origin for the Fondo Negro Formation based on a variety of lines of evidence, it is important to note that simply from the lack one cannot rule it out of structural complexity. Clearly one must weigh the mass of evidence, and not jump to conclusions based on single points.

Hispaniola Cross Section

Plate three consists of an interpretive cross section showing the major geologic features of Hispaniola, illustrating the broad nature of the present Plate Boundary Zone faulting, and the importance of pre-medial Eocene subduction and Tertiary secondary compression. Data for subsurface interpretation of the Cibao, San Juan and Enriquillo Valleys came largely from Nemec, in Klemme and others, (1982), whereas the coastal and mountainous regions are interpreted based on field relationships, and the northern offshore coastal region follows seismic reflection interpretations by Austin (1983, in press). Structures are obviously generalized, but every attempt has been made to keep their scale in perspective, and there is no vertical exaggeration.

Stratigraphic age correlations reflect the infant state of the data base and are necessarily vague. Especially problematic is the Oligocene designation for sediments south of the Cordillera Central, where Paleogene sedimentation was predominantly carbonate, and mappable litho-units with any Oligocene age connotation are difficult to establish. Designations of Eocene and Oligocene units north of the Cordillera are substantially more precise.

Clearly the island can be divided into three distinct litho-stratigraphic zones with different basement types which remained relatively intact while accommodating a great left-lateral offset in zones between them. This gives us a southern block with basaltic basement of both early arc and oceanic affinities (B") (Maurrasse, 1982) that extends beneath the San Juan basin; a central block of plutons and andesitic volcanics, and a northern block comprised of metamorphosed Cretaceous (forearc) sediments and ocean floor together with an early Tertiary accretionary zone and a paired metamorphic belt. In this northern litho-stratigraphic zone the Amina schist, exposed near the Tavera basin, appears to be metamorphosed forearc sediments (Draper and Lewis, 1980) of the Hispaniola arc which formed before its medical Eocene collision with the Bahamas. Metamorphism appears less intense in the north (Pedro Garcia complex) although north of the Camu fault, ultramafic slivers of either the arc or the consumed proto-Caribbean crust are exposed.

The Basins

The monoclinal Cibao basin is bounded to the north by the Septentrional fault, which has perhaps the greatest Neogene vertical offset of any fault on the island with the possible exception of the Hispaniola fault zone which brings ultramafic arc basement to the surface. The basin fill is predominantly post early Miocene, and wells were drilled to 10,000 feet without getting out of Pliocene - recent sediments. The early (medial) Miocene, Cercado - Janico unconformity seen on the south of the Tavera basin can be traced on seismic data deep into the basin. As interpreted from surface exposures the Cercado formation was deposited in a very shallow high energy environment while the overlying Gurabo formation was deposited in slightly deeper water, and the Mao formation above the Gurabo may have evaporitic facies.

The Tavera basin discussed previously is an Oligocene pull-apart basin lying on basement, and similar discrete basins with Oligocene marine sediments are indicated on seismic interpretations of the Cibao. Eocene marine sediments are presumed to exist in the Cibao basin, but this is strictly speculation. Eocene marine sediments are however exposed north of the Septentrional fault.

The distribution of secondary compressional structures in the pre-Miocene section as mapped by seismic interpretation (M.Nemec personal communication), shows a completely different orientation of strike-slip faulting from the present, and indicates that motion has been accommodated over a broad area. The simplest Riedel (1929) shear zone type analysis for the pre-Miocene structures would predict a right-lateral offset to produce the structures, although there may have been some subsequent rotation to complicate matters, and render any simple analysis naive.

The San Juan and Enriquillo basins are different from the Cibao, in spite of the fact that all three owe their existence to strike-slip faulting. They are both structural ramp valleys, and the mountain ranges bounding them resemble giant flower structures. Unlike the Cibao, Paleogene sedimentation in the Enriquillo and San Juan Valleys was almost entirely carbonate, although upper Oligocene sandstones and shales are identified on the northern margin of the San Juan Valley. The Sierra de Neiba did not form until post upper Miocene (NN9) times based on thrust relationships (Eocene on top of Upper Miocene), and the center of deposition and wrench fault activity moved progressively southward with time. Apparently the initiation of the Enriquillo Basin did not occur until upper lower Miocene time. It seems likely that the San Juan and Enriquillo basins were one and the same system before the Late Miocene, when the Sierra de Neiba began to form between them, although shortening, and strike-slip faulting have juxtaposed areas that were once separated within a large basin, which consequently has juxtaposed significant facies variations.

The migration of strike slip activity and subsequent migration of the center of deposition southward is illustrated by thick early Miocene sediments in the San Juan Basin (similar lithologically to the Fondo Negro formation, but older) yet with only an estimated 800 meters of post early Miocene sediments, whereas the Enriquillo has an especially thick Middle Miocene to Pliocene section, including more that a kilometer of evaporites not present in the San Juan. It seems likely that in upper early Miocene times the San Juan acted as a sediment sink or barrier for sediment derived from the Cordillera Central, and the shallow Enriquillo area was a giant evaporite basin. Sediments of this age and younger in the Sierra de Neiba have been eroded. Farther to the south in the Sierra de Bahoruco Miocene sediments are entirely carbonate, although these all occur to the southeast of the cross-sectional line, and are not shown in the figure.

Biju-Duval and others (1983, in press) identified Upper Cretaceous deformed sediments (turbidites) in the San Cristobal area south of the Cordillera central. Their extent in the San Juan basin is unknown, but gravity data (Bowin, 1976) suggests that the basin contains an especially thick sedimentary sequence, and Upper Cretaceous clastic turbidites are reasonable.

Offshore

Offshore from the northern coast, seismic surveys (Austin, 1983, in press) reveal substantial secondary compression related to strike-slip faulting, and this is similar to the San Pedro basin (Ladd, et al., 1981) south of Santo Domingo. The offshore geology to the south of the cross-section is especially complicated due to the Beata Ridge structure, and is omitted due to lack of data.

Cordillera Central

Little has been said about the Cordillera Central the arc edifice formed as a result of the prolonged subduction of proto-Caribbean (Atlantic) sea-floor beneath Hispaniola. Undoubtedly the structure is more complicated than shown in the cross section, reflecting the lack of mapping in that area.

An outline of the tectonic evolution of the Greater Antilles.

The preceding section discussed the lithostratigraphic units of Hispaniola, the expression of a diffuse PBZ,, and the migration of faults, depositional centers, and the kinematics of thrusting in Hispaniola. This section outlines the overall tectonic evolution on a very broad scale.

The consensus of opinion maintains that the Greater Antilles arc originated in the Pacific, perhaps in late Jurassic times, far to the west and migrated to its present position, subducting proto-Caribbean sea-floor, only to collide with the Bahamas carbonate bank, terminating subduction in medial Eocene times. Whether the arc maintained a constant polarity (subduction direction) or flipped its polarity or was at one time two arcs will likely be debated for some time, until detailed field mapping and geochemical analysis is completed.

Certainly by the end of the Cretaceous the arc comprised a southward dipping subduction zone and was migrating northward relative to North America. Some western parts of the arc may have collided with Yucatan causing compressional structures in Jamaica and the Nicaragua Rise in Paleocene time and Western Cuba (Islas Pinos, Pinar del Rio) may have clipped off and attached to the arc. Concurrently the Yucatan basin began to form by back-arc spreading (Gealey, 1980) rifting the Cayman Ridge and Nicaraguan Rise from the Arc, with the Cauto Basin the hinge, similar to the Taupo Volcanic zone of New Zealand evidenced by 3100m of Lower Eocene volcano clastic deposits in the Cauto (Furrazola-Bermudez and others, 1964), as well as rift sediments along most of the southern margin of Cuba at that time.

In addition to the rifting seen in the Greater Antilles, uplift and block faulting clearly occurred along the eastern margin of Yucatan from Late Cretaceous to Paleocene times (Uchupi, 1972). This is interpreted as transpressional strike-slip motion as Cuba progressed along the margin during the back-arc spreading period. Subsidence of the transpressional regime thereafter led to down dropping of marginal blocks adjacent to the then juvenile sea.

Left lateral strike-slip faulting probably displaced Oriente Province Cuba, south of the Cauto Basin and the Bahamas, perhaps as much as 100 km before a major PBZ initiated in the Cayman Trough, offsetting the Caribbean Plate 1200 km eastward with respect to North America since

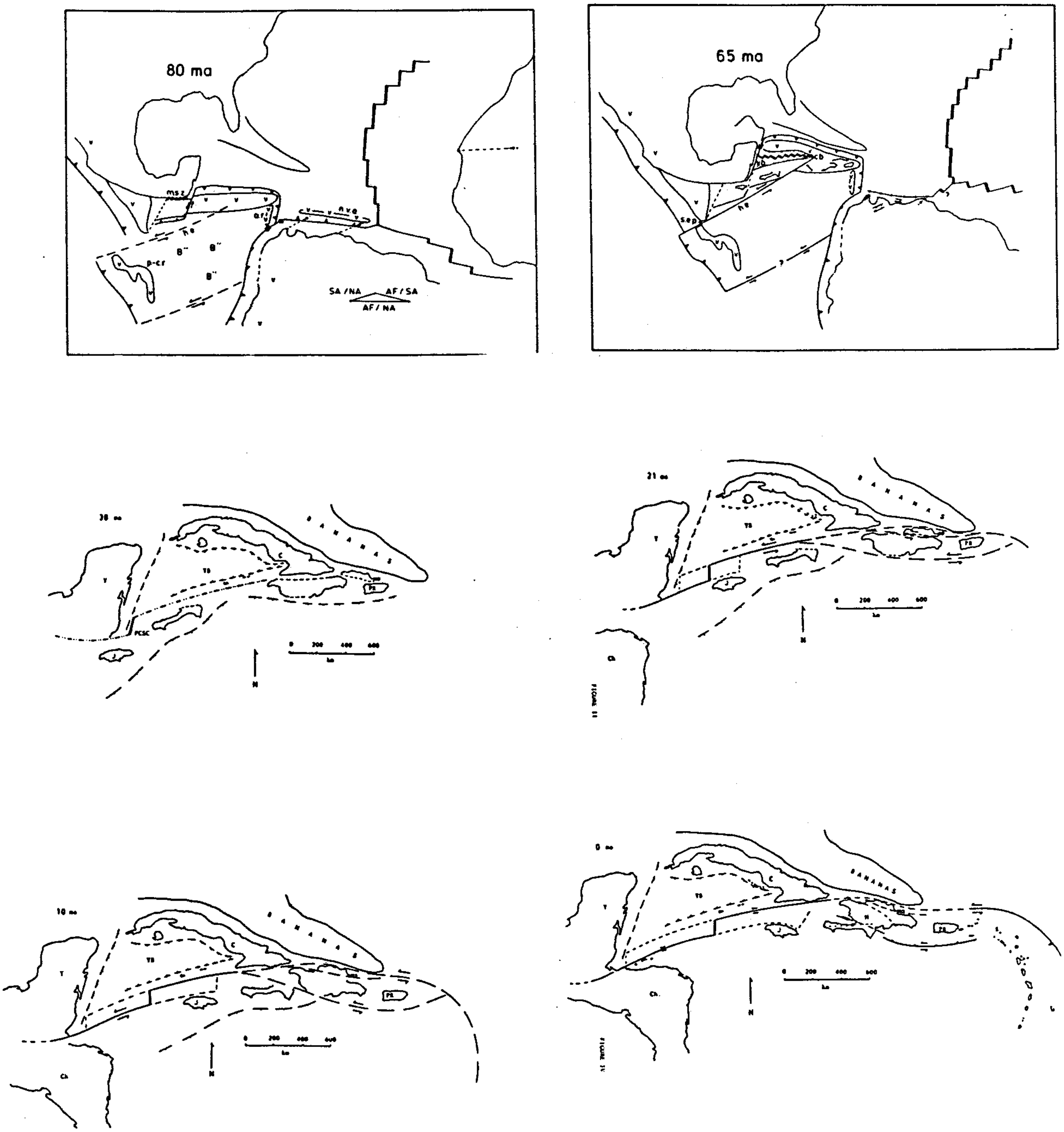


Figure 5.3

Greater Antilles Tectonic evolution, pre-38ma from Pindell and Dewey,(1982).

earliest Oligocene times. The PBZ is distributed over a wide zone (Burke et al, 1980) with no single fault accommodating the displacement. In Hispaniola substantial offsets (200-400 km) occurred between the three major blocks as described in the cross section, and especially in Late-Miocene-Pliocene times, secondary compression caused the development of the Sierra de Bahoruco, and the Sierra de Neiba, as well as great uplift in the Cordillera Septentrional, and the Sierra de Martin Garcia, and led to the formation of the offshore San Pedro basin. This secondary compression obviously is a consequence of wrench faulting, but is also enhanced by the NE motion of the Santa Marta block of NW America (Colombia), the general North America - South America convergence, and restraining bends in the plate boundary system. These relationships are shown schematically in Figure 5.3, and more detailed discussions can be found in Burke and others, (1983, in press), and Pindell and Dewey, (1982).

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Appendix The Application of Stretching Models to island arc Subisdence.

ABSTRACT

The McKenzie stretching model for the evolution of basins is examined in a range of values appropriate for island arc basins (not accretionary prisms). The mathematical behavior of the equation renders it inappropriate for estimates of basin stretching in most island arc terranes, especially due to the extreme sensitivity of the equation to estimates of crustal density for typical arc profiles. Likewise the equation is quite sensitive to the ration of the thickness of crust to the thickness of lithosphere. Hypothetical modeling reveals that the equation predicts great subsidence with a small amount of stretching for island arcs with thick crusts, and this seems to be true from a survey of Western Pacific and Caribbean arc basins. Generally the thicker the crust (h_c/h_1) the less sensitive the equation is to minor density fluctuations, and the more accurate the estimates of stretching; although one can only speculate what the values of crustal and lithosphere thickness were at the time of formation. Stretching calculated from the Le Pichon and Sibuet equation is similar to the McKenzie model in most theoretcial cases, although there are discrepancies in some actual basins which may reflect inaccurate stratigraphy, compression of the Caribbean region in the Tertiary is reviewed and examples of extensional features seen in the field in the Fondo Negro basin of the southwest Dominican Republic are pointed out.

INTRODUCTION

Basins in wrench-fault domains form as a result of both stretching with extension (pull apart basins), and compression causing loading. Often, in this geologic environment, it is difficult to distinguish the fundamental cause of basin subsidence, whether extensional or compressional, because one can continuously evolve into the other. For instance a basin which initiates as a consequence of extension may be maintained as a consequence of compression. In spite of this obvious limitation it has recently become fashionable to quantify the amount stretching in order to predict such things as heat flow, and consequently the potential for thermal maturation of Hydrocarbons. This paper examines the predictive value of such models in island arc terranes, and demonstrates that the application of current models yields dubious values at best.

THE McKENZIE STRETCHING MODEL

McKenzie (1978 a,b) proposed a simple model for the evolution of sedimentary basins on continents based on the concept of stretching. The model depends on instantaneous stretching in which initial rapid subsidence of the continental lithosphere causes the asthenosphere to thin and upwell passively. Block faulting and often rapid subsidence dominate this early stage of basin development, and with time, progressive heat conduction to the surface thickens the lithosphere toward pre-stretching thicknesses, so that further subsidence occurs relatively slowly, generally not associated with faulting. In McKenzie's model the slow subsidence and heat flow depend only on the amount of stretching, which can be estimated from these quantities and from the change in the thickness of the continental crust caused by extension. Thus as McKenzie notes the model is easily testable, and several attempts (Sclater and Christie, 1980, Dewey, 1982), have been made to use the model as a predictive tool on stretched continental crust, and to examine the geologic consequences of stretching continental crust (Le Pichon and Sibuet, 1981, Dewey, 1982).

Because of the geological implications of local thermal heating which is a consequence of stretching, we are interested in quantifying the amount a basin has stretched in order to attain a particular thickness. The high heat flow associated with stretching has profound implications on the maturation of hydrocarbons, and the upwelled asthenosphere will affect the production of volcanic magmas and the metamorphism of surrounding rocks. We cannot measure the heat flow in a basin 20 mya, so our predictive capacity focuses on determining the amount of stretching, or as defined by McKenzie, the factor beta (β), which in turn should give us an estimate of relative heat flow.

Clearly the McKenzie stretching model was constructed for the case of stretching and forming basins on thinning continental crust. Tests and applications of the McKenzie model to basin formation on continental crust have proved satisfactory. But thus far every test or application of the model has assumed continental crust and lithosphere as an initial condition. The obvious question is how well does the McKenzie model predict stretching and subsidence on non-continental crust such as island arc terranes? Are the same equations which predict beta and subsidence values on continental crust applicable for island arcs, or are there inherent limitations to the equations? Are there too many assumptions required to make for island arc terranes that render the predictive power of the model meaningless? What hypothetical values of beta result from variations in crustal thickness, density, sediment load and lithosphere thickness and are these realistic? Finally, what role do other dynamic processes play in basis subsidence and what evidence can a geologist find in the field to interpret stretching?

SUBSIDENCE EQUATIONS

In order to study the applicability of the stretching model to island arc terranes we must look at the equations that describe the model and what they mean. Initial subsidence due to rifting, or the formation of pull apart basins is considered instantaneous, and is described by McKenzie equation (1) as corrected by Sclater and Christie, (1980):

$$S_i = \frac{a\left[(\rho_o-\rho_c)\frac{t_c}{2}\left(1-\frac{\alpha T_1}{2}\frac{t_c}{a}\right)-\frac{\alpha T_1 \rho_o}{2}\right]\left(1-\frac{1}{\beta}\right)}{\rho_o(1-\alpha T_1)-\rho_w}$$

Rearranging the equation to solve for beta, we get:

$$\beta = \frac{a\left[(\rho_o-\rho_c)\frac{t_c}{a}\left(1-\frac{\alpha T_1}{2}\frac{t_c}{a}\right)-\frac{\alpha T_1 \rho_o}{2}\right]}{a\left[(\rho_o-\rho_c)\frac{t_c}{a}\left(1-\frac{\alpha T_1}{2}\frac{t_c}{a}\right)\right]-S_i\left[\rho_o(1-\alpha T_1)-\rho_w\right]}$$

where a is the thickness of the lithosphere

t_c is the thickness of the crust

ρ_o is the density of the mantle (3.33 g cm^3)

ρ_c is the density of the curst

T_1 the initial temperature of the asthenosphere

(1333 c°)

α the thermal expansion coefficient of both the mantle and the crust (3.28 x 10 -5)

S_i is the initial subsidence (in km)

ρ_w the density of seawater (or the density of the sediment load)

Jarvis and McKenzie (1980) have shown that the instantaneous stretching model is adequate provided the duration of stretching is less than 20 Ma. For subsidence beyond the initial stage McKenzie (1978) derives curves to predict beta based on subsidence rate and thermal cooling. Le Pichon and Sibuet (1981, equation 2) have derived a similar equation to describe subsidence at time infinite as a linear function of $(1 - \frac{1}{B})$.

In the Le Pichon and Sibuet equation the value of subsidence at infinite time is independent of the cooling history and consequently the lateral variation in temperature. It only depends on a unique equilibrium value for the thickness of the lithosphere at infinite time. This differs from the McKenzie model for subsidence beyond S_i which ignores the lateral variation in temperature. Thus the McKenzie solution gives a somewhat lower estimate of thermal subsidence, since the effect of lateral conduction should be to produce a faster cooling than computed by

McKenzie, except might be expected (Le Pichon and Sibuet, 1981).

Le Pichon and Sibuet, rearranged for B using the same variables as in the McKenzie equation:

$$\beta = \frac{t_c(\rho_o - \rho_c)\left[1 - \frac{\alpha T_1}{2}\left(\frac{t_c}{2}\right)\right]}{t_c(\rho_o - \rho_c)\left[1 - \frac{\alpha T_1}{2}\left(\frac{t_c}{2}\right)\right] - S_\infty\left[\rho_o(1-\alpha T_1) - \rho_w\right]}$$

In this version of the equation the factor epsilon (ϵ) in the original equation is neglected, and this produces errors not larger than 5 parts per thousand.

Looking at the McKenzie equation, and the range of values generally applied to the variables, we see that ignoring values multiplied by factors close to (1), or those subtracted with values close to zero, we get crudely and Airy Model:

$$S_i = \frac{(\rho_o - \rho_c)\, t_c}{\rho_o - \rho_w}\left(1 - \frac{1}{\beta}\right)$$

Considering the ρ_o is assigned a constant value, we immediately infer the β values are especially sensitive to the choice of density of the load (ρ_w), the density of the crust (ρ_c), S_i, and the thickness of the crust (t_c). The thickness of the lithosphere becomes a more significant factor with respect to the value of beta as it becomes larger.

THE BEHAVIOR OF THE MCKENZIE EQUATION

In active island arc terranes we expect the thickness of the lithosphere and crust and the density of the crust to be substantially different from the simple continental case. Thus we need to study the behavior of the McKenzie equation with the appropriate range of values for these variables.

The crustal thickness of island arcs varies significantly on a world-wide basis (Gill, 1981). Estimates are based on interpretations of mass deficiency from gravity measurements, which depend in turn on assigning some portion of the anomaly to hot molten material, and some to the lighter crustal material, which is usually a somewhat arbitrary process. In some places seismic velocity studies substantiate claims for crustal thickness, but in general we must admit that the element of interpretation is extreme.

Density estimates are just as imprecise. We know that arcs lie somewhere between continental densities and oceanic densities. Most literature assigns a value of 2.90 gm/cm^3 to average arc composition. However we realize that pluton emplacement style can substantially alter average densities on a local level, and a precise determination of density to within 0.01 gm/cm^3 is essential to subsidence analysis for arcs with thin curst.

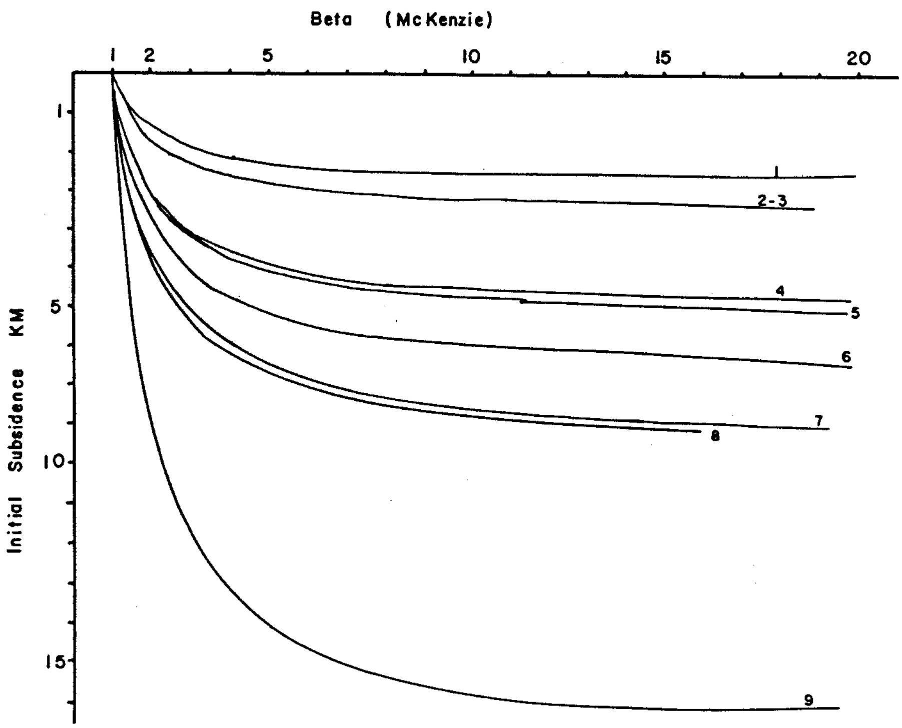
If precise densities of arcs were known, it would be a relatively simple process to use geologic data to establish crustal thicknesses. Thick carbonate sequences on remnant arcs such as the Nicaragua Rise would constrain subsidence rates so that crustal thickness could be obtained. The problem is that this result is sensitive to the density chosen.

Perhaps the least constrained variable is the thickness of the lithosphere. Estimates of 60-80 km are inferred from Ringwood's petrologic models, however they could just as easily be 100 km, for some arcs. In this paper most combination are chosen arbitrarily, for illustrative purposes.

No matter what values we assign (to the crust and lithosphere thickness, and the average density) based on the most accurate geophysical measurements of present arcs, we have little constraint on these values at the time the basin initiated as necessary to solve the McKenzie equation, and thus we cannot avoid speculation.

VARIATION OF S(I), T LITHO, T CRUST, LOAD DENSITY

Figure A.1 is a graphical representation of the effect of initial subsidence on the calculated value of beta from the McKenzie equation for various combinations of thickness of the crust and lithosphere and density of the applied load (seawater or sediments). In all cases solutions to the McKenzie equation are hyperbolas of the form f(x)- c/c-x, and geologically one of the two hyperbolas is meaningless. In other words the negative hyperbola indicates uplift for



	T-Litho km	T-Crust km	D-Load gm/cm^3	D-Crust gm/cm^3
1.	20	18	1.03	2.80
2.	125	31.5	1.03	2.80
3.	100	35.0	1.03	2.90
4.	80	25.0	2.40	2.90
5.	100	50	1.03	2.90
6.	20	18	2.40	2.90
7.	125	31.5	2.40	2.80
8.	100	35	2.40	2.90
9.	100	50	2.40	2.90

Figure A-1

The effect of initial subsidence on calculated beta values (McKenzie) for various combinations of crustal thickness and density, lithosphere thickness, and density of applied load.

positive subsidence, which is ridiculous. This is not to say that negative beta values have not meaning, for they do and indicate shortening of uplift, but they are not appropriate in the context of this graphical analysis.

Careful scrutiny of the graph reveals that:

(1) Other conditions being equal, the greater the ratio T crust/ T litho, the greater the initial subsidence for a particular amount of stretching. This holds true up to a value of approximately (0.6) when the order is reversed.

(2) Typical island arc conditions (curves 4 or 6) yield substantially less subsidence for a given amount of stretching than continental conditions (7). This however is dependent on the choice of density of the crust, which we assume to be greater for typical island arcs.

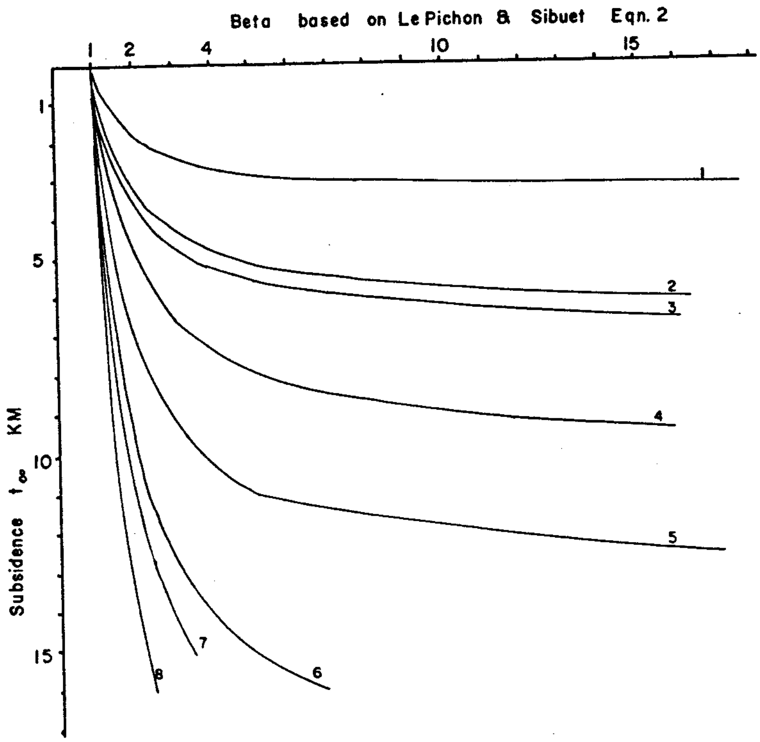
(3) In all cases the greater the density of the load the greater the subsidence. This is an obvious result, and the specific degree of sensitivity of subsidence to load density is considered later.

(4) By contract, values which approximate arcs along continental margins (curves 8,9) can show

substantially more subsidence for a given amount of stretching than even continents. Put more conservatively, the combination of thicker crust and thinner lithosphere for arcs such as Turkey-NW Iran, Japan, Kamchatka, the Andes, and New Guinea than for corresponding continental conditions leads to greater sedimentary thicknesses for a given beta factor. In the continental analogy, Dewey (1982) shows that especially deep basins can form when thickened continental crust is stretched.

Figure A-2 represents beta solutions to the Le Pichon equation for various amounts of subsidence. For the most part, the behavior of the equation is not much different from the behavior of the McKenzie equation. The relationship that the greater the value of the ratio T crust/ T litho, the greater the subsidence seems to hold true for this equation, like the McKenzie equation, for values less than about (.6), when the results reverse themselves. As expected, a particular subsidence value gives a much lower beta value for the Le Pichon equation than the McKenzie equation, but this simply reflects the difference between infinitely prolonged subsidence and initial subsidence.

The graph demonstrates that the Le Pichon equation is especially sensitive to changes in the thickness of the lithosphere, a poorly constrained variable in island arcs.



	T-Litho km	T-Crust km	D-Load gm/cm3	D-Crust gm/cm3
1.	20	18	1.03	2.90
2.	100	50	1.03	2.90
3.	100	35	1.03	2.90
4.	20	18	2.40	2.90
5.	80	25	2.40	2.90
6.	100	35	2.40	2.90
7.	125	31.5	2.40	2.80
8.	100	50	2.40	2.90

Figure A-2

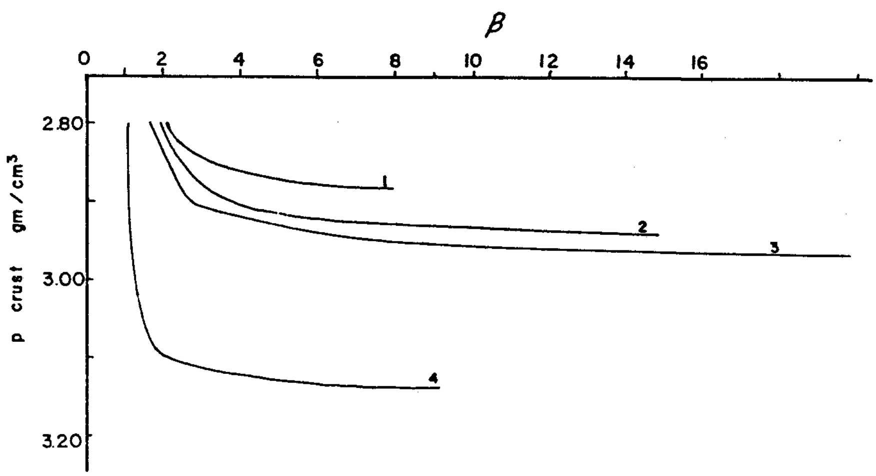
The effect of total subsidence on calculated beta values (le Pichon and Sibuet) for various ranges of crustal and lithosphere thickness, and density of applied load.

However the McKenzie equation for thermal subsidence is just as sensitive to fluctuations in heat flow which are likewise poorly constrained.

DENSITY SENSITIVITY

We have already shown that the McKenzie equation is sensitive to the density of the load and yields progressively greater beta values as the density of the load increases with other conditions constant. In other words, if we thought a basin were full of sandstones and shale, and calculated the amount of stretching we would get a smaller value.

Likewise figure A-3 illustrates that as the density of the crust increases for a particular amount of subsidence, the beta factor increases exponentially. The fact that the amount of calculated stretching is sensitive to the density of the crust is expected when we consider that the equation to a first approximation is an isostatic Airy model. The shocking revelation is the degree of sensitivity. Figure 3 shows that for reasonable island arc conditions, increasing the estimate for the arc material by as little as 0.01 gm/cm^3 in the range of 2.90 gm/cm^3 will send estimates of stretching skyrocketing. This is a most distressing finding as the density of arcs is only imprecisely known. The general estimate of 2.90 gm/cm^3 falls at one of the most sensitive critical points in the McKenzie equation for predicting beta values for most island arc type crustal



	T-Litho km	T-Crust km	S(I) km	Dens. Load gm/cm^3
1.	100	22.5	2.5	2.30
2.	80	25	4.0	2.40
3.	80	22	2.5	2.30
4.	100	50	2.5	2.40

Figure A-3

The effect of changing crustal densities on the calculation of beta factors in hypothetical island arc terranes.

thicknesses. Those arcs with unusually thick crusts are less sensitive to the value chosen for density of the crust as shown by curve. Combined with the fact that the thickest crusts give the greatest subsidence, we conclude that the most accurate estimates of stretching can be made for especially thick arcs.

ESTIMATES OF STRETCHING IN BASINS OF THE GREATER ANTILLES

Beta factors for selected basins of the Greater Antilles have been calculated assuming that they formed by a stretching process, with a crustal density of 2.90 gm/cm^3 and sediment density of 2.38 gm/cm^3, for values of crustal and lithospheric thickness depicted in table A-2.

As discussed in the thesis, the Greater Antilles has been dominated by strike-slip faulting since the early Oligocene which has led to the development of spectacular pull-apart basins as well as compressional ramp valleys. The Tavera basin is the earliest and best preserved of the pull-aparts which initiated with offsets along the Cayman Trough in a left lateral PBZ. As shown in table 1, depending on values assigned to variables it was stretched by a factor of 1.2-1.4, more probably near the greater value. Faulting quickly migrated northward causing displacement of northern Hispaniola with respect to central Hispaniola, and local pull-aparts known from geophysical surveys developed in the Cibao valley with beta factors predicted by the McKenzie equation of 2.5, and the Le Pichon equation of 4.0. Similar values are found in the San Juan valley, which currently has especially thick crust, but probably did not have such thick crust in Miocene times. The discordance in these values suggests that repeated stretching events occurred, or some tectonic thickening, or

TABLE A-2 Beta values for selected Caribbean Basins. (Instantaneous Subsidence). Density of sediment assumed 2.38 g/cm^3, density of crust assumed 2.90 g/cm^3 LP=LePichon equation-infinite time; others McKenzie equation.

BASIN	T-LITHO (km)/ T-Crust (km)/ T-SEDS (km)	BETA
Enriquillo	80/30/7	1.8 (LP)
	80/20/7	2.9 (LP)
San Juan	80/30/2	1.3
	80/20/2	2.5
	60/20/2	1.6
Cibao -	Same as San Juan.	
Tavera	80/30/5.1	1.47 (LP)
	80/30/1.5	1.2
	60/20/1.5	1.4
Fondo Negro	80/30/3	1.54
	60/20/3	2.4
	80/30/4.2	1.97 (LP)
Wagwater	80/30/5.8	3.1
	60/20/5.8	7.4
	100/23/5.8	4.1
	80/30/9	2.3 (LP)
Blue Mountains	80/30/1.5	1.2
	60/20/1.5	1.4
Cauto	60/30/5.8	7.4; 2.2 (LP)
	60/20/3.4	3.1
	80/30/3.4	1.7
San Cristobal and Jatibonico	60/20/2	1.6
	80/30/2	1.3

perhaps even extreme lateral heat loss.

If we assume that the Fondo Negro basin formed as a result of stretching as a spectacular pull-apart instead of by some combination of compression then by changing crustal thicknesses to low values, or increasing crustal densities slightly, one can get beta values of up to 8, but conservative estimates are in the vicinity of 2.4.

Estimates of the amount of stretching in the Wagwater Trough of Jamaica, and several subparallel basins offshore which may have formed as impactogens when the Greater Antilles arc collided with Chortis, are fraught with uncertainty about the thickness of the crust and lithosphere. Assigning litho/crust values of 80/30km gives beta = 3.1, 60/20 B= 7.4, 100/23, B= 4.1. This variation is symptomatic of estimates of stretching in island arc terranes. One can just about make the data fit any estimate of stretching, especially if the sediment pile is thick, and the crustal thickness is poorly constrained.

The Cauto basin of Cuba is considered the hinge of a back arc basin, and the Bayate, basin a marginal rift so we might expect them to have high Beta values. Beta factors depend once again on ones choice of T-litho/T-crust but values ranging from 3.1 to 7.4 are completely reasonable. The failed arms of the rift system, the San Cristobal and Jatibonico rifts have as expected much lower beta factors, in the range of 1.3 - 1.65.