30. THE GEOLOGY OF SITE 98 AND THE BAHAMA PLATFORM

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INTRODUCTION

On April 9, 1970 the drilling ship *Glomar Challenger* spudded the first core test ever to be drilled in the deep Bahama channels. Located in 2769 meters of water, the site was the 98th to be core-drilled under the auspices of the Deep Sea Drilling Project. Site 98 was selected by the Atlantic Advisory Panel for the purpose of determining whether the Bahama channels are primarily the product of: (1) differential rates of deposition, (2) tectonism (block faulting), or (3) erosional processes, or possibly a combination of these phenomena.

Site 98 core data have clarified the geologic history of the Bahamian carbonate province. More specifically, they suggest: (1) that the strong bathymetric relief in the Bahamas is primarily the result of differences between depositional rates of shallow water bank deposits and the rates of pelagic deposition in the channels; (2) that present day submarine erosion, described by Andrews *et al.* (1970), has also been active in the past (Pleistocene-Pliocene unconformity in Core 1), and has no doubt been instrumental in the reduction of the overall rate of sediment accumulation in the deep channels during at least late Cenozoic time; and (3) that perireef limestones present in late Cretaceous (Campanian) bioclastic turbidites not only lend support to Newell's atoll reef origin for the escarpments flanking the Bahama banks (Newell, 1955) but would also extend the reef event back to at least early Campanian time.

This report is a résumé of Bahamian geology including not only the new data obtained at Site 98 but also the new concepts recently published for the deep water channels and the Bahamian Platform in general. The report is primarily concerned with that portion of the Bahama Platform described by Uchupi *et al.* (1971) as the northwestern Bahamas. They divided the platform into northwestern and southeastern sectors as a result of their recent studies which led them to develop the concept of separate origins for the earth's crust in each sector. These sectors are herein referred to as the northern and southern Bahamas (Figure 1).

Prior to 1970 our knowledge of the subsurface rocks of the northern Bahamas was limited to well samples from two deep tests on Cay Sal Bank and Andros Island, and three shallow bore holes on the islands of New Providence, Eleuthera, and San Salvador. Locations are shown in Figure 2 and listed in Table 1. Lithologic logs for the Cay Sal and Andros wells are shown in Figure 3. Supko (1970) has published a detailed and exceptionally well illustrated log for the San Salvador hole. Bahama drilling was resumed in April, 1970 when the Deep Sea Drilling Project core-drilled its Site 98 in the deep water channel 32 kilometers north of Nassau. Two deep oil company tests were spudded during the second half of 1970—the No. 1 Long Island and the No. 1 Great Isaac (Figure 2, Table 1). No geological information has been released for these two exploratory wells.

The geology of the northern Bahamas has been thoroughly studied and the available literature is vast. The origin and diagenesis of the Bahama bank sediments and their characteristic environments are well known through the works of Illing (1954), Newell and Imbrie (1955), Lowenstam and Epstein (1957), Newell *et al.* (1959), Cloud (1962), Imbrie and Purdy (1962), and Purdy (1963 a, b). The work of Newell and Rigby (1957) is the most inclusive single reference for almost all aspects of earlier research. Significant deep channel studies were recently reported in Andrews *et al.* (1970). One of the more comprehensive studies of the shallow subsurface rocks is that by Supko (1970). Supko's report presents a detailed analysis of petrographic and geochemical evidence as a basis for interpretation of (1) the depositional environments and diagensis of the limestones, and (2) the time and mode of the genesis of the dolomites. Additional references include specialized reports on the nature and distribution of reefs (Newell *et al.*, 1951; Storr, 1964), the nature of exposed cay rock (Ball, 1967a; Doran, 1955; Friedman, 1964; Müller, 1970), subsurface geology (Goodell and Garman, 1969; Furrazola-Bermúdez, *et al.*, 1964), deep channel turbidites (Rusnak and Nesteroff, 1964; Andrews, 1970), and origin of the Bahama banks (Hess, 1933, 1960; Newell, 1955; Talwani *et al.*, 1960; Ball, 1967b; Ball *et al.*, 1968b; Dietz *et al.*, 1970; Uchupi *et al.*, 1971). These references contain bibliographies which can lead the interested reader to other important works.

PHYSIOGRAPHY OF THE BAHAMA PLATFORM

There are more than 20 principal islands and over 3000 small cays and rocky islets in the Bahamas which

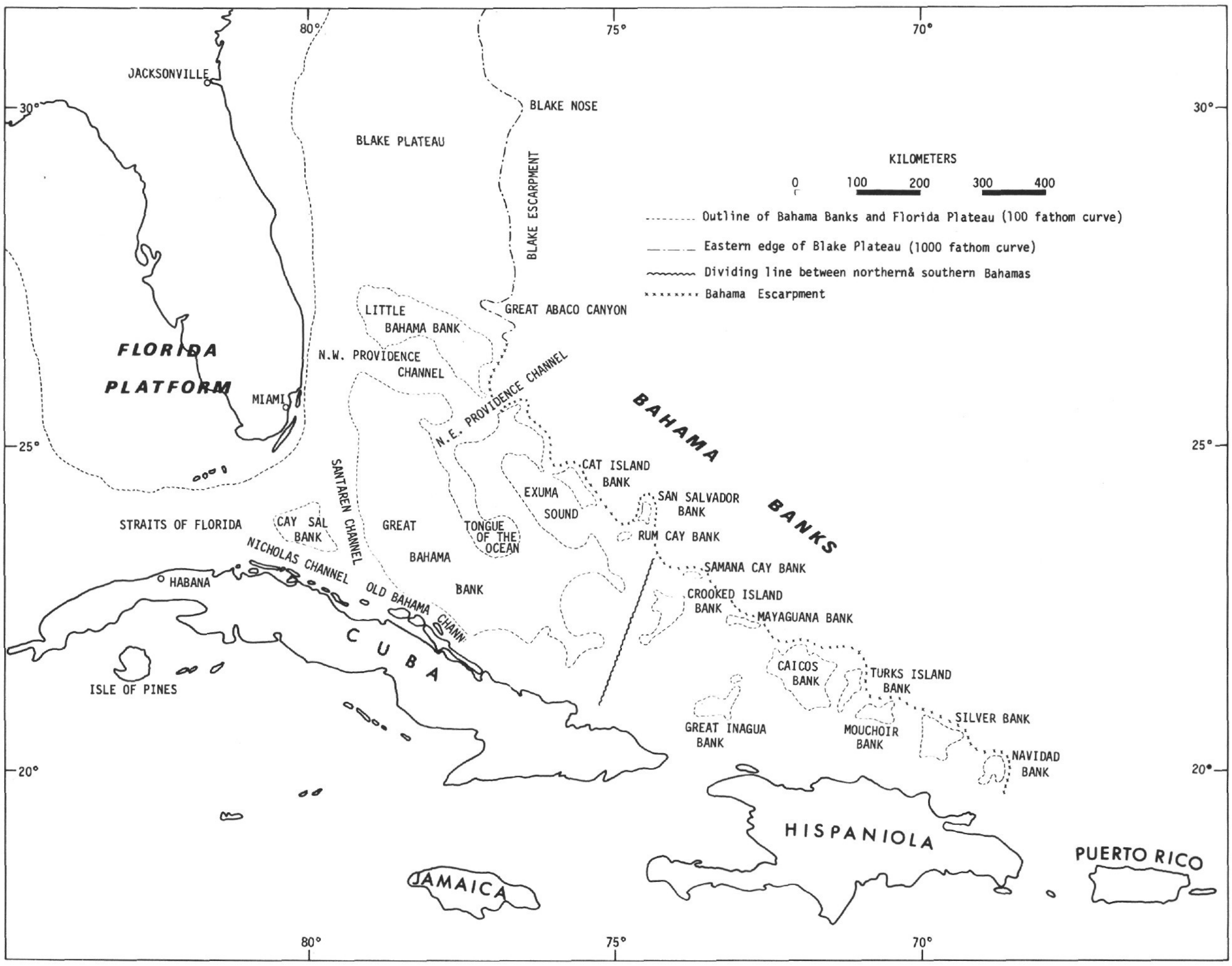

Figure 1. *Index map showing the Bahama banks and the Florida Platform as outlined by the 100-fathom curve. The banks are known collectively as the Bahama Platform which together with the Blake Plateau and the Florida Platform make up one of the largest carbonate provinces in the world. The division of the Bahamas into northerly and southerly sectors is based on the concept of separate modes of origin for the crust beneath each sector (Uchupi* et al., *1971).*

extend for over 1000 kilometers from Florida to Haiti. The islands are situated near the submerged rims of irregularly shaped carbonate platforms known collectively as the Bahama Platform (Figure 1). The Bahama Platform physiographically constitutes an elongate extension to the North American continental shelf of over 300,000 square kilometers. The eastern edge of the Platform is marked by the Bahama Escarpment which drops about 4500 meters from shallow bank waters into the abyssal depths of the Atlantic Ocean with slopes often ranging up to 28 degrees. Slopes of 40 degrees have been reported off San Salvador Island (Emiliani, 1965). The Platform is limited to the southwest by the Cuban orogen and is terminated at its southeasterly end by the Caribbean tectonic plate. The northerly and westerly flanks are geologically contiguous with the carbonate province of the Blake Plateau and the Florida Platform.

Island elevations occasionally exceed 134 meters on Cat Island, 46 meters on Exuma Cay, and 30 meters on Andros and New Providence Islands. The hilly elevations constitute only a small portion of the approximately 12,000 square kilometers of land area. If sea level were to rise as much as 3 meters, 50 per cent of the land area would be inundated. A 20-meter drop in sea level would expose a relatively flat carbonate surface of more than 200,000 square kilometers. There is abundant evidence that even greater sea level fluctuations occurred during Pleistocene time (Newell and Rigby, 1957).

SURFACE GEOLOGY OF THE BAHAMA ISLANDS

The land surface of the Bahamas consists mainly of very pure oolitic limestone of Pleistocene age and Holocene calcium carbonate mud and sand. Except for

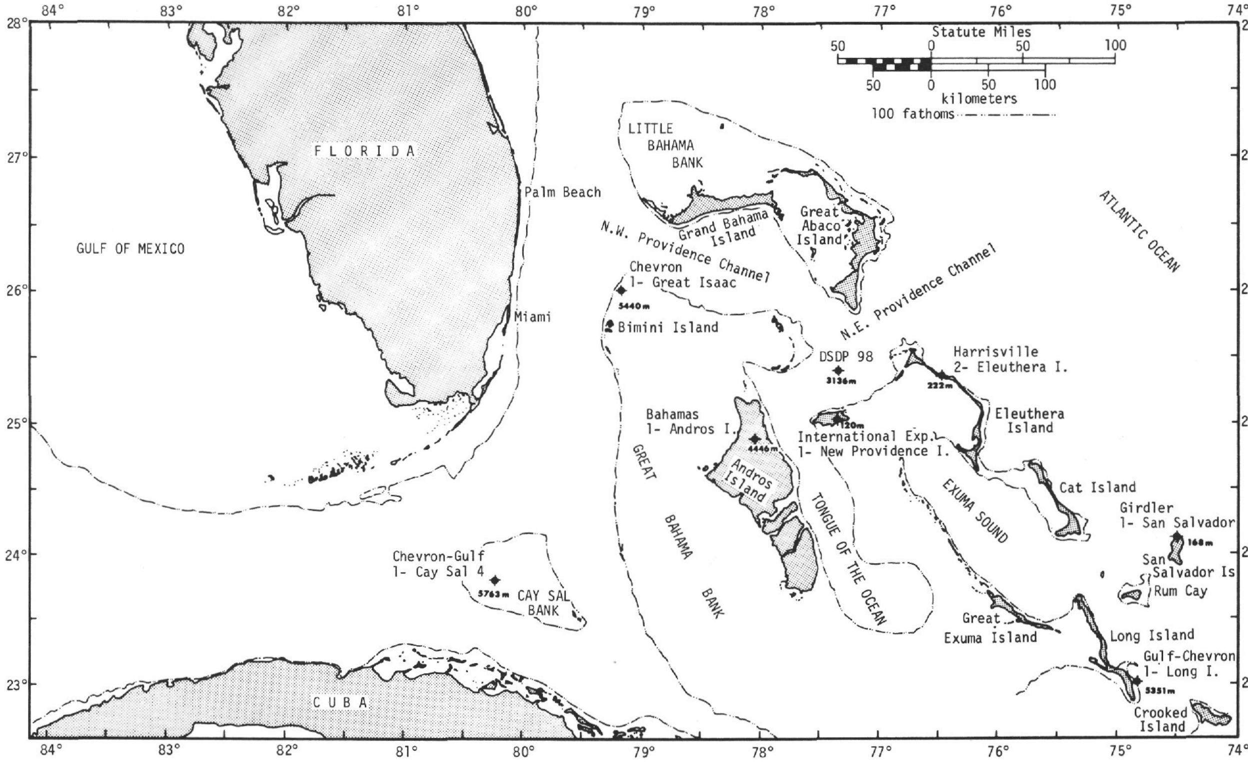

Figure 2. *Bore holes in the northern Bahamas. Bahamas = Bahamas Oil Co., Ltd. (The Superior Oil Co.); Chevron = Bahama California Oil Co.; Gulf = Bahama Gulf Oil Co.*

a very few localities there is little or no cover of residual soil. Oolite deposition was dominant during high sea level stages in the Pleistocene at a time when there were no large islands on the platforms to prevent the agitation of waters so necessary to the formation of oolite sands. Pleistocene dune deposits, consisting chiefly of oolite sand, are highest on the windward sides of the islands and account for the high elevations on the normally low-relief islands. The orientation of these fossil dunes with respect to present day prevailing easterly and southeasterly winds is compatible with directional studies of Pleistocene dunes on Bermuda, where MacKenzie (1964) concluded that Pleistocene wind patterns were about the same as those of the present.

Supko (1970, p. 4) describes the Pleistocene cay rock of San Salvador Island as:

> . . . generally a porous to well sorted, cleanly washed, medium to coarse grained oolitic to biogenic sand.

He also reports that in-place fossil coral reefs of Sangamon (Riss/Würm) age occur at elevations of about 2 meters along the present shore. His work should be consulted for the age analysis of the fossil reefs and the relative stand of sea level in the Bahamas during the Pleistocene. Newell and Rigby (1957) report that hills higher than about 3 meters above high tide level on Andros and New Providence Islands are composed of coarsely cross-bedded oolitic limestone which they concluded to be of eolian origin. They found fossil coral reefs with in-place molluscan shells and coarse skeletal debris to be limited to levels less than 3 meters above high tide. They noted the absence of typical barrier reef coral species, and concluded that the fossil reefs are patch reefs which were formed when the Pleistocene shelf lagoon completely covered the tops of the carbonate platforms.

LAGOON SEDIMENTS ON THE BAHAMA BANKS

Vast deposits of nearly pure calcium carbonate sand and mud are now forming in the shallow bank waters. In these sediments aragonite is much more abundant than calcite and is reported to make up about 60 per cent of the oolite sands and from 85 to 96 per cent of the pellet muds on the Great Bahama Bank between Bimini and Andros Ilsands (Goodell and Garman, 1969). The aragonite deposits constitute an important economic resource for the Government of the Bahamas which is receiving royalty revenue from aragonite production. A 200-acre island has been dredged about 30 kilometers south of Bimini as a base of operations for a privately owned mining company which will ship the aragonite to processing plants on the east coast of the United States.

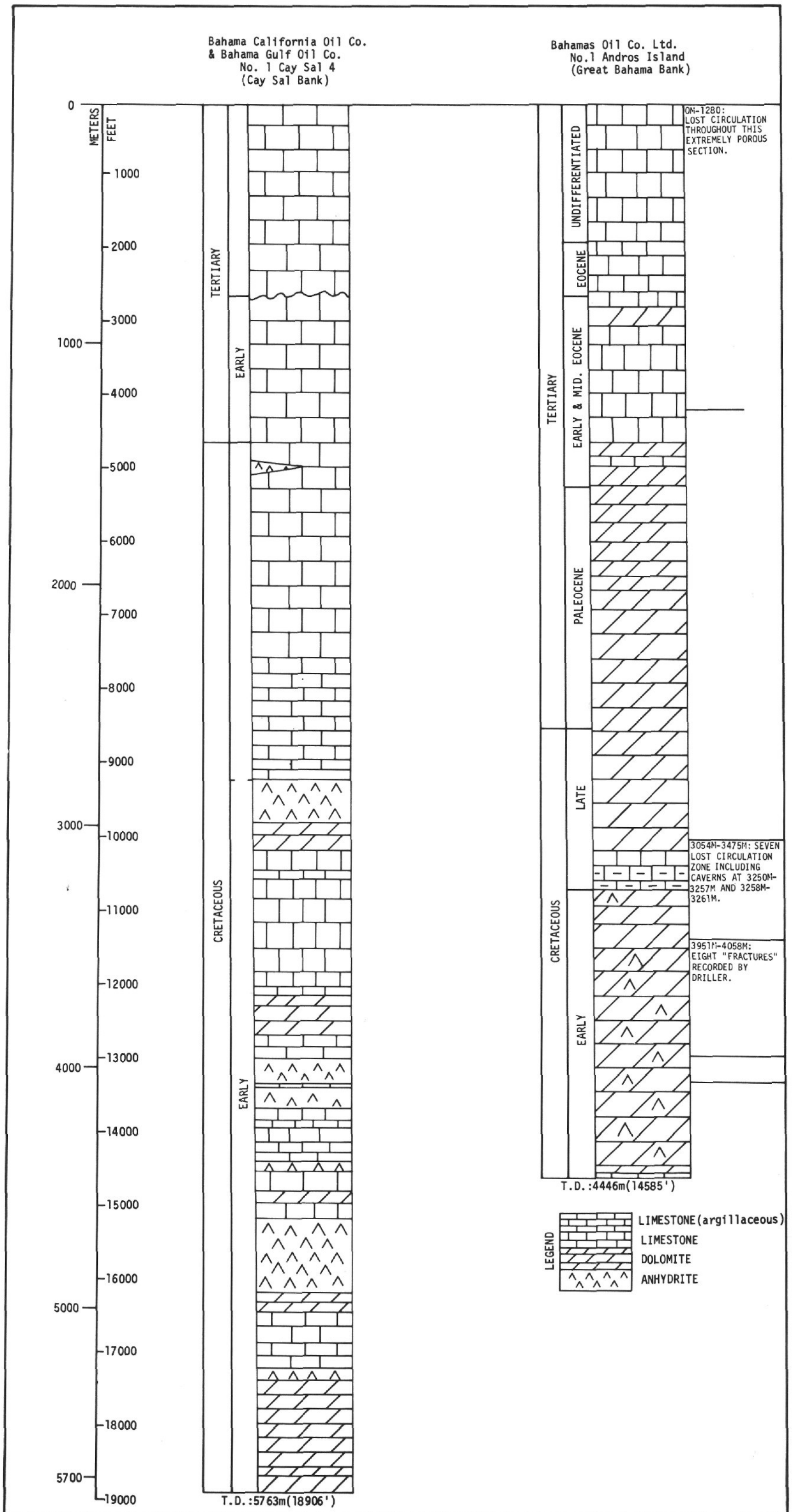

Figure 3. *Generalized lithologic logs for the deep bore holes on Cay Sal Bank and Andros Island. Adapted from Figure 89 in* Geologiá de Cuba *(Furrazola-Bermúdez* et al., *1964). Ages mainly from other sources (Rainwater, in press; Spencer, 1967). Khudoley (1967) considers the Cay Sal well to have possibly bottomed in uppermost Jurassic carbonates.*

TABLE 1
Bore Holes in the Northern Bahamas

Well Name	Location	Alt.	Total Depth[a] (ft/m)	Oldest Rocks Reported	Notes
Bahama California Oil Co. & Bahama Gulf Oil Co. No. 1 Cay Sal 4	Lat 23°49′24″N Long 80°12′24″W.; Cay Sal Bank	?	(18906) 5763	Lower Cretaceous	P & A early 1959. Reference: (1), (3), (5), (10).
Bahamas Oil Co., Ltd. No. 1 Andros Island	Lat 24°52′37.2″N Long 78°01′54.7″W; Stafford Creek, Andros Island	(20 ft) 6m	(14585) 4446	Lower Cretaceous	Electric log from 1982m (6503 ft) to 3252m (10670 ft); P&A 4-27-47. Reference: (3), (4), (8).
Harrisville Co. No. 2 Eleuthera Island	Lat 25°20′45″N Long 76°28′30″W; Eleuthera Island	(123 ft) 37m	(730) 222.5	Miocene (?)	No electric log available Tested salt water at 61m (200 ft)–149m (490 ft) in Miocene. Water level in hole is 37m (123 ft) below surface. Reference: (6).
International Expedition No. 1 New Providence Island	Lat 25°00′53″N Long 77°22′01″W; South of Nassau, New Providence Island	(6 ft) 0.6m	(395) 120	Miocene	No electric log; drilled in 1932. Pleistocene-Miocene contact at 44m (145 ft). Reference: (2), (4), (7).
Girdler Foundation & Exploration Company No. 1 San Salvador Island	Lat 24°06.9′N Long 74°29.2′W; north tip San Salvador Island	(9 ft) 3m	(550) 168	Pliocene	No electric log; drilled in 1967. Continuously cored to total depth. Reference: (9)
Deep Sea Drilling Project No. 98 NE Providence Channel	Lat 25°23′N Long 77°18.7′W; north of Nassau, New Providence Island	(33 ft) 10m	(10290) 3136	Upper Cretaceous; Campanian	No electric log. Water depth: 2769m (9086 ft). Spud date: 4-10-70. P & A 4-11-70.
Bahama Gulf Oil Co. & Bahama California Oil Co. No. 1 Long Island	Lat 23°00′N Long 74°50′W; offshore SE tip of Long Island	?	(17555) 5351		Water depth: about 15m (50 ft). Spud date: 7-14-70. P & A late October 1970.
Bahama California Oil Co. No. 1 Great Isaac	Lat 26°00′N Long 79°10′W; north end of Great Bahama Bank.	?	(17847) 5440		Water depth: ? Spud date: about 11-9-70. P & A April 1971

[a]Approximate (feet) meters taken from drilling records.

Note: References (1) Chen, 1965. (2) Field and Hess, 1933. (3) Furrazola-Bermúdez *et al.*, 1964. (4) Goodell and Garman, 1969. (5) Khudoley, 1967. (6) Maher, 1967, p. 233. (7) Newell and Rigby, 1957. (8) Spencer, 1967. (9) Supko, 1970. (10) Wassal and Dalton, 1959.

DOLOMITIZATION OF BAHAMA SEDIMENTS

The lithification and early diagenesis of Bahamian carbonate sands and muds are discussed by Beales (1965), Kahle (1965), Friedman (1964), and most recently by Supko (1970). There is general agreement that limestone diagenesis is enhanced by exposure to subaerial conditions. Supko (1970) emphasizes the importance of eustatic changes in sea level as a means of exposing subsurface rocks alternately to the vadose, phreatic, normal marine and hypersaline environments which in turn control the diagenesis and dolomitization of the carbonate sediments. According to Supko the Bahamian dolomites were formed by the reaction between pre-existing carbonate sediments and hypersaline brines rich in magnesium. The stratal dolomites, which are finely crystalline, generally thin and often bedded, are the result of the reaction between the supratidal facies and upward moving hypersaline magnesium-rich sea water. The massive dolomites, consisting of secondarily replaced limestones of subtidal facies, were formed by downward seepage refluxion of the brines. Bub and Atwood (1967) concluded that the cay rock samples collected from beneath the town salina on Great Inagua Island were dolomitized by downward seepage refluxion of hypersaline brines. Referring to the work of Bub and Atwood, Supko (1970, p. 150) concluded that:

> . . . The existence of such a geochemical engine operating in the Bahamas today makes it plausible to suggest the same mechanism to have dolomitized large sections of the rock columns of San Salvador, Andros, Grand Bahama, and doubtless other Bahamian islands in the past.

Dolomitization has occurred in at least 75 percent of the rock column of the Andros well (Goodell and Garman, 1969, p. 528), and is responsible for obliterating most of the fossil record. Table 2 list depths at which dolomite first occurs in some bore holes of the northern Bahamas. The rock is all limestone above these depths. All rock types were deposited in shallow subtropical waters similar to those covering the Bahama banks today. The dolomites in these holes are primarily of the massive type which Supko (1970) interprets as having been formed by downward seepage refluxion.

The depositional environments and modes of dolomite genesis represented by the rocks in the Bahamian bore holes show that the deposition of calcareous sediments was at such a rate as to be able to maintain the surface of the banks at or near sea level during the entire 5 kilometers of subsidence which has occurred in the Bahamas since early Cretaceous time. Lithologic and paleontological details for the bore holes on Grand Bahama, New Providence, and San Salvador Islands are thoroughly reviewed by Supko (1970). His rock-type log for the San Salvador well contains an excellent display of these details.

TABLE 2
Depths to First Occurrence of Dolomite in Bahamian Bore Holes

Location[a]	Depth to First Dolomite (Supko, 1970)
Andros Island	121+ meters
Grand Bahama Island	26 meters; 29 meters
New Providence Island	44 meters
San Salvador Island	34 meters

[a]Andros, New Providence, and San Salvador samples were taken from the bore holes shown in Figure 1. Grand Bahama samples were from hotel foundation test holes in Freeport.

SUBSURFACE GEOLOGY OF THE BAHAMA BANKS

Bahamian Basement and Early Mesozoic Sediments

The reader must refer to Dietz *et al.* (1970) and Uchupi *et al.* (1971) for complete discussions on the origin of the Bahamian basement and the mechanism for bringing the surface to a near sea level condition for the accumulation of shallow water Bahamian carbonates. The two discussions differ principally in that the Dietz group would have the entire Bahamian carbonate platform built upon a thick prism of early Mesozoic clastic sediments, whereas, the Uchupi group would have only the northern Bahamas formed in this manner with the southern Bahamas consisting of 5 to 10 kilometers of post-Triassic carbonates resting directly upon oceanic crust.

Briefly stated, Dietz and his colleagues propose: (1) that the crust beneath the Bahama Platform is an oceanic one formed during an early stage of continental rifting, (2) that this initial rifting formed a small ocean basin which became filled with Triassic and early Jurassic clastics, thus elevating the depositional surface to a near sea level condition, and (3) that upon renewal of rifting, the clastic prism remained attached to the North American continent while continued rifting opened the Atlantic so as to allow the circulation of the open ocean to supply the Bahama area with calcium carbonate-rich waters which permitted carbonate buildup to keep pace with the subsidence of the Bahama region.

The Dietz group proposes the name Bahama Cryptobasin for the hidden Mesozoic section of clastic rocks which they believe are most likely Triassic in age with some early Jurassic. They relate the postulated clastic sequence to the San Cayetano Formation of northwestern Cuba. All data pertinent to the age and thickness of this formation were carefully reviewed by Meyerhoff (1964), who concluded that the San Cayetano spans the middle Jurassic and is probably as much as 3048 meters in thickness. Other estimates of thickness range up to 5000 meters (Bryant *et al.*, 1969; Hatten and Meyerhoff, 1970). The recovery by Fox *et al.* (1970) of a shallow-water type of consolidated calcareous sandstone of late Jurassic age from outcrops at the abyssal margin of the South Atlantic (east of Amazon delta) not only lends support to the Bahama Cryptobasin concept but would also suggest a slight upward extension of the age limit which the Dietz group proposed for the Cryptobasin clastics.

Jurassic evaporites may also be present in the Bahama Cryptobasin. Meyerhoff (1964) noted the age of the very thick Punta Alegra salt beds of northern Cuba as being Jurassic in age with a possibility that they may be as old as Triassic. The thickness of the Punta Alegra Formation has been reported as being on the order of 2000 to 5000 meters (Meyerhoff and Hatten, 1968, p. 323). It is possible that the Jurassic salt of Cuba could be continuous with or at least the stratigraphic equivalent of the salt beds which are believed to be underlying the northern Bahamas as inferred by the probable salt domes along the axis of Exuma Sound (Ball *et al.*, 1968a).

Sheridan (1971) has presented an interesting and informative appraisal of the proposals made by the Dietz group. A particularly interesting feature of this paper is the subsurface geologic map for the reconstructed North American and African continents in the Blake-Bahama area. The paper also updates the work of the Dietz group in the light of both the JOIDES drilling during Leg 11 and the recovery of faulted limestone blocks from the Blake Escarpment by Sheridan, *et al.* (1970; 1971).

As stated earlier, the Uchupi group concurs with the Dietz group on the origin of the northern Bahamas but would propose a different mode of origin for the southern Bahamas. Briefly stated, the Uchupi group use their seismic, magnetic, and gravity measurements as the basis for their proposal that the southern Bahama Escarpment overlies a buried ridge of oceanic basement which developed along a fracture zone generated during continental rifting. Uchupi *et al.* (1971, p. 702) visualize that as:

> . . . the continents began to move apart during the Middle Jurassic (Ewing *et al.*, 1970; Dickson *et al.*, 1968) this fracture zone was at first very shallow and carbonate sediments were able to accumulate on it. The surface of the fracture zone probably was very irregular and was marked by ridges trending northwest and southeast. The most prominent of these ridges is beneath the present Bahama Escarpment, which delineates an ancient transform fault, and the banks themselves are along subsidiary ridges.

Since the above brief statements cannot do justice to the well prepared arguments of both the Dietz group and the Uchupi group, the reader is again urged to review the original texts of these authors.

Late Mesozoic Sediments

The Bahama Platform has been the site of calcium carbonate deposition since at least early Cretaceous time as shown by the shallow water limestone-dolomite sequence in the deep borings on Andros Island and Cay Sal Bank. Lithologic logs of the Cay Sal and Andros wells appear in Figure 3. Sample descriptions have been published by Spencer (1967) and Goodell and Garman (1969). After examining the cuttings and making thin section studies, Goodell and Garman concluded that the rocks in the Andros well before dolomitization were, for the most part, pelmicrites and biopelmicrites derived from aragonite-pellet mud such as now accumulates on the Great Bahama Bank. They report that exceptions to the pellet mud lithology include: (1) coralgal sand near the top of the well, (2) pelsparite; depth not given—a single instance of high energy deposition, and (3) only one lithologic type (224 to 228 meters) which could possibly suggest proximity to a reef environment. They found no sediments which were originally of the oolite or grapestone type or which were of biohermal origin. Therefore, according to Goodell and Garman, the Andros well did not penetrate a reef section in either the Cretaceous or Tertiary formations. E. H. Rainwater (personal communication) has also reported the absence of a reef lithology in the samples examined by him at the Florida Geological Survey. Spencer (1967), however, infers that the Andros well penetrated a reef section. On the basis of the descriptions contained in the reference it would have to be assumed that Spencer was referring to the samples from the Tertiary interval at 12 to 495 meters that she described (pp.263-264) as limestone which ". . . probably represents limestone reef similar in origin to present day reefs in this area."

The top of the Cretaceous in the Andros well occurs at about 2591 meters (Rainwater, in press) or at 2670 meters according to Spencer (1967). Both authors pick the top of the early Cretaceous at about 3231 to 3261 meters. Spencer (1967), on the basis of thin dried coatings of bituminous matter, suggested that the Sunniland oil production zone of South Florida may occur at 3962 to 4115 meters. The bitumen, however, occurs elsewhere in the early Cretaceous section of the Andros well and should not be considered diagnostic (Rainwater, personal communication). Rainwater is of the opinion that the well stopped in beds which are slightly younger than the Sunniland zone (personal communication). Because the Sunniland zone has been placed at the base of the late Trinity (Applin and Applin, 1965) and because the late Trinity is the approximate equivalent of the early Albian (Imlay, 1944); the Andros well is considered by the writer to have stopped just above the base of the Albian.

The early Cretaceous section of the Cay Sal well contains, in addition to the shallow water carbonates, an abundance of anhydrite beds (Figure 3) (Khudoley, 1967). The beds are approximately correlative with the anhydrites which characterize the early Cretaceous section of South Florida. The anhydrites of South Florida and Cay Sal represent a major evaporite province which extends throughout the well known South Florida Basin and its southerly extension along the north coast of Cuba. This basinal trend was recently named the South Florida-North Cuba Basin by Paine and Meyerhoff (1970). In South Florida, massive anhydrite beds (Punta Gorda Formation) mark the top of the early Trinity (Applin and Applin, 1965). The absence of the massive Punta Gorda anhydrite beds in the Andros Island well may simply be due to an insufficient drilling depth since that well failed to reach the early Trinity (Rainwater, personal communication).

Cyclic carbonate-anhydrite deposition continued in South Florida until the end of early Cretaceous time (Oglesby, 1965). (The Paleocene series contains the only recurrence of anhydrite deposition in South Florida.) The top of the lower Cretaceous section for the Cay Sal well in Figure 3 is based on the postulation that the youngest beds of anhydrite appearing on the lithologic log of the well are correlative with the uppermost deposit of early Cretaceous anhydrite in South Florida.

Cretaceous rocks beneath Andros Island are cavernous as evidenced by the seven lost-circulation zones recorded during the drilling of the Andros Island well. These zones occurred within a 421-meter interval which includes the early-late Cretaceous boundary (Figure 3). Two caverns were found in this interval: a 7-meter void topped at 3250 meters and a 3-meter void topped at 3258 meters. Eight additional "fractures" were recorded by the drillers between 3951 and 4058 meters. The two caverns occur at the top of the early Cretaceous rocks and suggest an extended period of subaerial exposure for these rocks prior to the deposition of late Cretaceous sediments. Shorter periods of subaerial exposure apparently occurred in late Cretaceous time, as indicated by the subaerial diagenesis which has been described by E. G. Purdy in his following personal communication regarding some vugular late Cretaceous limestone recovered at Site 98. His remarks are based on an examination of a relatively large sample from Core 15.

1. The limestone is a calcite cemented skeletal grainstone in which mollusc fragments predominate among the *identifiable* constituents. Judging from the hand specimen, many of these are probably gastropod remains. Fragments of corals, calcareous algae, and echinoderms are also in evidence. There appears to be *one* good example of *Solenopora* in the thin section and another more problematic example of a Codiacean fragment. I also noted a possible rudist fragment.

2. Micrite envelopes serve to identify the periphery of many of the constituents that are so severely recrystallized (sensu lateralis) to calcite that their depositional identity is in doubt. Similar "dust lines" mark the walls of completely recrystallized coral fragments. Many of the smaller constituents are completely "micritized" and once again identification is doubtful. There is some difference of opinion in the literature on the origin of micrite envelopes and micritization, but there does seem to be ample justification for regarding both as a submarine diagenetic phenomenon.

3. Skeletal architecture is preserved best in the mollusc fragments and least in the coral and algal fragments. I hasten to add here that I have not x-rayed the sample, but I have little doubt that *all* the constituent grains have recrystallized to calcite, and that the observed differences in preservation of skeletal architecture are best attributed to original differences in crystal fabric and mineralogy.

4. In addition to recrystallization attributes, pore space precipitation and leaching effects are also in evidence. The last is made obvious by the molds of corals and gastropods, among other things, that are apparent in the hand specimen. Dissolution effects are also manifested in thin section, and not infrequently one can observe calcite crystals growing into the voids left by solution. The intimate textural relationship between intergranular calcite cement on the one hand and calcite replaced constituents on the other suggests that both events occurred at essentially the same time. In contrast, leaching, at least in some instances, seems to have been a post-replacement phenomenon. This, of course, does not rule out the possibility that leaching, replacement, and pore space precipitation all occurred in the same diagenetic environment: the subaerial one. Indeed, regarding this last point, it is my distinct impression that the diagenetic fabric of this particular rock is no

different than that of many of the Pleistocene limestones that I have seen in the Caribbean area. This being the case, I would favor a tentative conclusion that we are dealing here with a shallow water limestone that has been subjected to subaerial diagenesis.

The shallow-water limestone occurs in the top 5 centimeters of Core 13 at a sub-sea-floor depth of 278 meters and in the top 15 centimeters of Core 15 at a sub-sea-floor depth of 356 meters. Calcareous oozes and chalks intercalated with the limestones are Campanian in age as indicated by foraminifera. The limestone in both cores contains an abundance of macrofossil molds and fragments. All of the limestone samples from Cores 13 and 15 have been examined by Bob F. Perkins. The following observations are from his report (personal communication).

The macrofossils in the Site 98 core samples are preserved as fragments and molds of fragments. All of the samples contained: (1) fragments of calcareous algae, corals, gastropods, bivalves, and echinoderms, and (2) molds of fragments of calcareous algae, corals (scleractinian), gastropods, and bivalves. Due to the poor preservation and fragmentary nature of the fossils none could be identified as to taxonomic level.

Fragments of radiolitid and hippuritid(?) type rudists were found in Cores 13 and 15. Core 15 also contained fragments of the caprinid(?) type rudist. The rudist fragments are far too small and poorly preserved to be positively identified. Whereas the radiolitids and caprinids ranged throughout the Cretaceous, the hippuritids were more restricted and would indicate a Turonian through Maestrichtian age for the samples.

The abundance of coral and algal fragments and the fragments of reef-building rudists in the lime grainstone may indicate a nearby reef and the samples may be interpreted as perireef grainstones. None of the organisms were confined strictly to reef environments, but all are clearly very shallow water types. Although the perireef origin of the rocks may be challenged in the absence of more information, the shallow water origin of the organisms seems to be a reasonable interpretation.

The recovery of perireef limestone infers the existence of Cretaceous reefs. It is proposed that these inferred reefs are not only the ancestral counterparts of, but are also foundational to, and continuous with, overlying Tertiary reefs described by Newell (1955) and again by Newell and Rigby (1957) as forming the steep and even cliff-like upper parts of the marginal escarpments which surround each of the Bahamian carbonate platforms. The perireef limestone from Site 98 is the only known tangible evidence which could be used to infer the existence of true reef rock of Cretaceous age within the bank structures of the Bahamas.

Cenozoic Sediments

This section deals primarily with the Tertiary rocks, since the Pleistocene and Holocene sediments have already been discussed in the sections on surface geology and lagoon sediments. The Pleistocene-Tertiary contact in the Bahamas has not yet been identified with any great degree of certainty. Newell and Rigby (1957) postulated a Pleistocene age for the first 12 meters of sediments in shot holes near the Andros well. According to Newell and Rigby there is an abrupt change in the lithology of the shot hole cuttings at a depth of 12 meters from porous, white, oolitic limestone of Pleistocene(?) age to an underlying light gray, hard limestone of undetermined age.

The top of the Tertiary in the New Providence Island bore hole is described in Newell and Rigby (1957) as occurring at a depth of 44 meters which marks both a faunal change and a change from very pure limestone above to dolomite below. They reported the lithologic boundary as the Pleistocene-Miocene contact. They also reported that none of the sediment from the hole was typical reef rock, but was more of a lagoonal deposit which was associated with coral reefs.

The upper limit of the Tertiary on Eleuthera Island is reportedly somewhere above 61 meters according to data presented in a well summary sheet published by Maher (1967, p. 233). This data, which is included in Table 1 of this report, indicates a Miocene age from at least 61 meters to the total depth of 226 meters.

The Pleistocene-Tertiary contact in the San Salvador bore hole remains in doubt even after Supko's (1970) thorough analysis of all available data. He did conclude, however, that at total depth (168 meters), the well bottomed in rock probably as old as Pliocene which would give it an absolute age of a few to 10 million years. He suggested that the Holocene-Pleistocene contact may be represented by either the change from calcareous sands to firm coquina-rich limestone at about 7 meters, or by the inferred soil zone at 18 meters. The dominant rock type in the 168-meter San Salvador hole is a grain-supported biointrasparite (Supko, 1970).

None of the bore holes appears to have encountered typical reef rock. The only known report of a reef lithology in the samples from the bore holes on the Bahama banks was made by Spencer (1967) for an interval in the Andros well at 12-495 meters. A portion of the description for this interval was quoted earlier; however, as stated earlier, neither Rainwater nor Goodell and Garman found in their studies of the

Andros well samples any lithologies which they would consider indicative of true reef rock.

The Tertiary carbonates beneath Andros Island are extremely porous as shown by the almost continuous loss of circulation during the drilling of the upper 1280 meters of the Andros well. The lower 610 meters of this zone are in Eocene beds. These beds are the stratigraphic equivalent of the Floridian Aquifer of South Florida. The cavernous nature of the Floridian Aquifer is well-documented in the South Florida drilling records, some of which include downhole photographs of the caverns (Kohout, 1967).

The numerous sink holes which pock mark the surfaces of the larger islands in the Bahamas are further testimony to the cavernous nature of the shallow carbonate section. Many of these holes have links not only with each other but also with the sea. Water levels in the fresh water sinks near the sea have been observed to rise and fall with the tides (Newell and Rigby, 1957).

Submerged sink holes, known as Blue Holes by the local islanders, are a common feature throughout the shallow water bank areas. Agassiz (1894) mapped several Blue Holes at the south end of the Tongue of the Ocean. More recent mapping by Benjamin (1970) shows thirty-eight Blue Holes pinpointed along the eastern shore of Andros Island. Benjamin has charted several hundred possible Blue Hole locations on Great Bahama Bank and has explored 54 of these, some of which reach depths of more than 61 meters. The deepest yet explored is about 70 meters. Benjamin's report is accompanied by numerous spectacular color photographs of the physiography and biological content of these underwater limestone caverns.

The Blue Holes, like their landside counterparts, also have some type of connection with large sea water reservoirs as evidenced by the strong reversing currents associated with many of them. The "exhaling" cycle is characterized by an outpouring of water which causes the surface of the lagoon to "boil" with swirling currents and breaking wavelets. The "inhaling" or reverse cycle develops a downward sucking whirlpool of great force (Benjamin, 1970). Benjamin and his diving partners have also explored the face of the marginal escarpment in more than 200 dives, some as deep as 91 meters, in an attempt to discover cavernous tunnels which might connect the open waters of the Tongue of the Ocean with the submerged sink holes in the shallow windward lagoon of Andros Island. He reports that no large connections have been found, but that several "blind" caves might well be the stopped up mouths of old tunnels.

Blue Holes have also been noted in the southern Bahamas in the Bight of Acklins Island (Doran, 1955). Doran likened these holes to the sink holes on the islands of Acklins, Crooked, North Caicos, and Grand Caicos. He also reported that the water levels in these sinks vary (as do those described by Newell and Rigby, 1957, for the northern Bahamas) with the ebb and flood of the tides. Doran (1955, p.11) concluded that:

> The appearance of the (Blue) holes is much like that of limestone sinks on land and does not contradict the usual theory of formation by subaerial corrosion during the time of lowered Pleistocene seas.

Assuming the top of the Tertiary to be somewhere between 12 meters (Andros well) and 44 meters (New Providence well) it is apparent that karst topography of the Bahama banks must extend downward into the Tertiary carbonates for at least as much as 26 meters (note reference to Benjamin's deepest Blue Hole exploration of 70 meters).

GEOLOGY OF THE BAHAMA CHANNELS

In sharp contrast to the high depositional rate on the banks is the slow pelagic sedimentation in the deep broad troughs, or channels, which subdivide the Bahama Platform into irregularly shaped carbonate banks, the most westerly of which is Cay Sal Bank. Cay Sal is separated from the largest of the banks (Great Bahama Bank) by the 915-meter deep Santaren Channel. The second largest bank (Little Bahama Bank) is separated from Great Bahama Bank by the Northwest Providence Channel. Incised into the eastern portion of Great Bahama Bank is the 1829-meter deep Exuma Sound. The central part of the Great Bahama Bank is cut by the equally deep Tongue of the Ocean trough. Detailed profiling of the walls of the Tongue of the Ocean has been described by Rusnak and Nesteroff (1964). They report a smooth steep slope of up to 35 and 40 degrees for the upper 183 meters, while below about 183 meters to 274 meters the slope decreases slightly and the walls become exceedingly rough with prominences of 37 to 74 meters relief.

The sediments in the Tongue of the Ocean have been studied by several authors (Athearn, 1962; Busby, 1962; Rusnak and Nesteroff, 1964; Pilkey and Rucker, 1966; Gibson and Schlee, 1967; Andrews *et al.,* 1970). Rocks obtained by Gibson and Schlee from the wall of the Tongue of the Ocean near New Providence Island range in age from Miocene to Holocene and contain pelagic faunas indicative of deep-water deposition. Also recovered during the dives were samples of indurated slump material intercalated with the deep-water formations.

Coring at Site 98 not only corroborated the findings of Gibson and Schlee but also extended the known period of deep-water deposition back into the late Cretaceous (earliest Campanian). The coring recovered sediments from portions of each of the Tertiary epochs and from the Campanian stage of the Cretaceous. Maestrichtian sediments are assumed to be present in the 31-meter drilled interval between Core 12 (late Paleocene) and Core 13 (late Campanian). The bottom of Core 15, according to foraminifera, is in the Campanian-Santonian transition zone. The Site 98 core hole shall therefore be considered to have bottomed at the base of the Campanian. All of the sediments recovered at Site 98 (34 per cent of the 357-meter hole) are of the deep-water type being principally foraminiferal-nannoplankton oozes and chalks. Thin cherty layers of early Eocene age are the only exception to the carbonate lithology. Petrographic and paleontological details are found in the report for Site 98 (this volume). Bernoulli (this volume) presents petrographic and environmental analyses of the Site 98 Cretaceous sediments and their analogues from the Cretaceous of Europe. As mentioned earlier, Cores 13 and 15 contain—in addition to the deep water oozes and chalks—several centimeters of vugular, calcite-cemented, shallow-water, skeletal grainstone which appear to have been deposited in a perireef environment and to have undergone subaerial diagenesis. These perireef limestones appear strikingly similar to the Cretaceous turbidites in the Monte Sant'Angelo limestone of southern Italy (Bernoulli, this volume, especially Plates 12, 13 and 14). It is assumed that the perireef limestones recovered at Site 98 represent material which was removed from the shallow-water environment of the carbonate banks either by wave action or slumping and then deposited by turbidity currents as bioclastic turbidites in a mid-channel deep-water environment. This slump material could be considered as the Cretaceous analogue of Gibson and Schlee's Tertiary slump samples from the east wall of the Tongue of the Ocean.

Rusnak and Nesteroff (1964) described several bioclastic turbidites recovered in their piston and gravity cores from throughout the Tongue of the Ocean, including localities a few kilometers to the southwest of Site 98. Their survey indicated that 70 to 90 per cent of the modern sediments were laid down by turbidity currents. They noted that the bioclastic turbidites generally had (1) obscure basal contacts, (2) poor sorting, (3) poorly developed grading, and (4) no cross-bedding. Their analysis of sediment sources for the turbidity flows showed that fine carbonate silts and clays were washed into the basin continously whereas the carbonate sands and silts spilled down the slopes and onto the basin floor only intermittently. They concluded that the process of basin filling occurs in two ways: (1) removal of sediments from the shallow water bank areas to a temporary position on the deep water slopes, and (2) removal of the slope deposits to the basin floor through a combination of slumping and turbidity flows.

As stated earlier, bioclastic turbidites containing vugular perireef limestone were recovered at Site 98 in Cores 13 and 15. Finer grained bioclastic turbidites were observed in Core 14 which contained at least three fine-grained beds consisting dominantly of calcite grains with very abundant foraminifera. Coarse-grained calcarenites of turbidity-flow origin and consisting almost entirely of shell debris were found in the core catchers of Cores 13 and 14 and throughout the lower portion of Core 15. It is possible that other turbidites have escaped detection owing to both their obscure contacts and to coring disturbances. The coarse, vugular, shallow-water, perireef limestone found at the top of Core 13 and again at the top of Core 15 is underlain by soft, white, foraminiferal-nannoplankton ooze and firm, white, nannoplankton chalk, respectively. This evidence suggests that limestone of shallow-water origin was washed over the bank edge and carried in a turbidity current of such velocity as to be able to move the coarse material over a relatively long distance to a deep water environment near the axis of Northeast Providence Channel. Rusnak and Nesteroff in their study of the modern sediments found no evidence of turbidity currents originating on the bank edge and carrying far out onto the basin floor; however, they recognized that one could not rule out this possibility.

Free fall cores and a few box cores from the deep Bahama channels were recently described by Andrews *et al.* (1970). Cores taken at axial positions in the channels contain gravel-sized fragments of coral and shells, in addition to the deep water pelagic sediments and coarse, graded turbidites. Andrews and his colleagues concluded that the large fragments probably came directly downslope from the banks and had to travel at least 19 kilometers to reach the channel axis. This coarse material is apparently a modern day analogue of the perireef limestone found in Cores 13 and 15 at Site 98.

The graded bioclastic turbidites in Core 14 are 3 to 4 centimeters thick. The intervening beds of pelagic micritic chalk are 10 to 15 centimeters in thickness. Using a rate of deposition for the middle Eocene – Campanian section at Site 98 of about 0.7 cm/1000 yrs, one may arrive at a turbidity flow frequency in Core 14 of one in every 14,000 to 21,000 years. Rusnak and Nesteroff, using depositional rates of 1 to 3 cm/1000 yrs, found flow rates of one every 500 to 1000 years, depending on the location in the channel. Andrews *et al.* (1970) point out that the interval of 500 years represents the high incidence of local slumping near the steep walls whereas the 10,000-year interval has been lengthened beyond the actual rate by erosion of one or more flows in the measured interval. Fine-grained turbidites in the fan valley continuation of the Great Bahama Canyon system have flow frequencies based on carbon-14 dates of about one every 5000 years (Andrews, 1970).

ORIGIN OF THE BAHAMA CHANNELS

Explanations for the origin of the deep troughs in the Bahama Platform generally fall into three main categories: (1) differential rates of deposition (reef hypothesis), (2) graben faulting (graben hypothesis), and (3) submarine erosion (erosional hypothesis). Evidence in support of each hypothesis is summarized below.

Reef Hypothesis

According to the reef hypothesis the deep Bahama channels have long been the site of slow, pelagic deposition while the walls of the channels were the site of a more rapid rate of carbonate upbuilding. Hess (1933) was one of the first to propose that the Bahama banks were initiated by the rapid deposition of calcareous deposits on the higher prominences of a slowly subsiding ancient land surface. Newell (1955) was the first to describe the general characteristics of the Bahamian platforms as those of coral atolls with nearly filled lagoons. He points out that the marginal escarpment which is so characteristic of each of the Bahamian platforms closely resembles the upper steep slopes of typical coral atolls (Figure 4). He concludes on page 314:

> . . .there is no reason to doubt that coral-reef development flourished in the region during Tertiary time when the platforms must have been encircled by the retaining wall of a healthy coral-reef growth. . . .The combination of Pleistocene cooling and drop in sea level evidently brought about the local extermination of the coral reefs which only now are being established again. The platforms are envisioned as Tertiary coral atolls which have gradually spread laterally and coalesced with the North American continent. They are now mantled by a thin cover of Pleistocene oolite which masks their fundamental character.

The recovery of late Cretaceous perireef limestone at Site 98 not only lends support to Newell's conclusions but would also extend the reef period back to at least early Campanian time. Bahamian reefing is discussed at greater length in later sections where it is shown that evidence is mounting in favor of a differential rate of sediment accumulation as a prime factor in the history of Bahamian channel development.

Graben Hypothesis

The graben hypothesis receives support from: (1) a discussion of gravity anomalies beneath the channels (Talwani *et al.*, 1960; Ball *et al.*, 1968b), (2) the inferred fault scarp along the bank off Great Abaco Island (Andrews, 1970), (3) the recovery of faulted late Cretaceous limestone blocks from the northern end of the Bahama Escarpment (Sheridan *et al.*, 1970; 1971); and (4) the faulting noted on seismic profiles across the northerly flank of Old Bahama Channel to the northwest and southeast of Great Inagua Bank (Uchupi *et al.*, 1971).

The only evidence of faulting in the vicinity of the northern Bahamas consists of the faulted limestone blocks described by Sheridan *et al.* (1970; 1971). Although these blocks did not come from within the physiographic boundary of the Bahama Platform their proximity to the platform warrants their discussion here. The late Cretaceous limestone blocks were recovered in dredge hauls from the upper part of the Blake-Bahama Escarpment immediately south of Great Abaco Canyon. According to Sheridan *et al.* (1971) these rocks contain shear planes and well-developed slickensides as well as other definite lineations and grooving, and are the first conclusive evidence for faulting under high tectonic stress in the Blake-Bahama area. Sheridan *et al.* (1970; 1971) believe that the faulted limestones came from a transform fault zone which is approximately coincident with Great Abaco Canyon. They concluded that a northwest striking transform fault at this location is compatible with the fracture zones and other related phenomena associated with the concepts postulated for North Atlantic sea-floor spreading (Le Pichon, 1968; Taylor *et al.*, 1968).

The only reported faulting for the southern Bahamas is that described by Uchupi *et al.* (1971). The faulting was noted on seismic reflection profiles where they crossed the northerly flank of Old Bahama Channel to the northwest and southeast of Great Inagua Bank. The Uchupi group relates the faulting northwest of Great Inagua Bank to the Cuban middle Eocene orogeny, and that to the southeast of Great Inagua to the frictional movement between the Caribbean and North American tectonic plates.

Erosional Hypothesis

It was recently proposed by Andrews *et al.* (1970) that submarine erosion has been, and still is, a prime factor in the development of the deep Bahamian troughs. The Andrews team noted that V-shaped valleys with winding courses have been incised into the broad-floored Bahamian troughs. The authors present a picture of a large valley system which they name the Great Bahama Canyon with two major branches: the Northwest Branch (Northwest Providence Channel) and the Tongue Branch (Tongue of the Ocean) (Figure 5). These two branches join northwest of New Providence Island (not too distant from Site 98) and continue

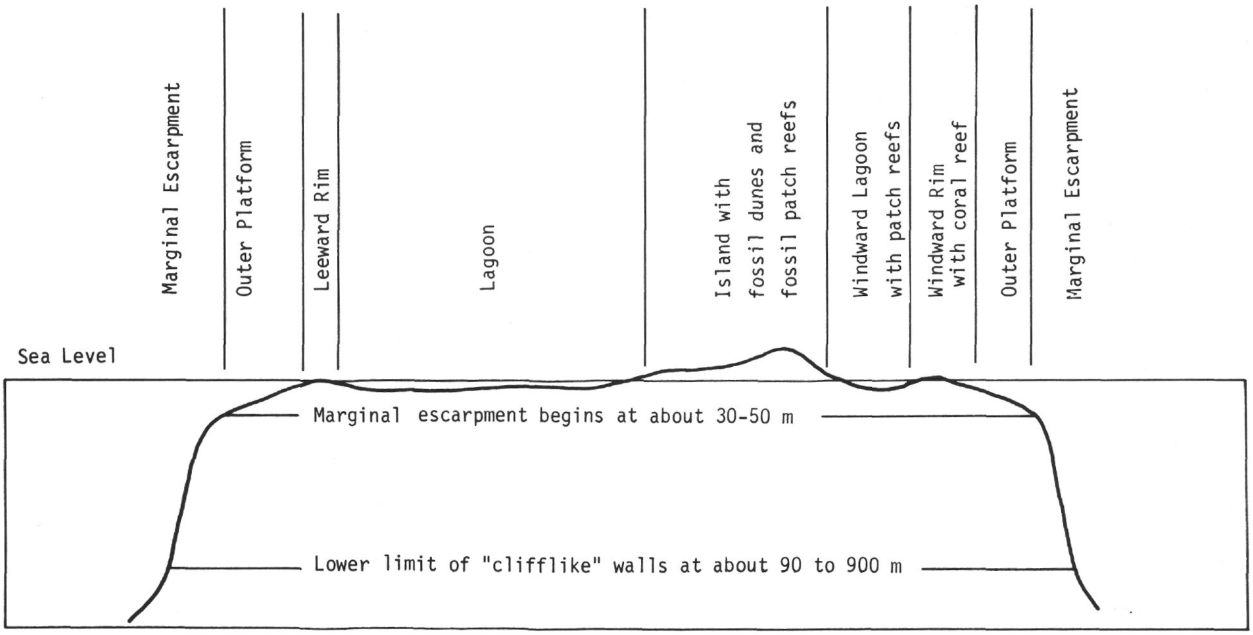

Figure 4. *Typical profile across a Bahamian platform. Diagrammatic and not to scale. Adapted from Newell (1955).*

seaward as a submarine canyon with walls almost 5 kilometers high. The canyon terminates in the Bahama Outer Channel which is a fan valley running between Abaco and Eleuthera Islands. The fan valley, 64 kilometers in length, has been described as the final pathway for the large volume of sediment leaving the Bahama banks in the form of turbidity currents (Andrews, 1970).

Bottom photographs and box cores recovered from throughout the Great Bahama Canyon by Andrews and his co-workers show that strong currents are transporting sand-sized material down the canyons and that active erosion is taking place as indicated by the abundant rounded cobbles along the canyon floors and steep rock walls. They also recorded seismic profiles which show that the valleys at the head of Northwest Providence Channel are cut through older formations. They noted grooves in the sides of the canyons which suggested erosion by sediment-laden currents. They also present other arguments to show that erosional processes have been operating in the canyons for a long period of time. After noting the winding course of the V-shaped valleys, the truncated layers, and all of the other erosional evidence which was documented during their survey, Andrews and his colleagues concluded that the history of the Great Bahama Canyon has been one of upbuilding on the walls while the valleys were preserved by submarine erosion and sediment transport.

The erosional hypothesis receives support from evidence contained in cores recovered at Site 98 and at a piston core site about 30 kilometers southwest of Site 98. Erosion at Site 98 is indicated by the absence of late Pliocene and early Pleistocene sediments. This unconformity, overlain by late Pleistocene sediments, was found in the first core at a depth of 8 meters below the sea floor. Piston core evidence indicated a Pleistocene–middle Eocene unconformity (Stehman, 1970). The 6 meter piston core contained 3 meters of lower middle Eocene calcareous ooze overlain by 3 meters of Pleistocene ooze, which in itself contained several discontinuous sedimentary sequences.

The recovery at Site 98 of shallow-water perireef limestones intercalated with deep water late Cretaceous calcareous ooze and chalk suggests that slumping could have been an active erosional process in the late Cretaceous as it was in the Tertiary (Gibson and Schlee, 1967) and modern times (Andrews *et al.*, 1970).

Dietz *et al.* (1970) disavow that submarine erosion was a prime agent in the development of the Bahama channels, but would agree, as does the writer, with Newell (1955) and Hess (1960) that the Bahama banks are principally the product of rapid localized carbonate upbuilding with reef growth forming the containing walls for the accumulation of carbonate sediments in the lagoonal area while the channel floors were receiving deposits at the much slower rates of pelagic deposition. The relatively slow rate of pelagic deposition must have been an important factor in the development of the Bahama channels since core recovery at Site 98 consisted entirely of deep-water deposits. (The few centimeters of shallow-water limestone in Cores 13 and 15 are considered to be part of a

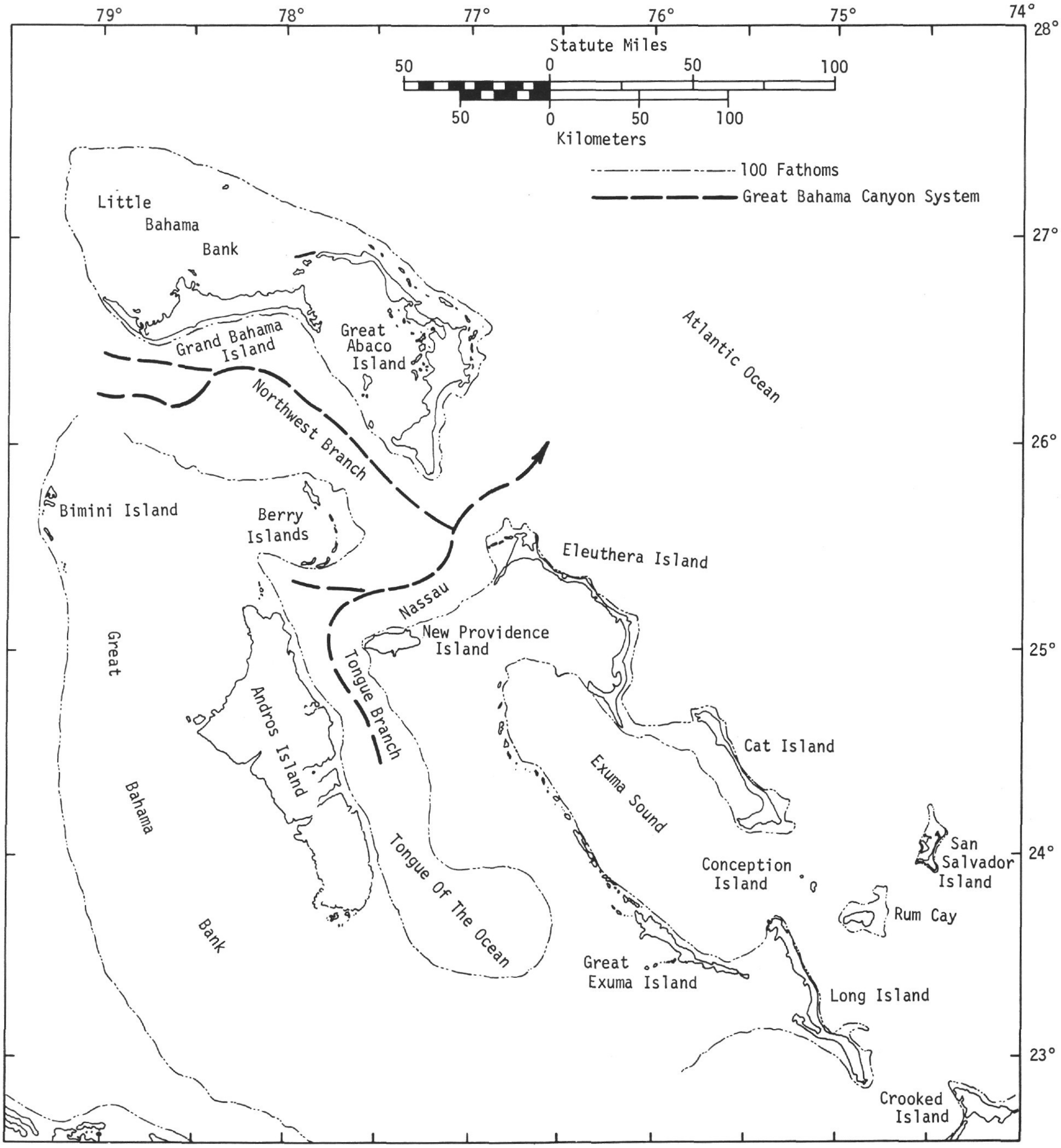

Figure 5. *Index map of the Great Bahama Canyon System showing the two major branches: Northwest Branch and Tongue Branch. Modified from Andrews* et al. *(1970).*

deep-water bioclastic turbidite sequence). There seems to be no doubt, however, that the rate of accumulation in the channels has been further reduced, at least in more recent geologic times, by strong down-canyon currents and submarine erosion.

BAHAMIAN REEF DEVELOPMENT

Age of Atoll Reefing

Although it has long been the consensus among some authors, including the writer, that the Bahama banks are principally the product of atoll-like reef buildup, it wasn't until the core-drilling at Site 98 that an age estimate could be determined for the beginning of the atoll-like reef growth on the Bahama Platform. It is postulated that the atoll reefing began at or shortly after the close of early Cretaceous time. The basis for this postulation is discussed in the following paragraphs.

Since it is believed that the stratigraphic sequence at Site 98 represents a complete section from the base of the Campanian through the lower Pliocene, and because five stratigraphic boundaries occur within the cored intervals, it is possible to calculate depositional rates for several parts of the geologic section at Site 98 using the geologic time values from the Geological Society Phanerozoic time-scale (1964) (Table 3) and the data listed in Table 4. The depositional rate for the interval from the base of the Campanian (bottom of Core 15) to the top of the middle Eocene was calculated to be 0.7 cm/1000 yrs. Using this rate and the time interval in Table 3 from the base of the Campanian to the base of the Cenomanian it is possible to calculate a sub-sea depth of 3294 meters for the top of the early Cretaceous at Site 98. This depth was plotted on the geological cross section for Site 98 (Figure 6).

Note that the projected top for the early Cretaceous at Site 98 is only 55 meters deeper than where the top of the early Cretaceous was encountered in the deep well on Andros Island. As stated earlier, the Andros well is believed to have stopped just above the base of the Albian. Using the pelagic rate of 0.7 cm/1000 yrs, the base of the Albian at Site 98 would be about 1100 meters higher than the corresponding stratigraphic horizon in the Andros well. Such a structural relationship is unrealistic since it is based on deep-water depositional rates for an area which would be considerably higher than the adjacent shallow-water bank deposits. It is therefore apparent that at Site 98 the pelagic rate is not applicable to sediments older than about earliest Cenomanian time. This would suggest that atoll-like reefing and deep channel development were not a major part of the Bahama Platform scene until the end of early Cretaceous time. This inference is depicted on the Site 98 cross section which shows the foundation of the atoll reefs to be an early Cretaceous carbonate platform consisting of patch reefs and shelf deposits. This concept receives support from seismic profiling evidence reported by Uchupi *et al.* (1971, p. 694). The cross section also shows that the major portion of vertical reef growth occurred during the Paleocene and Eocene. Vertical growth rates are listed in Table 5. The rates are based on the stratigraphic sequence in the Andros well (Figure 3). Although the sediments in the Andros well were laid down in a lagoonal environment it is assumed that deposition kept pace with the adjacent reef growth which acted as a container for the lagoonal deposits.

TABLE 3
Excerpt From Geological Society Phanerozoic Time-Scale, 1964

	Age of Base (m. y.)
QUATERNARY	
Pleistocene	1.5-2
TERTIARY	
Pliocene	7
Miocene	
Upper	12
Middle	18-19
Lower	26
Oligocene	
Upper	?
Middle	31-32
Lower	37-38
EOCENE	
Upper	45
Middle	49
Lower	53-54
PALEOCENE	
Upper	58.5
Lower	65
CRETACEOUS	
UPPER	
Maestrichtian	70
Campanian	76
Santonian	82
Coniacian	88
Turonian	94
Genomanian	100
LOWER	
Albian	106
Aptian	112
Barremian	118
Hauterivian	124
Valanginian	130
Ryazanian	136
JURASSIC	
UPPER	
Purbeckian	141
Portlandian	146
Kimmeridgian	151
Oxfordian	157
Callovian	162
MIDDLE	
Bathonian	167
Bajocian	172
LOWER	
Toarcian	178
Pliensbachian	183
Sinemurian	188
Hettangian	190-195

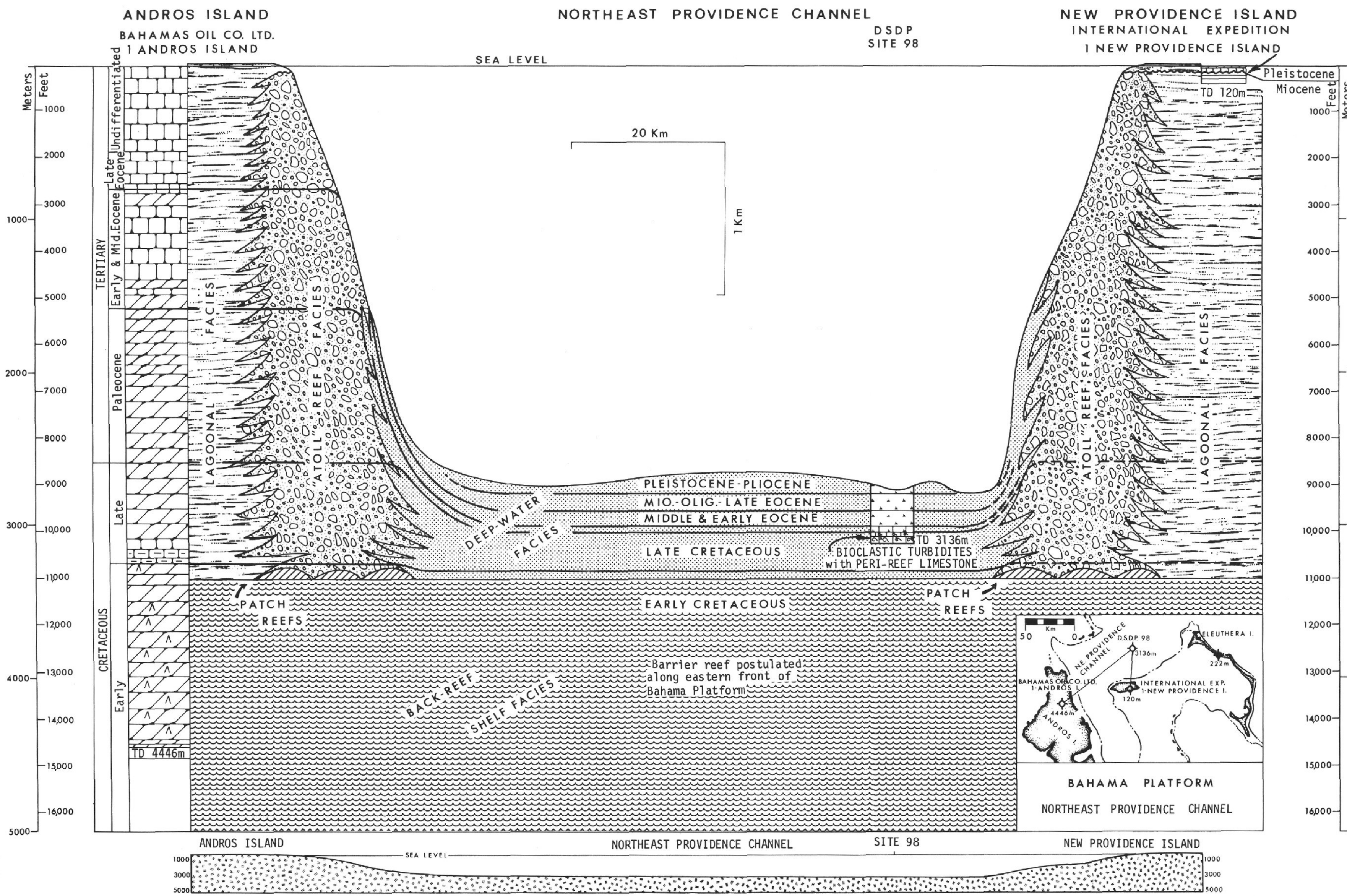

Figure 6. *This semi-diagrammatic cross section extends from the deep bore hole on Andros Island through DSDP, Site 98, to the shallow bore hole on New Providence Island. Vertical exaggeration is 20 to 1. The same section without exaggeration is shown at the bottom of the figure. Time lines have been extended from the Andros Island well into the core hole at Site 98. Early and late Cretaceous time lines are dashed where projected into the carbonate platform beneath New Providence Island. The depth to the early Cretaceous beneath Site 98 is based on a rate of deposition comparable to what was determined for the deep water facies found in the lower portion of the hole at Site 98. The nearly horizontal attitude of the early/late Cretaceous boundary is interpreted as suggesting the existence of an early Cretaceous shelf area which was foundational to the development of the Bahama banks in the late Cretaceous and Tertiary time.*

TABLE 4
Depths of the Stratigraphic Boundaries Cored at Site 98 as Indicated by Foraminifera

Stratigraphic Boundary	Sub-Sea Level (m)	Sub-Sea Level (m)	Core No.
Pliocene – Miocene	2788	19	3
Miocene – Oligocene	2863	94	5
Late Eocene – Middle Eocene	2906	137	6
Eocene – Paleocene	3009	240	12
Campanian – Santonian	3126	357	15

TABLE 5
Vertical Growth Rates of Bahama Banks as Indicated by Age Correlations for the Andros Island Well in Figure 3

Ages	Rates in Centimeters per 1000 Years
Late Eocene, Oligocene, Miocene, Pliocene	1.8
Early & Middle Eocene	8.9
Paleocene	9.0
Late Cretaceous	1.9

Initial Development of Atoll Reefing

Events leading up to the development of the atoll-like reefs in the Bahamas probably involved a network of patch reefs distributed across a wide back-reef carbonate shelf environment which was protected from the open waters of an early Cretaceous Atlantic Ocean by a major barrier reef system. Tidal currents undoubtedly breached the barrier thus forming tidal channels through which nutrient-rich oceanic waters flowed to wind their way through the patch reefs scattered across the wide back-reef area. The currents would generally be repetitious in their choice of passageways preferring those which followed lines of least resistance to flow. Patch reefs situated along the edges of the tidal channels would flourish more readily than elsewhere in the back-reef environment owing to the constant renewal of their supply of nutrients. Dietz *et al.* (1970, p, 1925) summarized the physiographic-ecological relationship of the Bahama channels and nutrient-rich ocean waters thusly:

> The deep passes indent the Bahama platform in such a way that all the portions of the platform have close access to oceanic waters. Without the deep passes, the center of the bank would be 100 km away from the deep ocean, but with them, no point is more than 50 km away from oceanic masses. In short, the geomorphic configuration of the Bahama platform may well be a response to ecological needs rather than a reflection of any inherited irregularities of the underlying basement.

In time, the faster-growing patch reefs would coalesce to form a more or less continuous reef line along the flanks of the channels. Thus, the stage would be set for the development of the fast-growing atoll type reef walls along the edges of the tidal channels–channels which were destined to become the ancestors of our modern-day Bahamian troughs.

Early Cretaceous Barrier Reef System

The existence of an early Cretaceous (Albian) barrier reef system is well-documented for virtually the entire circumference of the Gulf of Mexico Basin (Antoine and Jones, 1967; Uchupi and Emery, 1968; Bryant *et al.*, 1969) (Figure 7). The reef system has been actively explored by oil companies in Mississippi, Louisiana, and Texas (Tucker, 1962; Holden, 1963; Rose, 1963; Nichols, 1964; NcNamee, 1969). In Mexico the reef outcrops within 100 kilometers of the Gulf of Mexico shoreline. An atoll-like development of the reef is located about 100 kilometers south of Tampico and is known as the Golden Lane Reef (Figure 7). The onshore portion of this atoll reef was developed as a major oil producing province over 50 years ago. The offshore portion has been undergoing major oil exploration and development since the mid-1960's (Franco, 1969).

In Cuba the barrier reef system is represented by shallow water carbonate bank and reef deposits of Aptian-Albian age along the northern coast (Furrazola-Bermúdez *et al.*, 1964, p. 209, and 1968, p. 216; Meyerhoff and Hatten, 1968). The Cuban reef is bordered by lagoonal sediments on the north and deep-water deposits on the south and is pictured as fringing the southern edge of the great Florida-Bahama carbonate platform (Figure 7). As stated earlier, the deep Cay Sal Bank well, about 100 kilometers north of the Cuban coast, is characterized by an early Cretaceous shallow-water carbonate sequence containing an abundance of Cretaceous anhydrite which is part of the major back-reef evaporitic province extending throughout the South Florida-North Cuba Basin.

The existence of an early Cretaceous (Neocomian-Aptian) barrier reef along the eastern edge of the Blake-Bahama carbonate platform has been inferred from seismic reflection profiling (Ewing *et al.*, 1966; Emery and Zarudski, 1967; Uchupi, 1970; Uchupi *et al.*, 1971, p. 700) and bedrock outcrop sampling

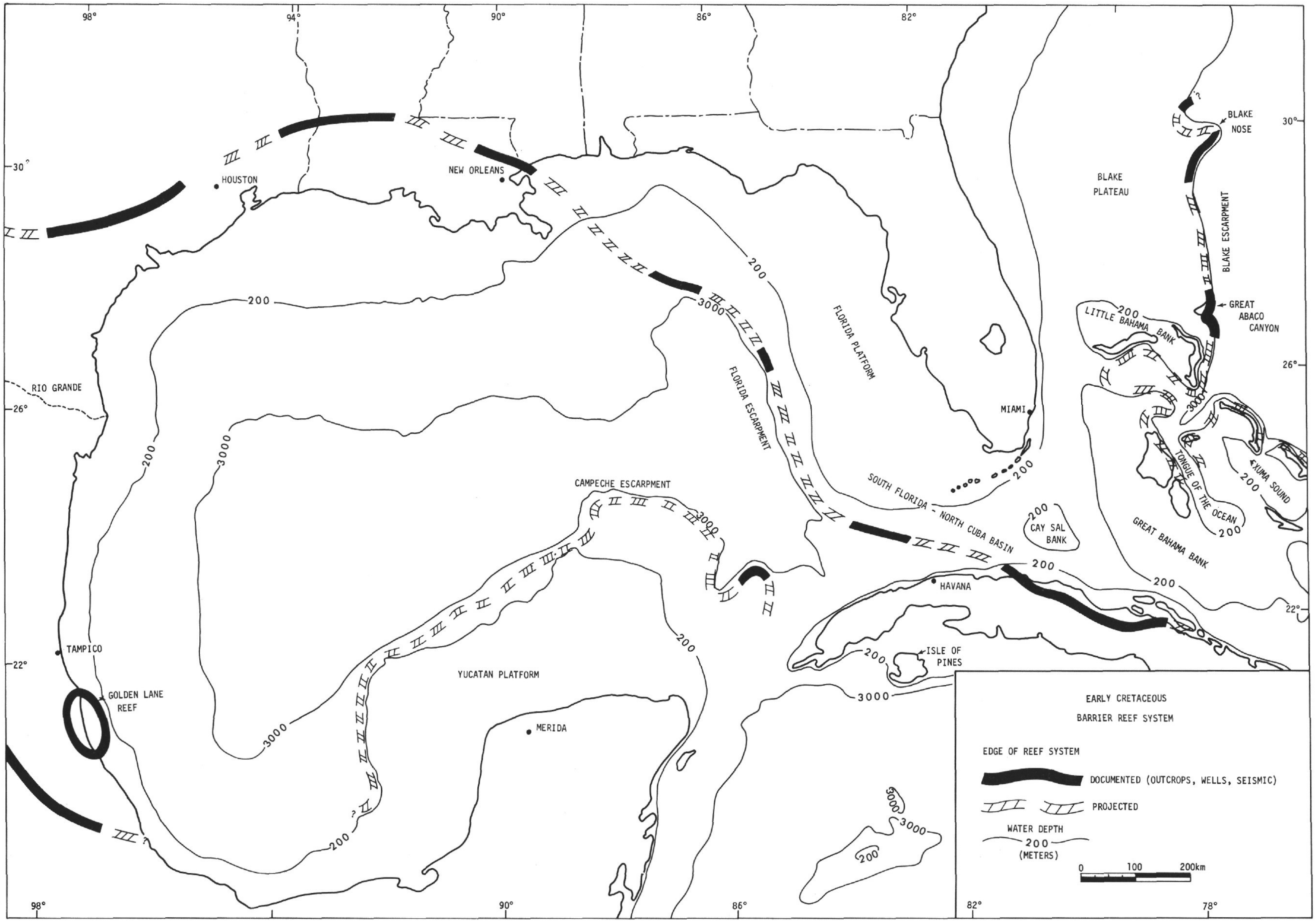

Figure 7. *Index map showing the location of the early Cretaceous barrier reef system around the Gulf of Mexico, across northern Cuba, and along the eastern edge of the northern Bahamas and the Blake Plateau. Modified from Bryant* et al. *(1969) and Paine and Meyerhoff (1970).*

(Heezen and Sheridan, 1966; Sheridan *et al.*, 1969). Heezen and Sheridan dredged Neocomian-Aptian algal-reef limestones from outcrops along the lower part of the Blake Escarpment in the vicinity of Blake Nose (Figure 7), and concluded that coral-algal banks formed a barrier reef structure extending northward from the Bahamas. Neocomian-Aptian algal limestones have also been dredged from the base of the Blake Escarpment at the mouth of Great Abaco Canyon by Sheridan's group. They concluded that the algal limestones were once the eastern edge of a shallow water reefal platform which extended westward across South Florida through early Albian time, and, that since the Albian, has subsided about 4500 meters.

Platform Subsidence

Subsidence and carbonate deposition were of comparable magnitude so that a shallow-water environment was maintained throughout the Blake-Bahama Platform during most of early Cretaceous time. Sheridan *et al.* (1969) propose an early Cretaceous depositional rate of 5 to 10 cm/1000 yrs. During the late Cretaceous depositional rates failed to keep pace with subsidence in the Blake Plateau area, but continued to equal the subsidence rate in the Bahama region. As a consequence, fine-grained, deep water calcilutites characterize the late Cretaceous and Tertiary of the Blake Plateau, while shallow-water carbonates make up the time-equivalent rocks of the Bahama banks. As stated earlier, the banks are postulated as being perpetuated by rapid reef growth along the walls of channels which were associated with major breeches in an early Cretaceous barrier reef system. Great Abaco Canyon, which cuts into the Blake Escarpment immediately north of Little Bahama Bank (Figure 7), has been cited as an example of a major breech in the early Cretaceous barrier reef (Sheridan *et al.*, 1969). If carbonate upbuilding had kept pace with the general subsidence of the Blake-Bahama region along both the northern and southern walls of the Great Abaco Canyon, it is postulated that a Bahamian-type deep water channel would have developed in an up-canyon direction from the present mouth of Great Abaco Canyon.

CONCLUSION

The conclusion now seems almost inescapable that the Bahama channels owe their origin to a combination of the relatively slow rates of sediment accumulation in the channels and the more rapid rate of vertical reef growth along the walls of the channels—channels which most likely were initiated by the normal breeching phenomena associated with a barrier reef system. These channels were the main avenues by which nutrient-rich waters, so necessary to healthy and luxuriant algal-coral growth, reached the back-reef area of the early Cretaceous shallow water platform. This platform, or back-reef shelf area, was foundational to the atoll-like reef growth which gave rise to the shallow water carbonate banks of the Bahamas.

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