PROCEEDINGS

OF THE THIRD SYMPOSIUM

ON THE GEOLOGY OF THE BAHAMAS

Editor

H. Allen Curran

Production Editor

Donald T. Gerace

Sponsored by CCFL Bahamian Field Station

June 6 - 10, 1986

Cover photo: *Diploria strigosa*, the common brain coral, preserved in growth position at the Cockburn Town fossil coral reef site (Sangamon age) on San Salvador Island. Photo by Al Curran.

Articles in this volume should be cited as follows:

Author(s), 1987, Article title, <u>in</u> Curran, H.A., ed. Proceedings of the Third Sympoisum on the Geology of the Bahamas: Fort Lauderdale, Florida, CCFL Bahamian Field Station, p. xx-xx.

ISBN 0-935909-24-9

Printed by Don Heuer in the U.S.A.

OCEAN DRILLING PROGRAM LEG 101[1] EXPLORES THE BAHAMAS

James A. Austin, Jr.
University of Texas Institute for Geophysics
4920 North I. H. 35, Austin, Texas 7875

Wolfgang Schlager
Vrije Universiteit
Instituut v. Aardwetenschappen
Postbus 7161
1007 MC Amsterdam
The Netherlands

ABSTRACT

Early in 1985, the D/V JOIDES RESOLUTION drilled 19 holes at 11 sites in the Bahamas during the inaugural leg (101) of the Ocean Drilling Program. Grids of high-resolution multichannel seismic profiles provided information crucial both for site selection and regional stratigraphic interpretations. Drilling and seismic results suggest platform expansion and retreat. Growth in the Late Jurassic-Early Cretaceous is followed by stagnation/drowning in the mid-Cretaceous and by renewed expansion in the Cenozoic. At Site 627 on the southern Blake Plateau, the stratigraphic succession consists of shallow-water platform carbonates/evaporites (late Albian), terrigenous/-carbonate shelf marly limestones/chalks (latest Albian-middle Cenomanian), open-marine plateau pelagic carbonate ooze (Campanian-Miocene), and oozes/turbidites of a re-advancing platform (Little Bahama Bank). The top of the late Albian shallow-water platform is characterized by an acoustic horizon underlying the Straits of Florida (Site 626) with the Great Isaac-1 industry well approximately 60 km away suggests that carbonate contourites in the Straits are also underlain by a mid-Cretaceous shallow-water platform.

Evolution of platform flanks was also studied. While modern facies belts are recognized in the continuously sampled Neogene record, drilling results suggest that Bahamian slopes respond to sea level fluctuations in a fundamentally different way from similar siliciclastic environments. Postulated eustatic lowstands at 2.3-2.9/5.0-6.6 Ma generally correspond to karst horizons on the platforms but to lower sedimentation rates at Site 632 in Exuma Sound. Slumping appears to be an important process along with turbidity currents in moving sediments from bank to basin. A recent slump on the upper slope north of Little Bahama Bank appears to have initiated imbricate thrusts of Miocene and younger sediments seaward of Site 628. Bank-derived aragonite, a major (up to 75%) component of slope oozes, is gradually replaced by calcite, although this general trend is sometimes reversed by depositional events related to climatic fluctuations. Miocene limestones at more than 200 m depths still contain 20% aragonite.

Hydrocarbon shows were encountered both on the southern Blake Plateau and in Exuma Sound.

[1] Leg 101 Scientific Party: James A. Austin, Jr. (Co-Chief Scientist), Wolfgang Schlager (Co-Chief Scientist), Amanda A. Palmer, Paul A. Comet, Andrè Droxler, Gregor Eberli, Eric Fourcade, Raymond Freeman-Lynde, Craig S. Fulthorpe, Gill Harwood, Gerhard Kuhn, Dawn Lavoie, Mark Leckie, Allan J. Melillo, Arthur Moore, Henry T. Mullins, Christian Ravenne, William W. Sager, Peter Swart, Joost W. Verbeck, David K. Watkins, and Colin Williams.

INTRODUCTION

In January-March, 1985, on its maiden international voyage for the new Ocean Drilling Program (ODP), the deep-sea drilling ship *JOIDES Resolution* (SEDCO/BP 471) conducted a geological investigation of the Bahamas. The scientific objectives of Leg 101 drilling in the Bahamas were two-fold: 1-to understand the evolution of the enigmatic bank-trough topography of the archipelago; and 2-to document the stratigraphic record of modern carbonate slopes and their response to sea level fluctuations. The decision to make carbonate platforms the focus of the inaugural scientific leg of ODP reflected a growing awareness of the importance of carbonate platforms as recorders of ocean history and reservoirs of oil, gas and metallic ores (e.g. Tator and Hatfield, 1975; Enos, 1977; Cook and Enos, 1977; Murris, 1980; COSOD, 1981; Tyler and others, 1985; and many others). For the Bahamas, Leg 101 marked the first significant drilling activity since the completion of the Great Isaac-1 industry borehole in 1971 (Fig. 1).

Leg 101 focused on both "deep" and "shallow" stratigraphic objectives. Deep drilling was designed primarily to test two fundamentally different concepts concerning the long-term crustal development of the Bahamas. One of these, termed the "graben" hypothesis (Talwani and others, 1960; Mullins and Lynts, 1977), suggested that the present configuration of shallow-water banks and intervening deep-water troughs (Fig. 1) was a faithful reflection of underlying horsts and grabens related to initial Mesozoic rifting of North America and Africa. The second, or "megaplatform", hypothesis, held that modern Bahamas topography was underlain by an extensive, buried shallow-water carbonate platform which encompassed the Bahamas, Florida, and the margins of the Gulf of Mexico until mid-Cretaceous time, when drowning occurred (Paulus, 1972; Meyerhoff and Hatton, 1974; Sheridan and others, 1981; Schlager and Ginsburg, 1981). According to this scenario, tectonism might subsequently have played a minor role in the evolution of banks and troughs, but only in terms of localizing deposition/erosion.

On regional multichannel seismic reflection profiles (Fig. 1), the top of the megaplatform had been interpreted to coincide with a prominent acoustic unconformity/pronounced compressional wave velocity increase downward to more than 4 km/sec (Sheridan and others, 1981; Van Buren and Mullins, 1983; Sheridan and others, in press; Ladd and Sheridan, in press). Original Leg 101 plans called for sampling this surface in at least two of the following locations: the Straits of Florida (Site 626), Exuma Sound (Site 632), or Northeast Providence Channel (Sites 634-636). However, successful penetration to and through the inferred megabank top occurred only at Site 627, north of Little Bahama Bank on the southern Blake Plateau (Fig. 1).

Leg 101 also examined in detail the three-dimensional development of Bahamian slopes using both the Extended Core Barrel (XCB) and Advanced Hydraulic Piston Corer (HPC). Previous investigations using both high-resolution, single-channel seismic reflection profiles and piston cores had demonstrated that these slopes appears to steepen with height and were characterized by facies belts which generally paralleled adjacent bank margins (Mullins and Neumann, 1979; Schlager and Chermak, 1979, Schlager and Ginsburg, 1981; Van Buren and Mullins, 1983; Mullins and others, 1984). Extending the accretionary/erosional carbonate slope types described by Mullins and Neumann (1979), Schlager and Ginsburg (1981) suggested an evolutionary pattern of carbonate slope development which could be broken into three stages: 1. "accretionary", characterized by gentle declivities and deposition dominated by slumps, gravity flows, and turbidites, all resulting in seaward progradation and convergence of chronostratigraphic lines; 2. "bypass", exhibiting steeper declivities, evidence for down-cutting and consequent development of gullies and hardgrounds/condensed sections on the upper slope, and net upbuilding as result of perennial sedimentation and the deposition of turbidites farther downslope, and finally; 3. "erosional", where outcrops of older material exposed by erosion of the upper slope gave way to a toe-of-slope either buried by talus or notched by bottom current erosion and/or carbonate dissolution. Theoretically, a platform slope could pass through all three of these stages with time as the platform grew higher, its flanks steepened and gravitational mass-wasting became more prevalent.

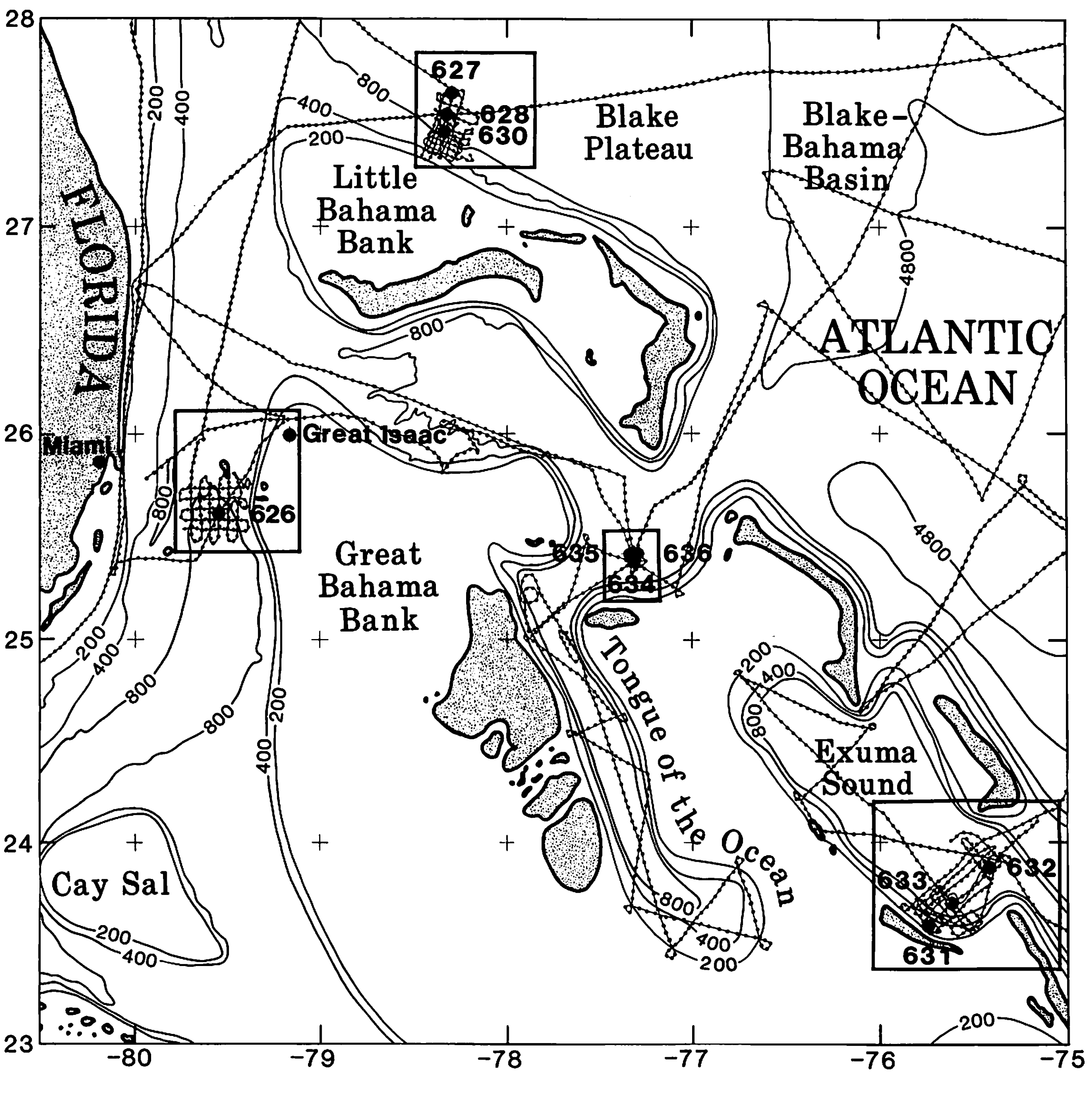


Fig. 1. Index map showing geophysical site-survey coverage and Leg 101 drilling sites in the Bahamas. Additional regional multichannel seismic coverage is also shown, as is the location of the Great Isaac-1 industry borehold completed in 1971. Bathymetric contours are in m.

Furthermore, a number of previous studies (Kier and Pilkey, 1971; Schlager and Ginsburg, 1981; Mullins, 1983; Boardman and Neumann, 1984; Droxler; 1984) had suggested that carbonate slopes might exhibit a fundamentally different response than their counterparts in siliciclastic environments to postulated global cycles of relative sea level change (Vail and others, 1977). Unlike clastic slopes, carbonate slopes appeared to shed a minimum of material during low-stands, when presented subaerial exposure of adjacent banks resulted in both rapid surface/near-surface lithification and low productivity and, therefore, low availability of sediment for off-bank transport. Conversely, sediment input to carbonate slopes seemed to reach maxima during highstands, as a results of high productivity on flooded banks and resultant availability of abundant sediments to be swept seaward.

In order to address the question of slope development adequately, longer sediment records than piston cores were clearly necessary. Consequently, Leg 101 examined two Bahamian slopes with three-hole HPC/XCB transects: the "accretionary" (i.e. gentle, 2-3°) slope north of Little Bahama Bank (Sites 627, 628, and 630) and the "bypass" (i.e. steep, 10-12°) slope in the southeastern part of Exuma Sound (Sites 631, 632, and 633) (Fig. 1). With the advanced drilling technology available, all of these sites were successful in continuously sampling sediments that may reveal the Neogene geologic history of these slope environments.

Prior to Leg 101, geophysical site-surveys were conducted by the University of Texas Institute for Geophysics research vessel *Fred H. Moore* in April-May, 1984. Approximately 1,200 n.mi. of 24-trace, 12-fold seismic reflection profiles were collected, along with 40 sonobuoys, bathymetry (underway 3.5 kHz), and magnetics. The sound source for most of the reflection data was a 400 cu.in. water gun. Most of the site-survey effort was concentrated in three grids: in the central Straits of Florida southeast of Miami, north of Little Bahama Bank, and in the southeastern part of Exuma Sound (Fig. 1). Such three-dimensional seismic coverage proved crucial for both initial site selections and at-sea modifications of drilling plans.

DRILLING RESULTS

The Deep Objective: Origin of the Platform-Basin Pattern

The Straits of Florida: Site 626. The designated first site of Leg 101 was also the most technically difficult, because Site 626 was located almost directly beneath the axis of the modern Gulf Stream (Figs. 1 and 2). Site 626 was intended to provide a complete late Early Cretaceous(?)-Recent stratigraphic succession beneath the Straits, which would in turn document the depositional/erosional history of the Gulf Stream as a complement to similar work being conducted both in the southeastern Gulf of Mexico (e.g. Schlager, Buffler and others, 1984; Buffler, Schlager and others, 1984; Angstadt and others, 1985) and on the Blake Plateau (Pinet and Popenoe, 1985a,b). This site also represented an attempt to sample the inferred buried megaplatform top previously described. A rectilinear grid of site survey profiles (Fig. 2) enabled both identification and mapping of the pronounced velocity discontinuity/impedance constrast characteristic of the top of the interpreted shallow-water carbonate section, which was estimated to be at 1.2 km sub-bottom where drilling operations finally took place (Figs. 2 and 3). Because of the depth of this designated target horizon, Site 626 was originally intended as a re-entry hole. However, attempts to place a re-entry cone there during the shakedown cruise of the *Resolution* were unsuccessful because of excessive current strength (Leg 100 Scientific Party, 1985).

During Leg 101, four different single-bit attempts to reach the target were made in the Straits (Fig. 2). In all instances, unconsolidated deep-water carbonate sands prevented continuous coring operations. Finally, Hole 626D had to be abandoned in latest Oligocene section at 447 m sub-bottom (Fig. 4).

Despite overall core recovery of only 3%, Site 626 provided some interesting results. First, the presence of winnowed, unconsolidated material throughout the cored interval confirms that the Gulf Stream has been a pervasive sedimentological agent for at least the last 24 m.y. Second, the recovery of a sequence of middle Miocene debris flows coeval with the intraclastic chalks of the Great Abaco Member of the

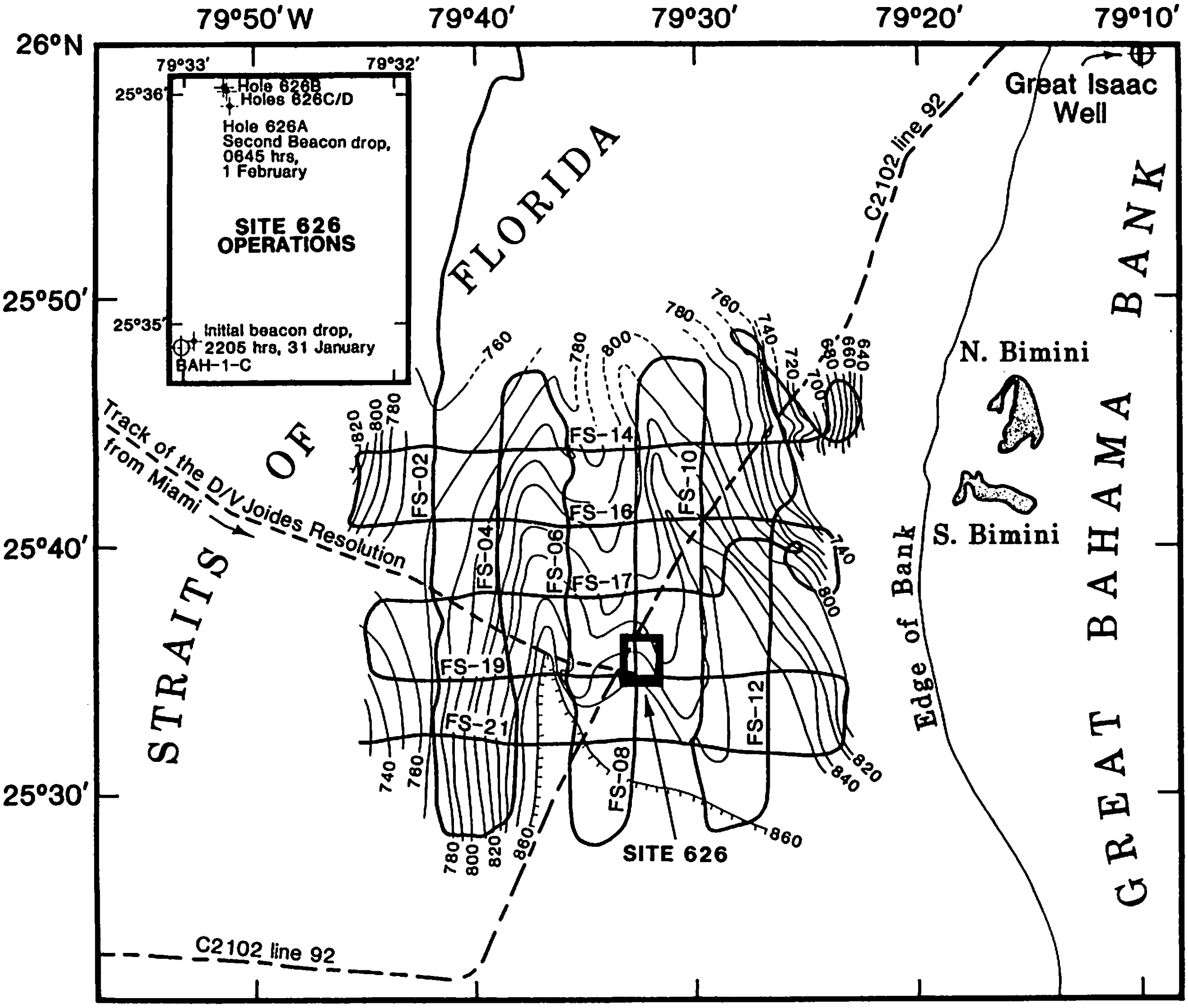


Fig. 2. Map of the geophysical survey grid for Site 626 in the Straits of Florida (see Fig. 1 for general location). The solid lines represent 24-trace, 12-fold seismic reflection profiles collected using a 400 cu. in. water gun. The inset details Site 626 operations, and the portion of line FS-08 contained within the box is shown in Fig. 3. Excessive current velocities prevented setting a re-entry cone in this location, so only single-bit holes were attempted. The Great Isaac-1 well is located about 60 km to the northeast. The dashed line is part of a regional multichannel seismic reflection profile discussed by Sheridan et al. (1981). Bathymetric contours are in m.

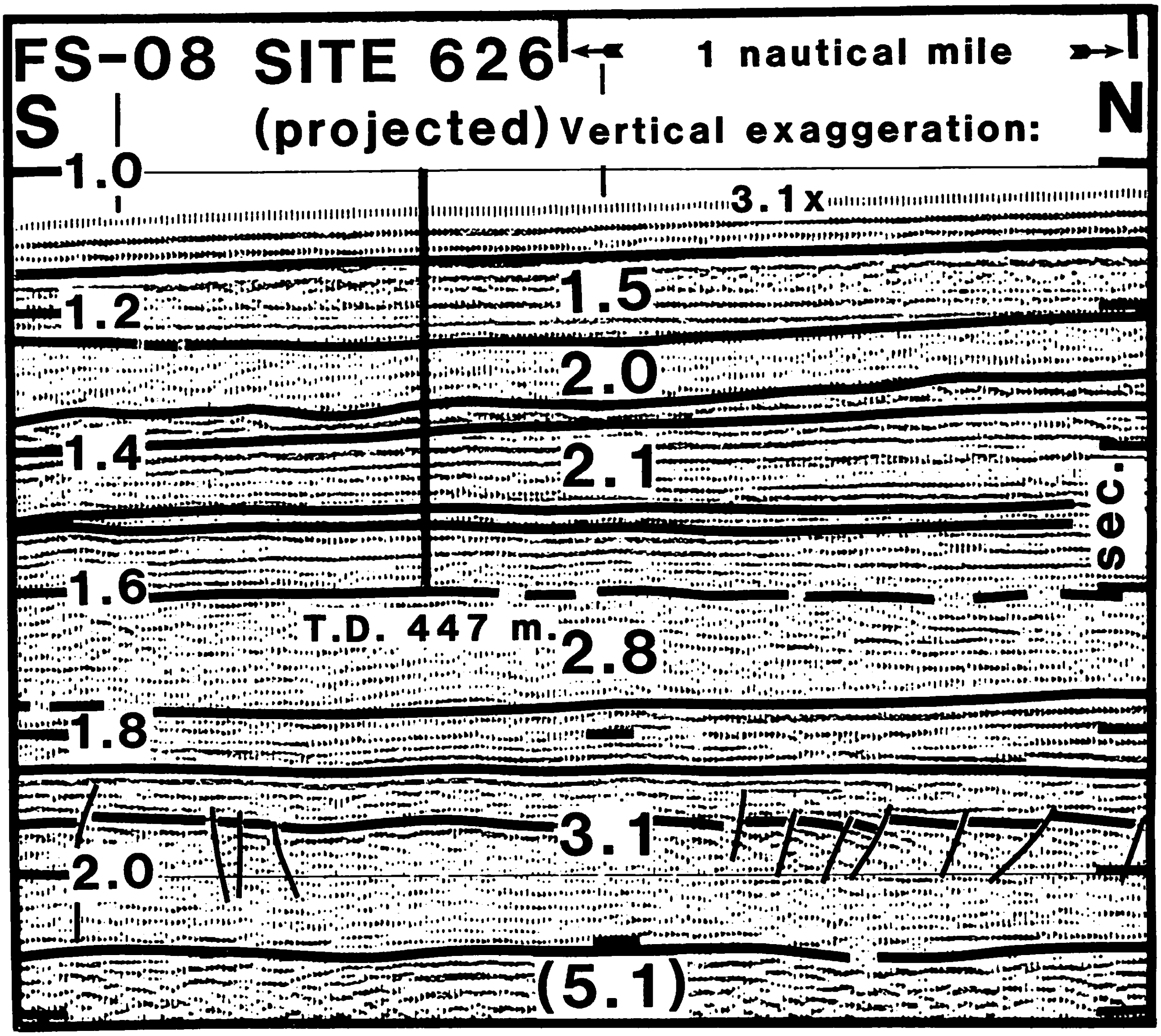


Fig. 3. Portion of interpreted site survey profile FS-08 in the vicinity of Site 626. Numbers to the left and right represent seconds of two-way travel-time, while the larger numbers vertically arranged in the center of the profile represent interval velocities in km/sec. The vertical bar represents the total depth (T.D.) of penetration of Hole 626D, which was located approximately 0.5 km off the trend of the profile. The velocity contract from 3.1 to 5.1 km/sec represents the original drilling target, the inferred top of the shallow-water carbonate platform.

Blake Ridge Fm. sampled in the Blake-Bahama Basin During DSDP legs 44 (Benson, Sheridan and others, 1978) and 76 (Sheridan, Gradstein and others, 1983) suggests a common cause, most likely either sea level changes or regional tectonism (Bliefnick and others, 1983). Third, Site 626 shows that the seismic stratigraphy in the Straits developed by Sheridan and others (1981) is too old by as much as 20 m.y. (Austin, Schlager, Palmer and others, in press). Finally, jump-correlation of the late Paleogene-Neogene stratigraphic successions sampled at Site 626 and the Great Isaac-1 industry borehold approximately 60 km to the northeast suggests tens of kms of northwestward progradation of Great Bahama Bank since the late Miocene (Figs. 1, 2, and 5; Leg 101 Scientific Party, 1985a,b). Mullins and others, (1980) had also observed northwestward progradation of contourite deposits in the Straits north of Site 626 in response to a postulated intensification of Gulf Stream flow in the middle Miocene. However, the late Early Cretaceous(?) time line at the shallow-water carbonate platform top inferred at Site 626 and observed in the Great Isaac-1 well (and marked by sympathetic velocity contrasts in both locations) is nearly horizontal, suggesting long-term depositional rather than tectonic controls of bank edges, a least in this location (Fig. 5). This result agrees well with recent interpretations of industry seismic control on adjacent parts of Great Bahama Bank (Eberli and Ginsburg, in press).

Southern Blake Plateau north of Little Bahama Bank: Site 627. Like the Straits of Florida, the seismic stratigraphy of the southern Blake Plateau included a high-amplitude surface accompanied by a pronounced downward velocity shift to values in excess of 4.5 km/sec. (Sheridan and others, 1966), which had been previously interpreted to be part of a platform-interior carbonate facies (Heezen and Sheridan, 1966; Sheridan and others, 1969; Sheridan and Enos, 1979; Mullins and others, 1982; Van Buren and Mullins, 1983). A site-survey grid reaffirmed the existence and lateral continuity of this surface just north of Little Bahama Bank, and further suggested that it occurred there at depths of generally less than 600 m (Figs. 1, 6, and 7; Austin, Schlager, Palmer and others, in press). Therefore, in the wake of the failure of Site 626 to reach its deep target in the Straits, the decision was made to attempt to sample the interpreted buried platform top in a region where it was shallower and covered by a more easily penetrable section which had presumably remained out of the winnowing influences of the Gulf Stream.

Two holes were drilled at Site 627 using HPC/XCB techniques, and Hole 627B succeeded in sampling the top of a buried platform as predicted: a sequence of intercalated dolomitized limestones and gypsum of late Albian age. The first dolostones, unequivocal evidence for shallow-water platform deposits, occurred at 477.7-487.1 m sub-bottom (1,513.5-1,523.1 m sub-sea level), in almost exact agreement with a local sonobuoy refraction solution for the depth of the platform top (474 m sub-bottom; Austin, Schlager, Palmer and others, in press). Abundant interbedded gypsum, suggestive of a very restricted platform interior, was not encountered until 514.2-519.2 m sub-bottom (1,550.2-1,555.2 m sub-sea level), in reasonable agreement with the velocity transition to 4.2 km/sec material as predicted by the multichannel seismic reflection results at closest-point-of-approach to the drill-site (531 m; Figs. 6 and 7; Austin, Schlager, Palmer and others, in press). Further penetration into this platform complex was halted and drilling terminated when shows of wet gas were encountered in the hole. However, before Hole 627B was cemented and abandoned, standard Schlumberger logs (Natural Gamma Ray, Litho-Density, and Compensated Neutron) were successfully run across the entire sampled shallow-water section (from 469 to 536 m sub-bottom).

The fact that the magnitude of the differential in the sonobuoy-reflection velocity measurements matched the extent of the vertical transition from shallow-water carbonates to the underlying carbonate-evaporite facies in Hole 627B appears to substantiate the validity of using such geophysical measurements for regional geologic correlations in the Bahamas. Furthermore, the results from Site 627 put narrow constraints on the timing of platform drowning on the southern Blake Plateau. The dolomites yield an assemblage of shallow-water benthic foraminifera of late Albian age, while the overlying sequence of deepening-upward marly limestones and chalk (Fig. 8) are latest Albian to middle Ceno-

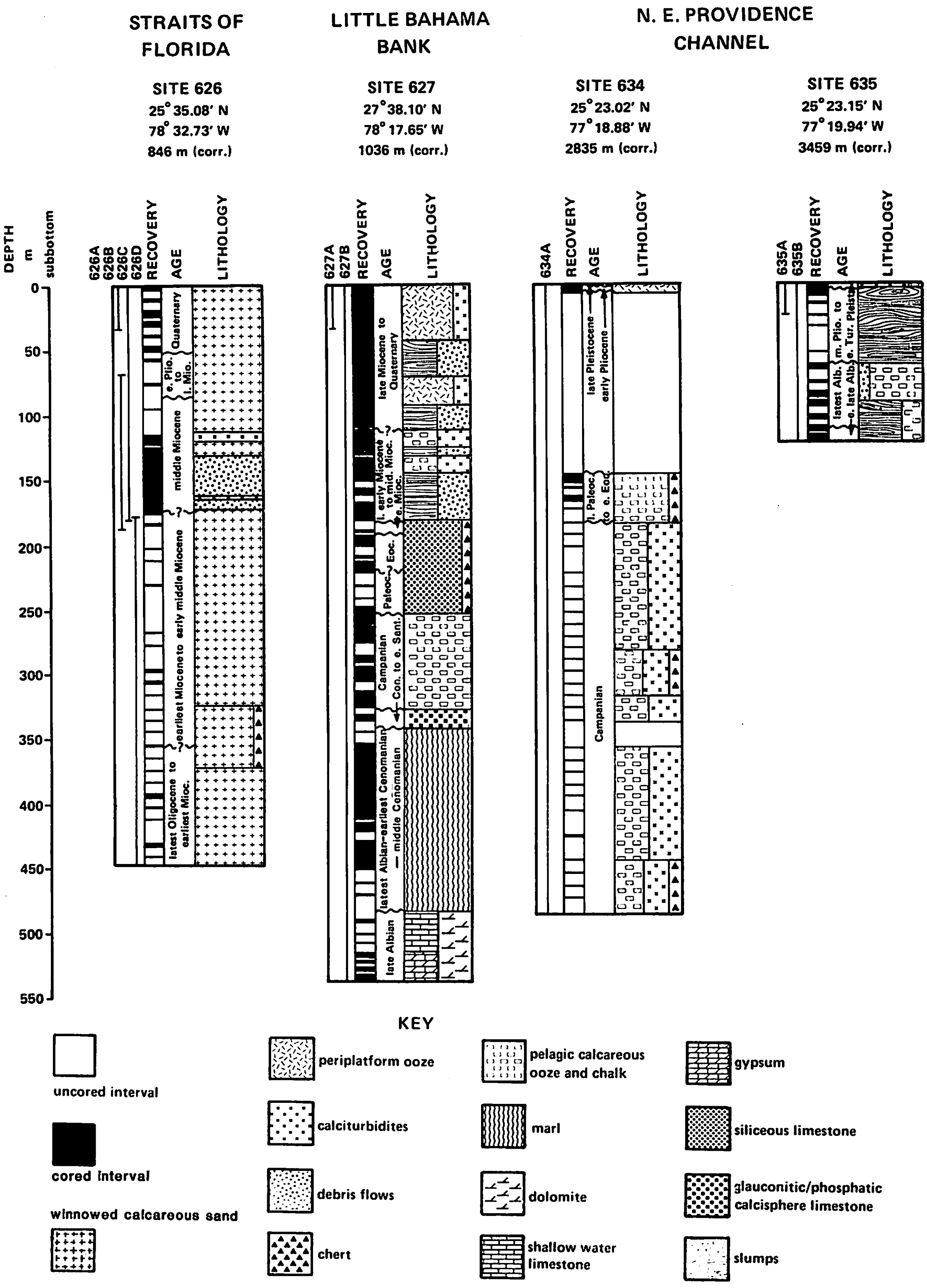


Fig. 4. Summaries of lithologies recovered in attempts to sample the top of the "mega-platform": Sites 626, 627, 634 and 635.

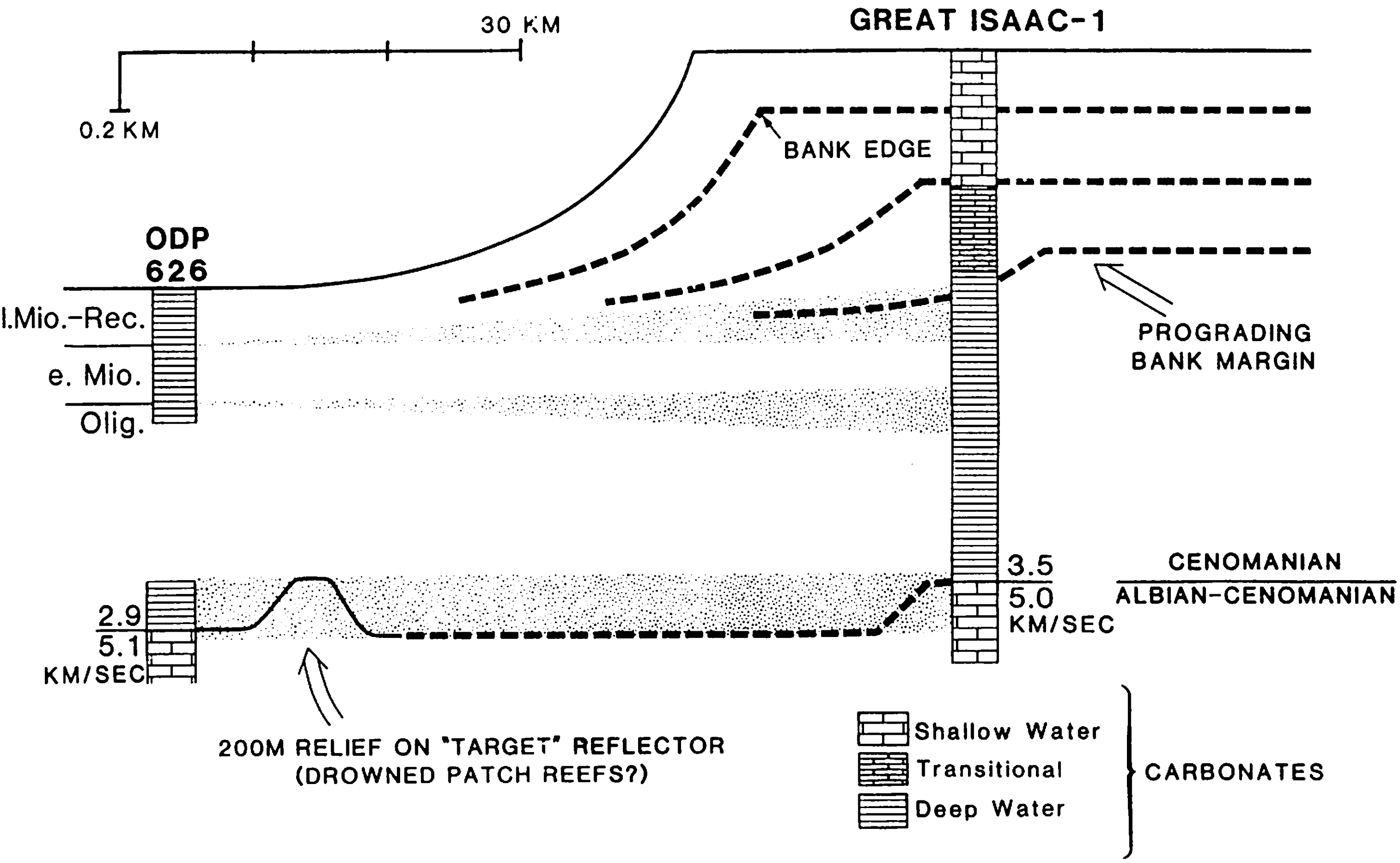


Fig. 5. Comparison of stratigraphy sampled at Site 626 and at the Great Isaac-1 industry borehold approximately 60 km to the northeast. (The Great Isaac samples were reexamined by Schlager and colleagues at the University of Miami as part of the Leg 101 site-survey effort.) The velocity contrast believed to be the top of a shallow-water platform beneath the Straits of Florida correlates in depth (approximately, assuming that local relief on the velocity contrast in the Straits is related to mid-Cretaceous(?) patch reef development) with a velocity contrast associated with the top of an Albian-Cenomanian shallow-water carbonate section in the Great Isaac-1 well. The latest Oligocene-Recent sediments at Site 626 are all deep-water deposits, but the Great Isaac section suggests that a shallow-water platform occupying what is now the northwestern corner of Great Bahama Bank drowned in the mid-Cretaceous, to be succeeded by a deep-water section until the late Miocene, when shallow-water conditions again prevailed (to the present). This observed succession suggests pronounced (at least tens of km) lateral migration of bank margins through time.

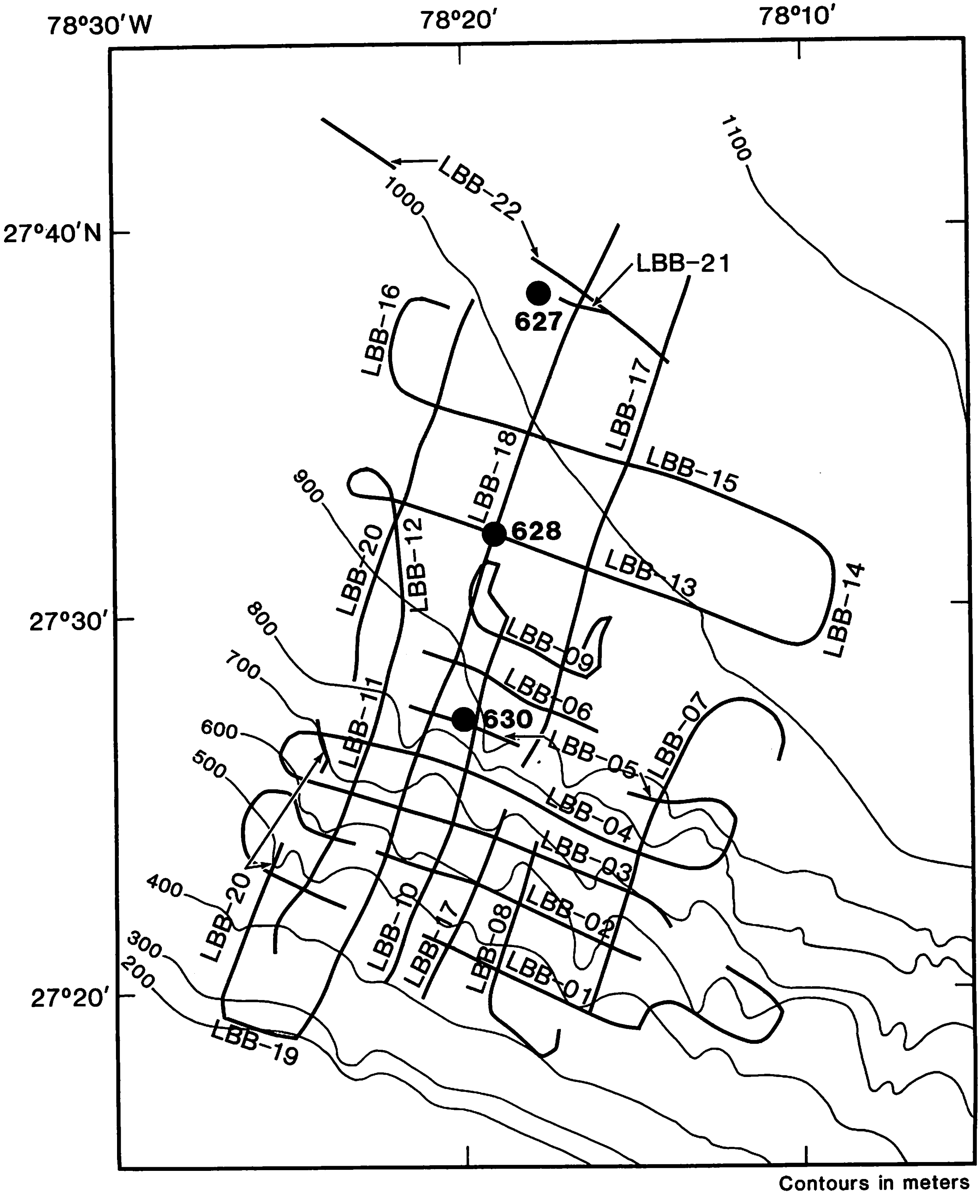


Fig. 6. Map of the geophysical survey grid for Sites 627, 628, and 630 on the slope north of Little Bahama Bank. The location of LBB-18, Figure 7, is shown by the bold line. As with the profiles shot with a 400 cu. in. water gun.

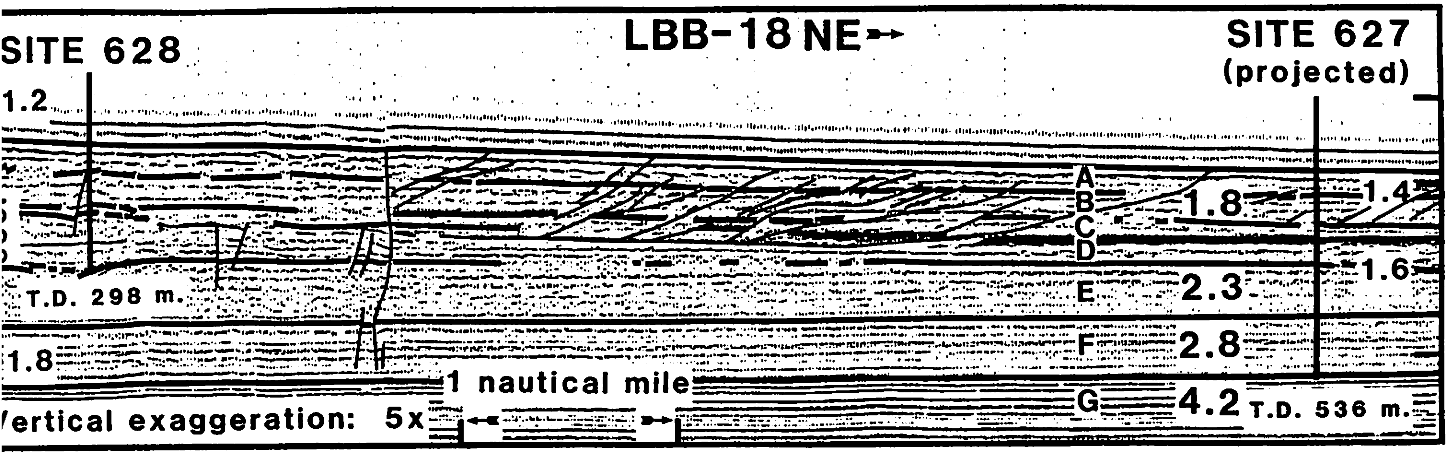


Fig. 7. Portion of site survey profile LBB-18 between Sites 627 and 628. Site 627 was in fact located approximately 2 km off this profile (see also Fig. 6). Annotations are the same as in Fig. 3, except that the letters refer to individual seismic sequences detailed in Fig. 8. Note in particular the imbricate thrusts soling out into bedding plane shears between the two sites, and the Walkers Cay normal fault (Van Buren and Mullins, 1981) located just northeast of Site 628.

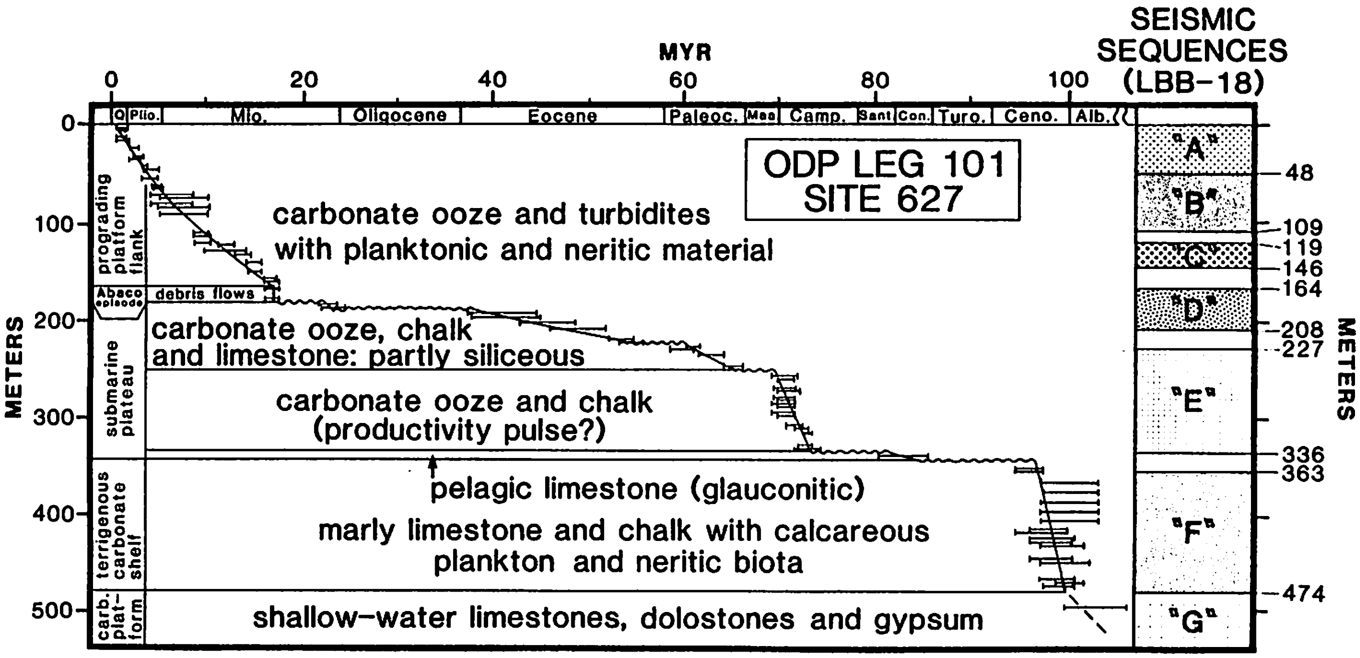


Fig. 8. Geologic history of Site 627. Accumulation rate curve includes biostratigraphic age control (horizontal bars) and hiatuses (wavy lines). The seismic stratigraphy at the site is located along the right-hand margin, and the preliminary interpretation of the sampled sediments on the left hand margin. The "F"-"G" sequence boundary is the top of the late Albian shallow-water platform.

manian in age (Austin, Schlager, Palmer and others, in press). Therefore, drowning, i.e. the transition from a shallow-water carbonate platform to an open marine, carbonate/terrigenous shelf, must have occurred between the latest Albian and the earliest Cenomanian at this location.

In addition to calibrating the age and depth of the top of the shallow-water carbonate section, Hole 627B illustrated the subsequent, successive transformation of this platform, first into the mixed carbonate/terrigenous shelf during the late Albian-earliest Cenomanian, then a marginal oceanic plateau characterized by frequent hiatuses between the Campanian and Oligocene, and finally into the prograding turbidite apron of Little Bahama Bank in the Neogene (Figs. 7 and 8). In general, the depositional record at Site 627 mirrors that encountered at Site 391 in the Blake-Bahama Basin to the north (Benson, Sheridan and others, 1978; Fig. 1), suggesting regional rather than local depositional controls. An exception to that correlation is a middle-upper Campanian sequence of carbonate oozes and chalk in Hole 627B not encountered at Site 391. These oozes are perhaps associated with a local productivity pulse related to upwelling associated with fluctuations in paleo-Gulf Stream/Antilles Current flow and/or the influence of the Suwannee Channel, which at that time connected surface circulation patterns in the Gulf of Mexico and the western North Atlantic across northern Florida (Pinet and Popenoe, 1985a). In addition, late early-early middle Miocene debris flows were again encountered at Site 627, substantiating their apparently ubiquitous occurrence from the Straits of Florida to the Blake-Bahama Basin.

Unequivocal ties between hiatuses encountered in Hole 627B and seismic sequence boundaries/acoustic unconformities identified on site-survey reflection profiles north of Little Bahama Bank could be made (Figs. 7 and 8). For example, the "F"-"G" sequence boundary marks the top of the intercalated carbonate-gypsum succession, while the "E"-"F" boundary correlates with a hiatus extending from the latest middle Cenomanian-earliest Coniacian. Higher in the section, such correlations are more ambiguous (Fig. 8; Austin, Schlager, Palmer and others, in press), perhaps because this entire region was sediment-starved from the middle Cenomanian to the early Campanian, and from the latest Campanian to the early Miocene. Within such a condensed stratigraphic interval, local depositional controls could have complicated any eustatic sea level signal. Site 627 is also located approximately two km off the nearest site-survey line (Fig. 7), further complicating such detailed correlations.

Northeast Providence Channel: Sites 634-636. Leg 101 operations in Northeast Providence Channel were originally envisioned only as an alternate, if successful penetration to and through the interpreted "megaplatform" top could not be achieved in at least two locations elsewhere. Unfortunately, this eventuality turned out to be the case, as deep drilling operations were unsuccessful in Exuma Sound (see Site 632 description below), as well as in the Straits of Florida. Site selection was based solely on existing regional multichannel seismic reflection control (Figs. 9 and 10; Sheridan and others, 1981). Site 634 was effectively a reoccupation of Deep Sea Drilling Project (DSDP) Site 98, which bottomed in late Santonian-early Campanian bioclastic turbidites containing peri-reef debris (Paulus, 1972). Its primary goal was to reach and sample a velocity discontinuity (2.87 km/sec above-4.89 km/sec below) at a depth of approximately 770 m interpreted by Sheridan and others, (1981) as the same shallow-water platform top successfully samples at Site 627. Furthermore, available seismic data (Fig. 10) suggested that a deep-penetration attempt on the flank of Northeast Providence Channel might recover a reasonably complete deep-water section above the inferred late Early Cretaceous shallow-water carbonates, thereby ensuring precise age and stratigraphic control of platform drowning.

Only one hole was drilled at Site 634 using standard rotary drilling techniques. Unfortunately, poor hole conditions in skeletal grainstones, rudstones, and debris flows with minor intercalated chalk of latest Santonian-earliest Campanian age prevented penetration beyond 480 m sub-bottom. These lithologies were also encountered at the base of DSDP Site 98. Their presence suggests the Campanian development of a talus apron derived from a nearby shallow-water carbonate platform of Cenomanian-Campanian age (Paulus, 1972; Austin, Schlager, Palmer and others, in press).

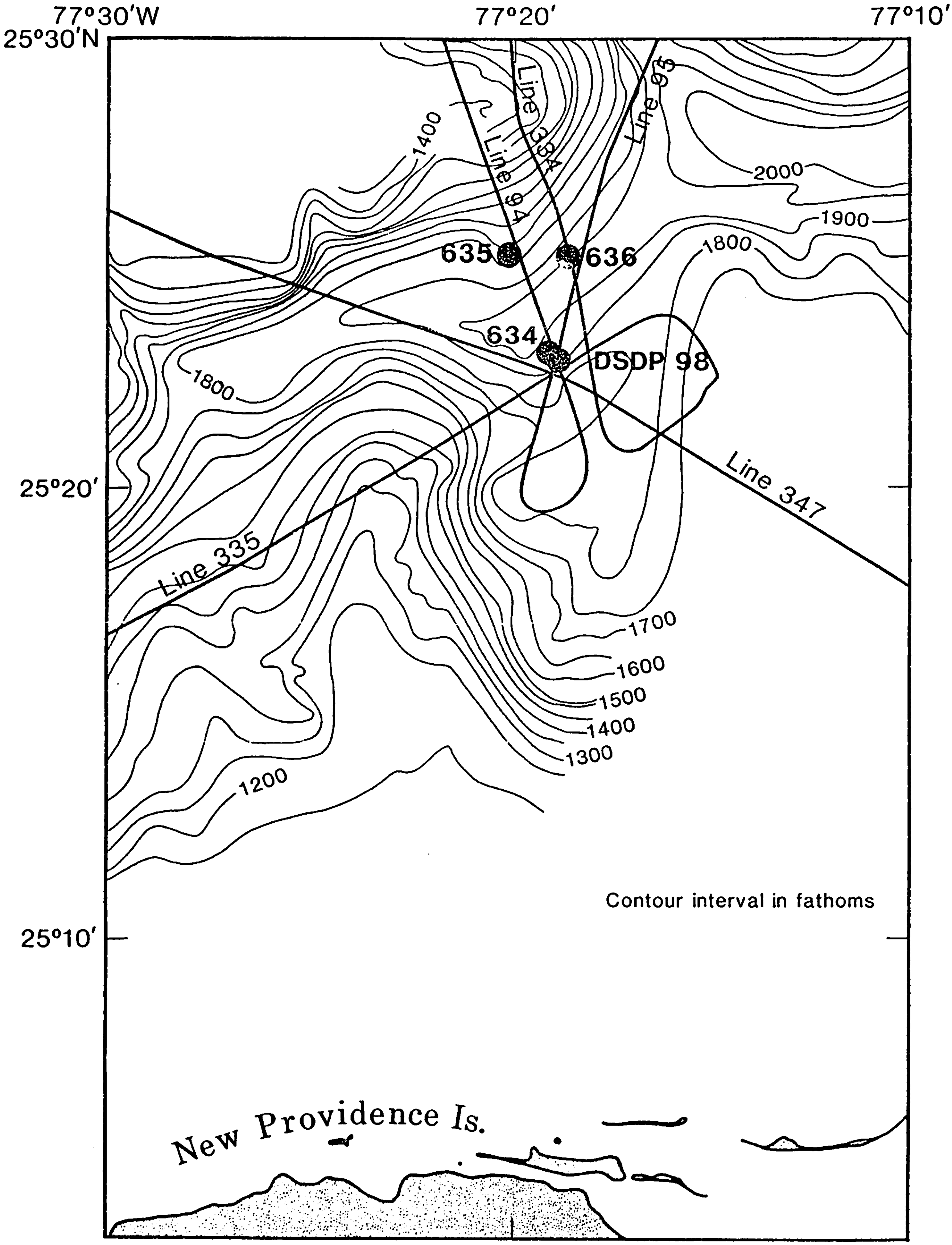


Fig. 9. Track chart showing relationships of Leg 101 sites in Northeast Providence Channel to DSDP Site 98 and regional multichannel seismic reflection coverage from Sheridan and others (1981). Bathymetry is from Andrews and others (1970). Contours in fm. The portion of line 94 connecting the ODP Sites is shown in Fig. 10.

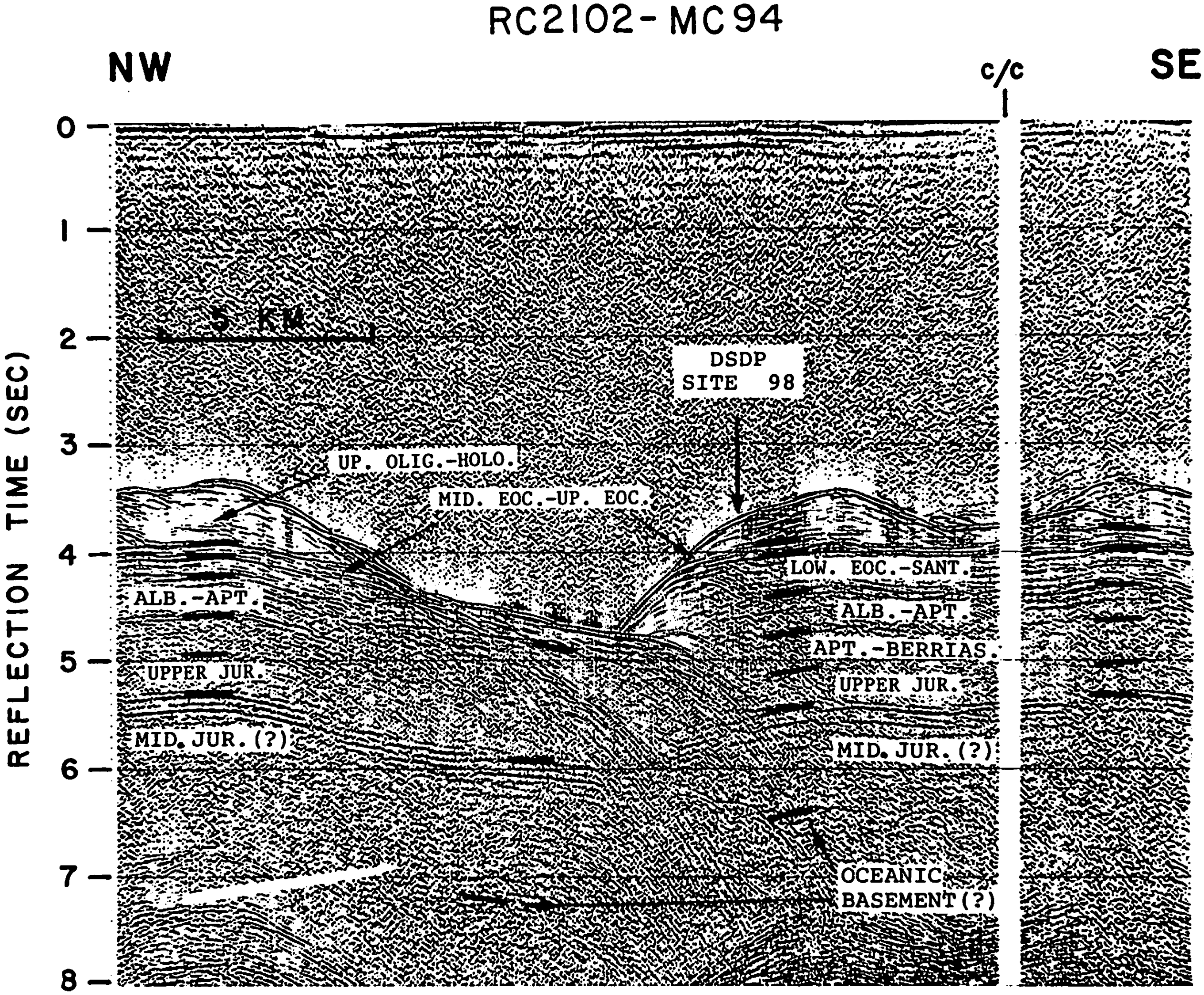


Fig. 10. Portion of multichannel seismic reflection line 94, with an interpretation taken from Sheridan and others (1981). This is a 24-trace, 24-fold profile shot with large airguns, unlike the higher-resolution water gun profiles shot during the Leg 101 site-surveys. Locations of Sites 634-636 and DSDP Site 98 are indicated. The exact relationship of Site 636 to the profile is indicated on Fig. 9. The "target" horizon, the inferred top of a mid-Cretaceous shallow-water carbonate platform, is the high-amplitude acoustic surface separating Albian-Aptian and lower Eocene-Santonian sequences on this profile. The two shallower sequence boundaries were recalibrated as a result of drilling at Site 634 (see the text, and Austin, Schlager, Palmer and others, in press).

Fortunately, a suite of Schlumberger logs (Compensated Neutron, Gamma Ray and Gamma Spectroscopy) run in the drill string provided some detailed information on both porosities and lithologies in the thick Campanian section, which was poorly sampled (Fig. 4). In conjunction with the rocks recovered, this information allowed recalibration of two previously identified and regionally correlated acoustic horizons (Fig. 10). Sheridan and others, (1981) upper Eocene-upper Oligocene sequence boundary correlated in depth either with the Paleocene-Eocene boundary or with the top of the Campanian section, and their lower Eocene-upper Eocene boundary fell within the Campanian calciturbidite section (Austin, Schlager, Palmer and others, in press).

With the interpreted platform top still unsampled and with only a limited amount of cruise time remaining, attention shifted to the thalweg of Northeast Providence Channel, where the target acoustic unconformity/velocity contrast was buried by less than 200 m of section (Figs. 9 and 10). Site 635 was located on the lower part of the opposite flank of Northeast Providence Channel from Sites 98/634. Concerns over the difficulty of drilling in an erosional canyon environment were soon justified when a hard formation prevented Hole 635A penetration beyond 20 m sub-bottom. However, Hole 635B reached 118 m sub-bottom before a stuck core barrel forced final termination of drilling at this location.

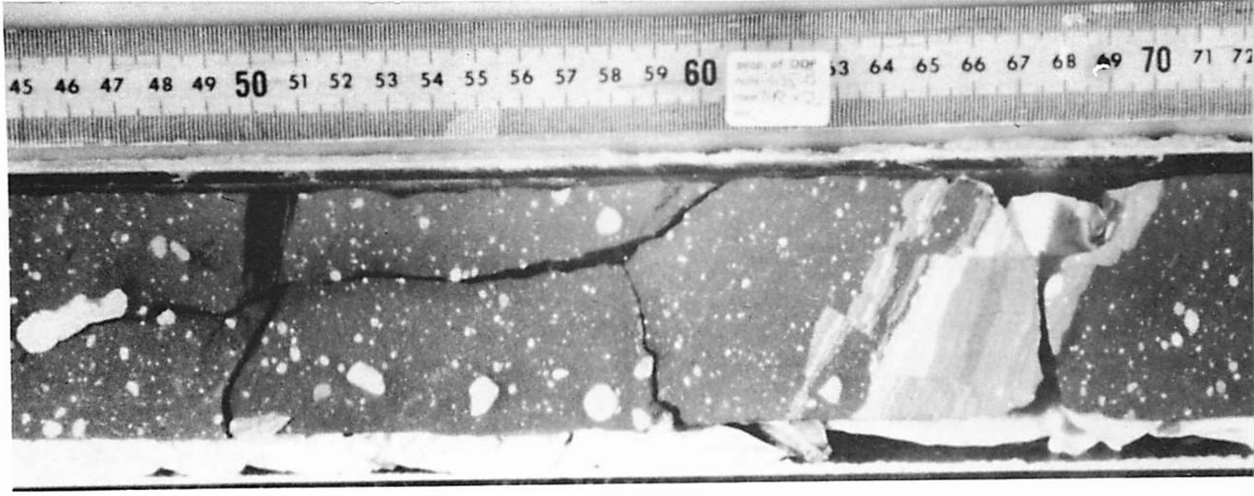
From 61-118 m sub-bottom, Hole 635B penetrated a sequence of slightly argillaceous chalk and limestone of late Albian age (Fig. 4). These carbonates were deposited in a bathyal slope environment characterized by intercalations of muddy debris flows and small slumps with minor faulting (Fig. 11). However, the lack of clasts derived from a shallow-water platform suggests that this slope was located farther from any such platform than the depositional environment suggested by the Campanian calciturbidite section sampled at Site 98/634. Of particular interest were dark-colored, laminated zones within these limestones which were characterized by high total organic carbon contents, occasionally in excess of 6%. This interval is coeval with the organic-rich "black shales" of the Hatteras Formation, encountered by drilling in the adjacent deep western North Atlantic basin (e.g. Hollister, Ewing and others, 1972; Benson, Sheridan and others, 1978; Tucholke, Vogt and others, 1979), lending additional support to some form of widespread oxygen deficiency in the Atlantic during the mid-Cretaceous.

In the final hours of Leg 101, a last-ditch attempt to penetrate the elusive interpreted shallow-water platform top beneath the middle of the thalweg of Northeast Providence Channel was made at Site 636 (Fig. 10). The plan was to wash through the overlying section using a new rotary coring assembly, but time ran out before significant penetration could be achieved. Two wash cores recovered only fragments of Neogene canyon-fill. As a result, the inferred megaplatform was never sampled beneath a Bahama basin during Leg 101.

The Shallow Objective: Evolution of Modern Carbonate Slopes

Transect of an "accretionary" (gentle, 2-3°)slope, Little Bahama Bank: Site 627-630. While the primary goal of Site 627 was to sample the inferred mid-Cretaceous shallow-water platform buried beneath the southern Blake Plateau, it also served as the seaward end of a three-hole transect designed to understand the stratigraphic record of an accretionary carbonate slope and its response to sea-level fluctuations. By using high-resolution HPC/XCB coring techniques, Site 627 successfully sampled more than 90% of the early Miocene-recent section, which records the prograding flank of Little Bahama Bank (Austin, Schlager, Palmer and others, in press; Figs. 8 and 12). Above some late early-early middle Miocene debris flows, believed to be coeval with the Great Abaco Member of the Blake Ridge Fm. sampled both in the adjacent Blake-Bahama Basin and at Site 626, the Neogene section was composed of a combination of periplatform ooze (Schlager and James, 1978) and turbidites with associated slumps and debris flows, as predicted. Numerous hiatuses in this section attested both to its largely redeposited nature and the intermittent influence of the Gulf Stream/Antilles Current system in affecting the depositional regime.

While the observed sedimentary facies samples at Site 627 supported prior assumptions derived from piston coring studies, the



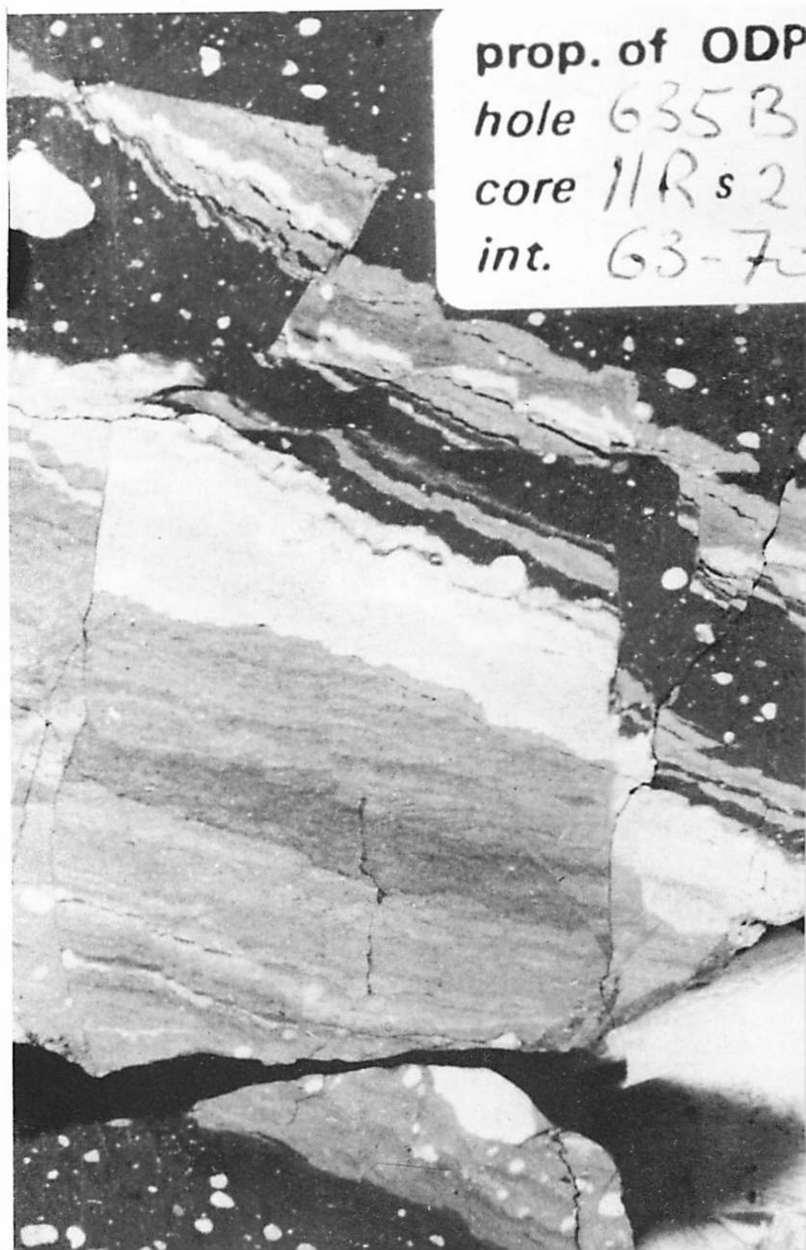


Fig. 11. Top: Section 2 of Core 11R (rotary), Hole 635B showing a sequence of white chalk clasts in a darker, micritic matrix. The micritic material is disrupted by an interval of faulted slump folds. This section is interpreted as a debris flow/slump that occurred in a dewatering carbonate slope environment during the late Albian. Bottom: Close-up of part of the same core, showing faulted slump folds with what could be primary dips (see also Austin, Schlager, Palmer and others, in press).

geochemistry of the Neogene section provided some surprises. First, interstitial pore water sampling revealed positive calcium gradients and negative magnesium/-strontium gradients downhole, a phenomena thought to be possible only where there was upward diffusion of water which had reacted with underlying igneous basement material (Gieskes, 1981). Perhaps alteration of the underlying Cenomanian marls (seismic sequence "F", Fig. 8) provides the source for the calcium and the corresponding sink for magnesium and strontium. Aragonite also decreased downhole, and was almost gone by the end of the Miocene. This trend probably reflects the seaward progradation of the bank toward Site 627, as well as aragonite dissolution as part of burial diagenesis. Finally, high-magnesian calcite seemed to disappear within the upper 10 m of the cored section, while there was a concomitant increase in dolomite. Dissolution of high-magnesian calcite might be producing dolomite (see Mullins and others, 1985), and in the process further reinforcing the observed gradients in calcium and magnesium.

Site 628 was located approximately 11 km upslope from Site 627 along the trend of LBB-18, one of the site-survey reflection profiles (Figs. 6 and 7). Based on the recent sediment cover, Mullins and others, (1984) had suggested that this region should be the proximal part of a debris apron characterized by mud-supported debris flows and more abundant, thick, coarse-grained turbidites. Sampling at Site 628 generally supported this view. One HPC/XCB hole was drilled to a depth of 298 m, recovering a sequence of late Paleocene-early Eocene to Recent periplatform ooze with intercalated debris flows, slumps and turbidites (Fig. 12). The thickness and grain size of sediment gravity flows increased upward from the middle Miocene, coinciding with a general upward increase in the incidence of slumps and calciturbidites throughout the drilled interval. Sedimentation rates in the upper Miocene-upper Pliocene section exceeded 30 m/m. y. The observed sedimentology attests to the gradual transition of the Site 628 located from a marginal oceanic plateau in the Paleogene to a prograding platform flank in the Neogene. However, the recurrence of middle Miocene debris flows coeval with those encountered at Site 626 and 627 and at DSDP Leg 44 and Leg 76 sites to the northeast supports a triggering mechanism more widespread than local bank progradation.

The site-survey line connecting Sites 627 and 628 indicates the presence of imbricate thrust planes soling out into bedding plane shears (Fig. 7). The presence of both folds and slumps within the cored interval at Site 628 supports this interpretation, suggesting that such processes may be important on gentle carbonate slopes where accumulation rates are relatively high. The thrusts affecting this part of the mid-to-lower slope may be connected to major slump scars located higher on the slope (Van Buren and Mullins, 1983; Austin, Schlager, Palmer and others, in press).

While seismic sequences could be traced laterally from Sites 627 to 628 despite numerous faults (Fig. 7), the intervals of deposition and erosion in the two sections do not match (Fig. 13). Most noticeable is a thick interval of Oligocene-earliest Miocene carbonate ooze at Site 628 that has no equivalent at Site 627. This pattern of local and intermittent sedimentation may be related to episodic scouring of the Gulf Stream system during a long period of general sediment starvation in the south-western North Atlantic.

Another important point is the apparent mixed response of this carbonate platform flank to postulated sea level fluctuations, particularly prior to the Oligocene (Fig. 13; Austin, Schlager, Palmer and others, in press). However, one significant correlation with a proposed lowstand may have been made at Site 628. An interval of early Oligocene carbonate ooze from 230-260 m sub-bottom contained an unusual amount of neritic benthos, and this interval is coeval with a regression noted by Olsson and others, (1980) on the northeastern passive margin of North America. Such a neritic pulse could be related to an Oligocene lowstand in one of two ways, either as redeposition from the adjacent platform during a short-lived seaward shift of carbonate production caused by bank exposure or *in situ* production of shallow-water material on a part of the Blake Plateau briefly exposed to the photic zone. Interestingly, the timing of the neritic input at Site 628 predates the pronounced early late Oligocene sea-level fall originally postulated by Vail and others, (1977) and

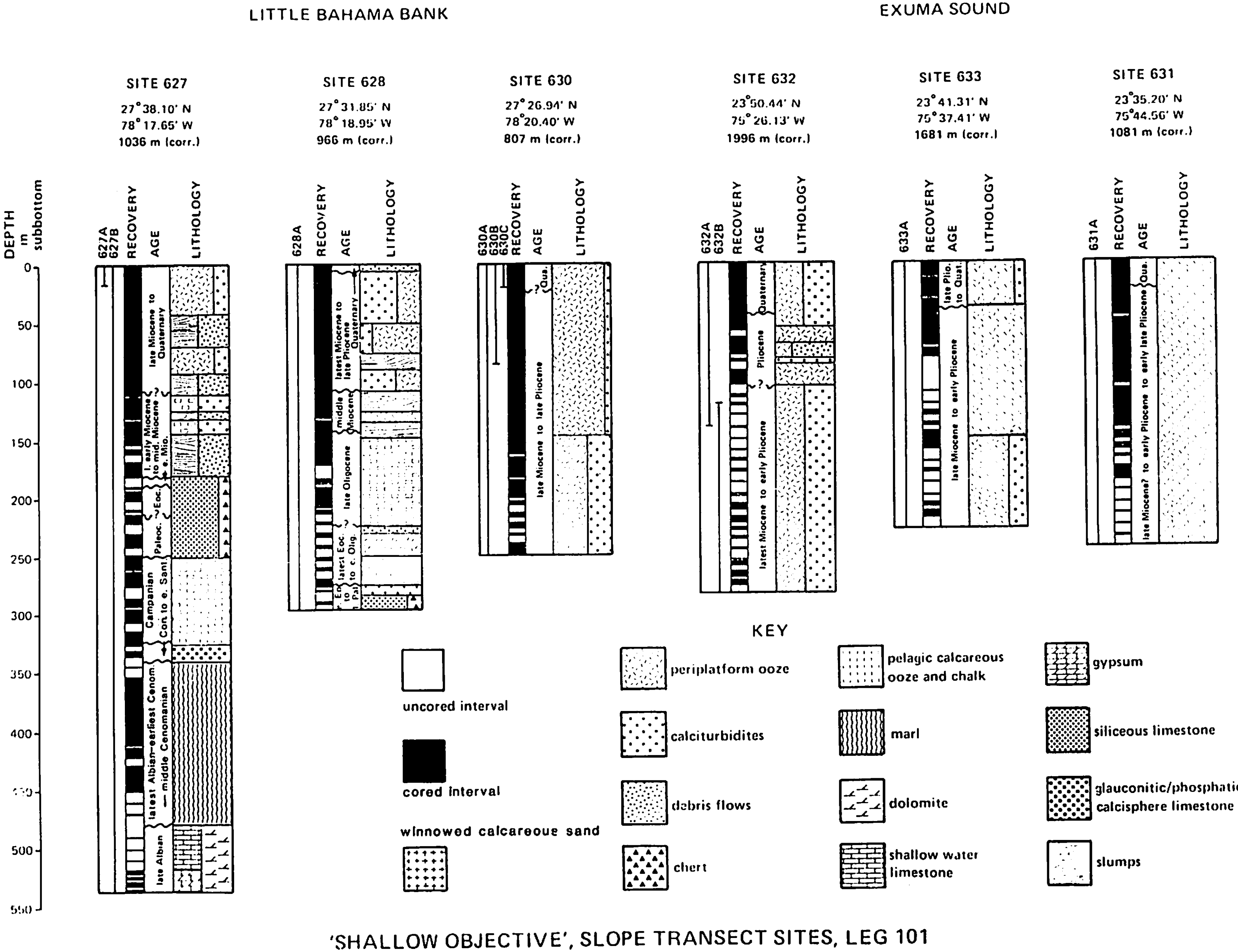


Fig. 12. Summary of lithologies recovered during the two carbonate slope transects north of Little Bahama Bank (Sites 627-630) and in the southeastern part of Exuma Sound (Site 631-633).

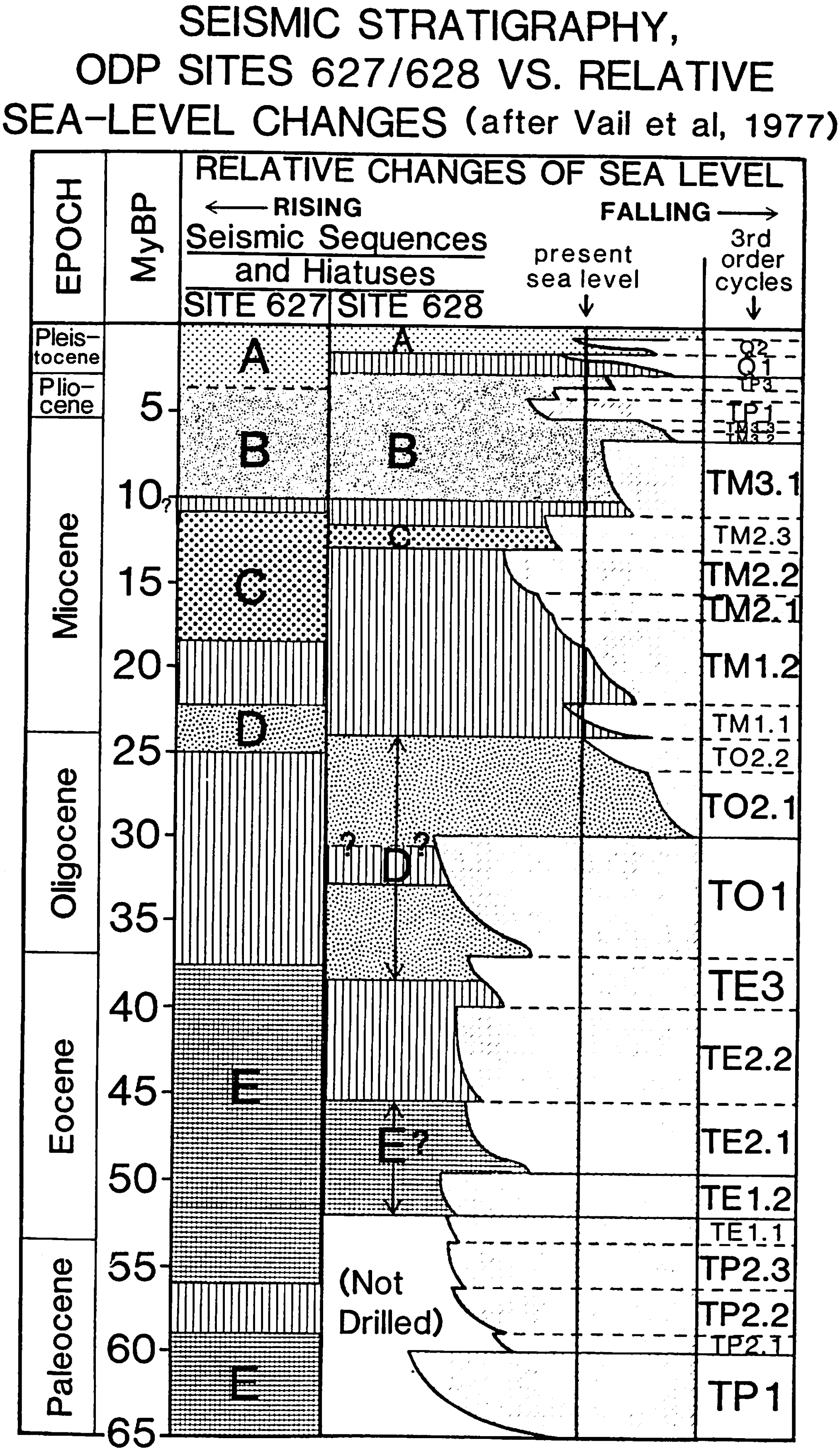


Fig. 13. Comparison of seismic stratigraphy sampled at Site 627 and 628 (only eleven km apart, see Fig. 6) north of Little Bahama Bank relative to the Vail and others (1977) and Haq and others (in press) global sea level curves. The patterns used to highlight the seismic sequences are the same as those used in Fig. 8. The successions at the two sites differ markedly, particularly in the Oligocene, suggesting that local topography and tectonism along with regional sediment starvation all play important roles in modulating a carbonate slope's response to sea level fluctuations.

recently reaffirmed by Haq and others, in press) (Fig. 13).

Geochemical results at Site 628 generally agree with those at Site 627. However, the elemental gradients for calcium, magnesium, and strontium previously described were more gradual, perhaps indicative of progressively greater depths to the underlying Cenomanian marls with distance up the slope.

Site 630 constituted the upslope end of the Little Bahama Bank transect (Figs. 1 and 6; Site 629 is not discussed here because it was simply an unsuccessful attempt to spud-in). The primary objective was to sample a complete sequence of periplatform ooze in order to monitor the perennial off-bank transport of sediment in an interfluve between gullies (Fig. 6; see also Austin, Schlager, Palmer and others, in press). Three HPC/XCB holes were drilled. Hole 630A achieved 88% overall recovery of a 250 m sequence of late Miocene and younger sediments (Fig. 12). A lower unit of periplatform ooze and turbidites was interpreted as analogous to the debris apron at the foot of the modern platform slope, whereas an upper unit of nearly turbidite-free ooze reflected the environment which still persists at this site: a slope characterized by numerous gullies which receives only the fine-grained sediment exported by the nearby platform (Sedimentation rates in this periplatform ooze were as high as 62 m/m.y.; Austin, Schlager, Palmer and others, in press). The observed sequence was consistent with results at Sites 627 and 628 which suggested pronounced Neogene progradation of Little Bahama Bank (Leg 101 Scientific Party, 1985a, b; Austin, Schlager, Palmer and others, in press).

Geochemical trends at Site 630 mimicked those at Sites 627 and 628, but calcium enrichment and magnesium depletion down-hole are less pronounced than at Site 628. This may once again be related to the progressively deeper burial of Cenomanian marls with distance up the slope. While trends in aragonite and high-magnesian calcite resemble those at the sites lower on the slope, burial diagenesis at Site 630 is rapidly converting upper slope periplatform ooze to chalk.

Seismic stratigraphy at Site 630 was more ambiguous than at Sites 627 and 628, primarily because of the gullied nature of the upper slope and the proximity of major slump scars on the mid-slope previously mentioned. However, two acoustic unconformities could be tied to the borehole stratigraphy: one to a Pleistocene hiatus near the surface and the other to a turbidite event and/or a diagenetic boundary (i.e. increase in lithification) at approximately 200 m sub-bottom (see Austin, Schlager, Palmer and others, in press).

Transect of a "bypass" (steep, 10-12°), Exuma Sound: Sites 631-633. The second slope transect of ODP Leg 101 was designed to compare and contrast the northern slope of Little Bahama Bank with a steeper and higher slope characterized by 10-12 declivities and a 1.6 km relief. In this setting, bypassing by turbidity currents was expected to be more complete, and sedimentation rates accordingly lower. In addition, Exuma Sound drilling provided a direct comparison of the effects of a closed-basin vs. open-ocean depositional setting on the response of a carbonate slope to sea level fluctuations, climatic effects and regional tectonism through time.

Site 631, like Site 630, was located on the upper, gullied slope (Fig. 14). One HPC/XCB hole was drilled to a depth of 244 m, recovering 65% of an Oligocene(?)-Miocene and younger section composed of periplatform ooze and chalk (Fig. 12). Accumulation rates of uppermost Miocene to mid-Pliocene oozes were extraordinarily high, on the order of 90 m/m. y., substantially exceeding the maximum rates observed at Site 630. The upper 100 m also contained greenish organic-rich layers exuding a strong odor of H_2S, suggesting active bacterial sulfate reduction in the presence of organic matter. Speculation on the source of the organic carbon led to the conclusion that it derived from rapid burial of bank-derived sea grass probably *Thalassia* sp.).

Diagenesis of periplatform ooze was much more rapid at Site 631 than at Site 627-630. Subsurface lithification at Site 631 began as shallow as 10.5 m sub-bottom, and calk rather than ooze was predominant below a depth of 20 m. Steeper diagenetic gradients at Site 631 were also indicated by more rapid decreases in water content and porosity, with concomitant increases in density and sonic velocity (Austin, Schlager, Palmer and others, in press). Unlike the slope north of Little Bahama Bank, aragonite remained abundant throughout the hole, and dolomite appeared in the lower part of the section. Thick overgrowths on planktonic foraminifera made dating at Site 631 difficult.

As could be expected from these results, pore water geochemistry was very different at Site 631 than at sites north of Little Bahama Bank. Calcium exhibited a uniform gradient, and alkalinity increased downhole, apparently a direct result of CO_2 liberated as a by-product of sulfate reduction. The greatest dolomite concentrations occurred in sediments with the highest alkalinities, suggesting that dolomite was being formed as a primary chemical precipitate in Exuma Sound sediments.

Because of the steepness of the slope and the rough bottom topography in the vicinity of Site 631, a coherent seismic stratigraphic framework could not be developed. However, the presence of hummocky clinoforms in the vicinity suggests an interfluve/levee sequence, which would explain the lack of turbidites in the section. Furthermore, a shingled seismic facies pattern on the site-survey dip-line crossing the drill-site (ES-7, Fig. 14; see Austin, Schlager, Palmer and others, in press) suggests progradation of the slope, but apparently without supporting sedimentological evidence for slumping and/or debris flows. Perhaps continuous downslope creep is responsible for the observed seismic pattern, which would also explain the lack of hiatuses in Hole 631A and the gradients in physical properties (Austin, Schlager, Palmer and others, in press).

Site 632 had two objectives. The first was to serve as the basinward end of the Exuma Sound slope transect in order to document the record of presumably rapidly deposited ooze and turbidites within an enclosed reentrant (Fig. 14). The second was to continue to calibrate seismic stratigraphic frameworks developed for various parts of the Bahamas (e.g. Sheridan and others, 1981; Van Buren and Mullins, 1983; Austin, 1983; Schlager, August and others, 1984) in order to make viable regional correlations. Only the first objective was achieved, as the presence of hydrocarbon shows below depths of 160 m prevented a projected 1.3 km penetration attempt to an inferred mid-Cretaceous(?) shallow-water platform top at this location (Austin, Schlager, Palmer and others, in press).

Two holes were drilled at Site 632, the first using HPC/XCB techniques to a sub-bottom depth of 141 m, and the second using a standard rotary approach to 283 m sub-bottom, where drilling had to be terminated and the hole cemented because of hydrocarbons. Hole 632A recovered 59% of the section, while Hole 632B obtained only 21% recovery. Both holes sampled a late Miocene-Recent sequence of periplatform ooze, chalk and platform-derived turbidites (Fig. 12) representative of a basin-floor facies (as opposed to the turbidite-free muds recovered on the bypass slope at Site 631).

Sedimentation rates in upper Miocene periplatform chalk and intercalated turbidites were at least 120 m/m.y. However, within the constraints of the depositional setting, sedimentation rates fluctuated considerably. Rapid deposition and frequent turbidites are encountered in the late Miocene, late early Pliocene, and the latest Pliocene-Quaternary, punctuated by either slow rates/few turbidites or hiatuses in the earliest Pliocene and the late Pliocene (Fig. 15). High sedimentation rates and major turbidite influxes correspond either to postulated sea level highstands or to times of frequent bank flooding and exposure (Quaternary), while the intervening periods of low rates are more closely approximated by postulated sea level lowstands (Fig. 15). This pattern correlates well with the global sea level curves developed by Vail and others (1977) and Haq and others (in press), and to a lesser extent, with the bank stratigraphy developed by Williams (1985) (Fig. 15).

As at Site 631, shallow subsurface diagenesis at Site 632 was raid, leading to extensive lithification and steep gradients in density, porosity, and sonic velocity (Austin, Schlager, Palmer and others, in press). Limestones were abundant in the earliest Pliocene section at depths below 100 m, and both turbidites and intervening oozes were equally well-lithified. Nonetheless, aragonite was present throughout the drilled interval, although its percentage declined to approximately 10% in the Miocene limestones at the bottom of Hole 632B. Celestite-filled fractures in these limestones may in fact have been related to aragonite dissolution and related increases in strontium in pore waters, along with incomplete sulfate reduction. High-magnesian calcite was also present down to a depth of 40 m, whereas it

0

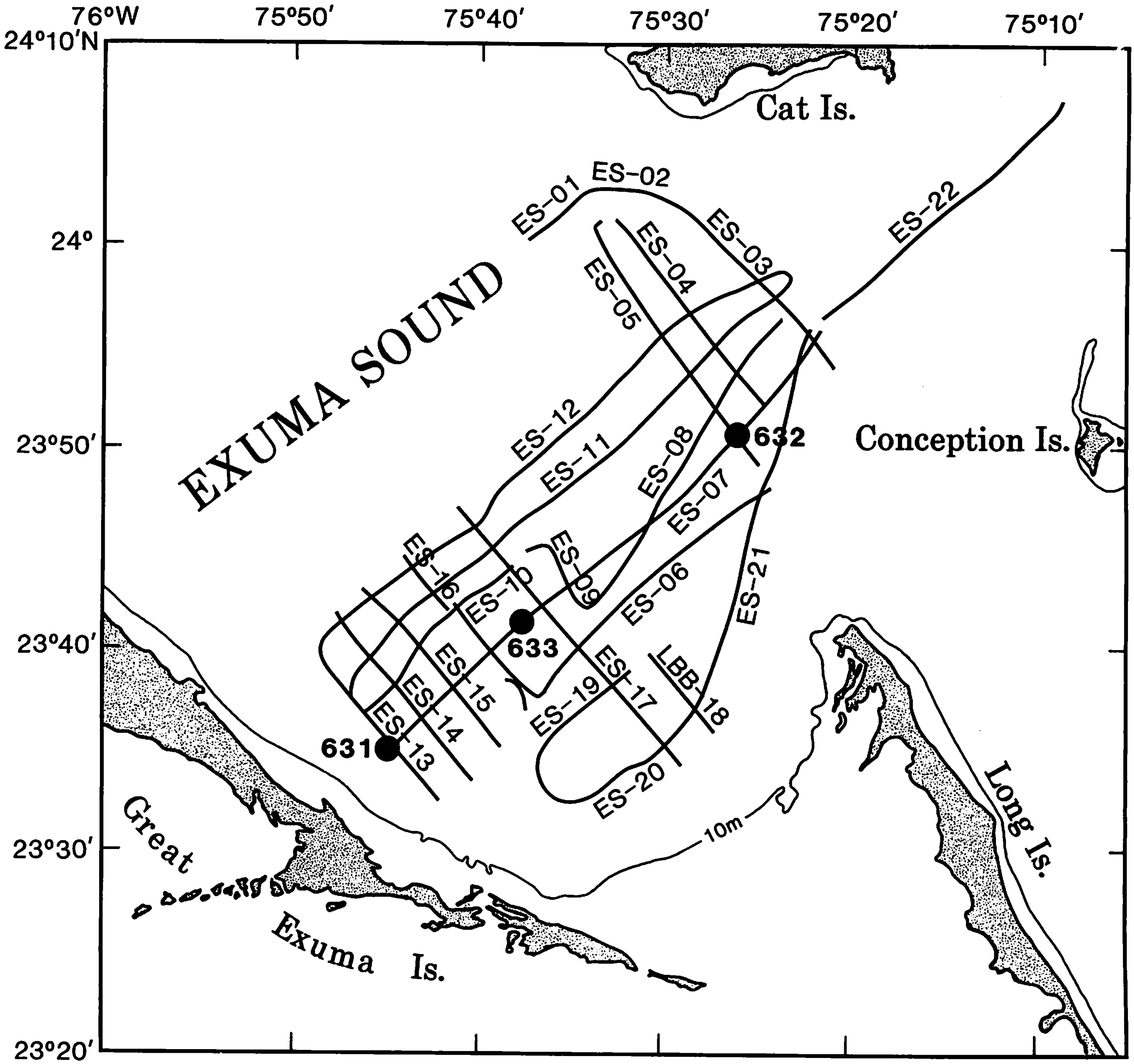


Fig. 14. Map of the geophysical survey grid for Sites 631-633 in the southeastern part of Exuma Sound. The highlighted portion of ES-07 is shown as Fig. 16. All of these profiles are 24-trace, 12-fold, collected with a 400 cu. in. water gun.

generally disappeared within the upper 10 m of the sediment column north of Little Bahama Bank. As at Site 631, the alkalinity and sulfate profiles suggested that alkalinity was controlled by sulfate reduction and oxidation of organic matter (with the associated liberation of CO_2).

Even though Site 632 could not be drilled to its original target depth, it provided some important calibration for the seismic stratigraphy of Exuma Sound. Most significant was the correlation of the top of a sequence of latest Miocene turbidites and periplatform limestones with a regionally identified sequence boundary (Sheridan and others, 1981; Ladd and Sheridan, in press) coeval with another calibrated by Site 626 in the Straits of Florida (Austin, Schlager, Palmer and others, in press). Seismic sequences above and below this marker showed distinct channeling on orthogonal site-survey lines (ES-05 and ES-07, Fig. 14; Austin, Schlager, Palmer and others, in press), suggesting that Neogene turbidites entered the northwest-southwest trending axial valley of Exuma Sound from a variety of directions.

Site 633 was the final hole of the Exuma Sound transect. Analogous to Site 628 north of Little Bahama Bank, its primary objectives was to examine the toe-of-slope environment (Fig. 14). One HPC/XCB hole was drilled, recovering 49% of a late Miocene-Recent sequence of periplatform ooze, chalk, and limestone with thin turbidites to a depth of 227 m (Fig. 12). An accumulation rate of at least 58 m/m.y. characterized the uppermost Miocene-lower Pliocene section, with rates potentially as high as 115 m/m.y. However, considering the magnitude of these rates and the proximal position of the site, turbidites were unusually few, thin, and fine-grained. The reason may be that Site 633 was located on a late Miocene(?) topographic high which might have originated in response either to progradation of a spur of the gullied slope or to slumping.

The slumping hypothesis gains support from the seismic stratigraphy at Site 633, which suggests at least three and perhaps more such episodes as indicated by a vertical stack of hummocky clinoforms (Fig. 16). Additional supporting evidence comes from the aragonite content in Hole 633A, which is nearly constant in the interval 52-142 m sub-bottom, unlike its steady decrease with depth at Site 632. Similar interruptions occur in the downhole trends for porosity, density and water content, all of which are consistent homogenization related to gravitational mass-wasting (Austin, Schlager, Palmer and others, in press). However, biostratigraphic dating at this site was difficult because of both low plankton diversity and diagenetic overgrowths, so these preliminary interpretations will probably be modified by supplementary onshore investigations.

Once again, pore water geochemistry at Site 633 points to extensive sulfate reduction coupled with oxidation of rapidly buried organic matter and a consequent increase in alkalinity. An alkalinity maximum coincides with sulfate and calcium minima at approximately 150 m sub-bottom. Despite this active diagenetic activity, Hole 633A contains abundant clay-sized aragonite, which persists in significant amounts (almost 60% of total carbonate) to the base of the sampled section.

DISCUSSION

The success of ODP Leg 101 must be viewed within the context of the dual nature of its scientific objectives: to sample an inferred Cretaceous "megaplatform" in at least two locations and to monitor the Neogene evolution of carbonate slopes in order to assess their complex response to sea level/climate fluctuations and regional tectonic effects. In retrospect, the first, or "deep", objective was only partially achieved, as actual sampling of a mid-Cretaceous shallow-water platform complex was accomplished at only Site 627 on the southern Blake Plateau, while the "shallow" objective was completely addressed by the success of the two transects in Exuma Sound and north of Little Bahama Bank.

Platform Drowning

Leg 101, Site 627 proved unequivocally that shallow-water carbonate platform complex occupied what is now the southern part of the Blake Plateau in late Albian time, DSDP Sites 390 and 392 on the Blake Nose, located approximately 300 km northeast of Site 627, had already shown that a similar bank complex existed there, but only until Barremian time (Benson, Sheridan and others, 1978). Therefore, diachronous,

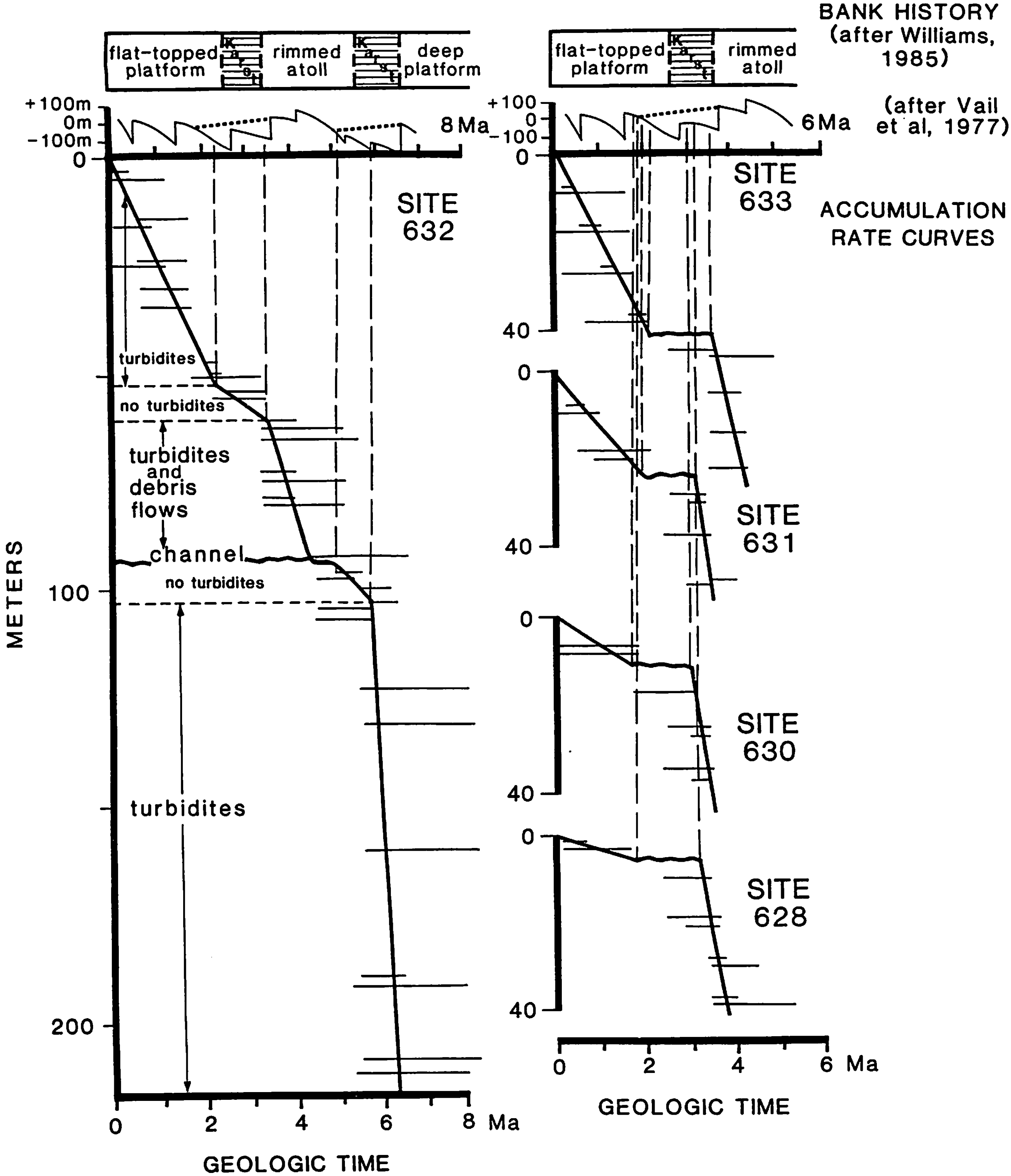


Fig. 15. Comparison of accumulation rate curves for all of the slope sites north of Little Bahama Bank and in southeastern Exuma Sound with calibrated stratigraphic successions on the banks themselves (after Williams, 1985) and Vail and others (1977) global sea level curve. Biostratigraphic control is indicated by short, horizontal line segments (see also Austin, Schlager, Palmer and others, in press). Depositional hiatuses (wavy lines)/low sedimentation rates (near-horizontal lines, accumulation rate curves) on the slopes generally correspond to lowstands and times of exposure (with associated development of karst surfaces) of the banks, while higher depositional rates (near-vertical lines, accumulation rate curves) on the slopes correspond to global highstands and periods of bank inundations. These results tend to support "highstand shedding" in carbonate depositional systems, a response which is nearly the opposite of that observed in siliciclastic regimes. The dashed line connecting parts of the sea level curve corresponds to the estimated subsidence rate for the Bahamas at present, 11-12 m/m. y., and indicates the approximate duration of bank exposure assuming the amplitude of sea level excursions proposed by Vail and others (1977).

stepwise drowning on the Blake Plateau is implied.

This concept of stepwise drowning of a preexisting megaplatform receives further support form Leg 101 results in both Northeast Providence Channel and in the Straits of Florida. At Site 635, late Albian limestones are bathyal, with only a minor platform-derived component. If the acoustic unconformity/velocity contrast left unsampled just beneath these limestones is indeed the top of a shallow-water platform, then that platform was probably drowned prior to the late Albian. At Site 627, on the other hand, the oldest "post-drowning" sediments are latest Albian-earliest Cenomanian, while the age of the underlying platform is late Albian (Austin, Schlager, Palmer and others, in press). This suggests a slight age difference between the drowning events at Sites 627 and 635. Another possibility is that Site 635 is located in a deep reentrant of an extensive Early Cretaceous shallow-water platform. Other such reentrants have already been documented in the southeastern Gulf of Mexico and the Bahamas (Schlager, Buffler and others, 1984; Buffler, Schlager and others, 1984; Schlager, Austin and others, 1984; Ball and others, 1985; Eberli and Ginsburg, in press).

The platform tops (drilled and inferred, respectively) at Sites 627, 626, and 635 also differ in elevation. In the central Straits of Florida, the inferred platform top is approximately 2 km below present sea level, with a mapped local relief (patch reefs?) of approximately 0.2 km (Fig. 5). North of Little Bahama Bank approximately 300 km to the northeast, the top of the platform is only 1.5 km below present sea level, with little apparent local relief (Fig. 7). In Northeast Providence Channel, the inferred top is roughly 3.7 km below sea level. Local relief is unknown. The differential of 0.5 km between Sites 626 and 627 translates to a southwesterly dip of the platform top of 0.1°, while the differential of 2.2 km between Sites 627 and 635 means a dip of 0.4° to the south-southeast. These dips are considerably higher than can be expected of the depositional surface of a reef-rimmed platform complex such as the mid-Cretaceous one that appears to have existed in Florida and the Bahamas. In direction and magnitude, these dips fit the regional patterns of differential subsidence that have characterized the passive margin off the east coast of North America over the past 100 m.y. (Watts and Steckler, 1981; Klitgord and others, 1984). Such gentle regional tilts to the south could also be explained by the collision of the Bahamas carbonate province with the Greater Antilles island arc in the Late Cretaceous-Paleogene (Malfait and Dinkelman, 1972). Similar southerly dips of deep reflections have been observed near the convergence zone of the southeastern Bahamas and Hispaniola (Goreau, 1981; Austin, 1983).

However, faulting cannot be excluded as a contributing factor in controlling Bahamas bank margins through geologic time. For example, the Walkers Cay normal fault originally identified by Van Buren and Mullins (1981) north of Little Bahamas Bank is visible on site-survey profile LBB-18 (Fig. 7). While it does not appear to cut the platform top ("F"-"G" sequence boundary), faults of this kind could be responsible for the upward migration of the hydrocarbons encountered at Site 627 and Site 632 in Exuma Sound. The vertical relief between mid-Cretaceous platform tops known at Site 627 and inferred at Site 635 could also be related to northwest-southeast trending Atlantic fracture zones, extensions of which have been mapped across the northwestern Bahamas using aeromagnetic data and basement depth estimates beneath the Florida Peninsula (Sheridan and others, 1981; Klitgord and others, 1984). These fracture zones are believed to control the placement and development of both Northeast and Northwest Providence channels and Great Abaco Canyon (Sheridan and others, 1969; Sheridan and others 1981; Mullins and others, 1982), and they may also be responsible for the faulting which appears to have produced Abaco Knoll, just northeast of Sites 634-636 (Corso and others, 1985). The collision of the Bahamas and the Greater Antilles in the Late Cretaceous-Paleogene produced faults in the southeastern Gulf of Mexico and in the southern Straits of Florida (Angstadt and others, 1985), and it may also have contributed to tectonic deformation in other parts of the Bahamas (Mullins and Sheridan, 1983; Austin, 1983). However, small faults in the vicinity of Site 626 (Fig. 3) may be related more to differential compaction and lithification than to regional tectonism. In summary, the degree

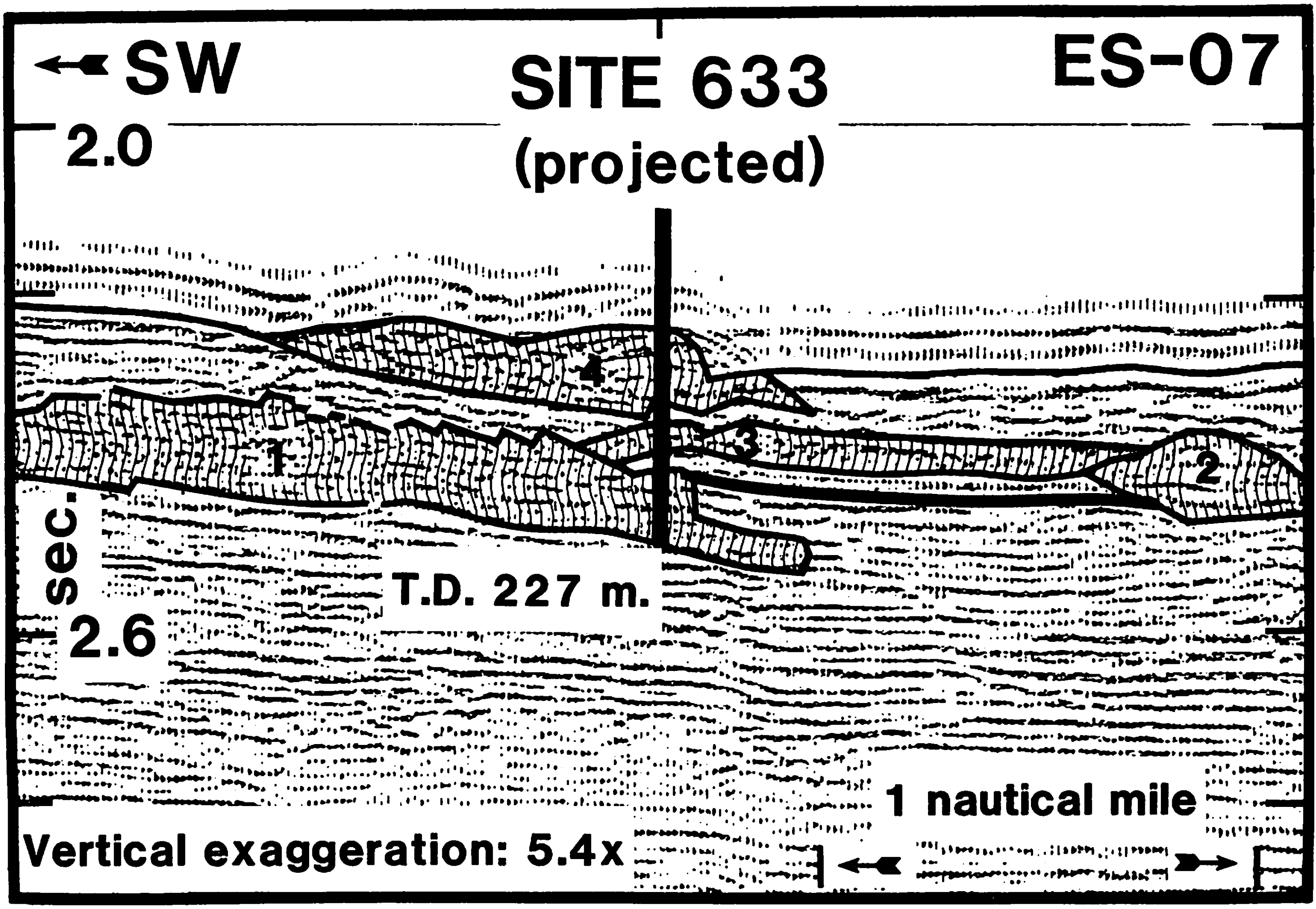


Fig. 16. The portion of site survey profile ES-07 which crosses Site 633, just basinward of the toe-of-slope in Exuma Sound (see Fig. 14 for location). Note the discrete slump/slide masses (each highlighted by a different number/pattern) which may be building the slope basinward. A regional seismic stratigraphic marker (heavy solid line) identified by Ladd and Sheridan (in press) marks the top of a sequence of latest Miocene turbidites and periplatform limestones at Site 632.

to which faulting rather than long-term depositional controls determines the placement and orientation of deep reentrants in the Bahamas carbonate platform must await further deep-penetration seismic reflection profiling (e.g. Eberli and Ginsburg, in press) and drilling.

Slope Evolution

Highstand shedding. By using advanced drilling technology designed specifically to recover soft and semi-lithified sediments, Leg 101 recovered near-complete sections documenting the Neogene evolution of a broad, gentle and a higher, much steeper carbonate slope. Preliminary results support the concept of "highstand shedding", whereby the maximum carbonate bank productivity and consequent off-bank transport of carbonate debris occurs during postulated highstands of sea level (Fig. 15; Droxler and Schlager, 1985). This response of carbonate banks to sea level fluctuations had been generally predicted by piston coring investigations in the Bahamas (Kier and Pilkey, 1971; Mullins, 1983; Droxler and others, 1983; Boardman and Neumann, 1984; Droxler, 1984; Boardman and others, 1986). Highstand shedding is also indicated by the correlation of sedimentation rates in Exuma Sound and the stratigraphy of the Bahama Banks themselves (Fig. 15), although the dating of karst horizons (exposure surfaces) on the platforms is less precise than the Leg 101 biostratigraphic control on the slopes (Beach, 1982; Williams, 1985). Highstand shedding is almost diametrically opposed to the response of such margins to such sea level changes (e.g. Vail and others, 1977; Poag, 1985; Haw and others, in press).

Local influences, i.e. bank/slope topography, hydrography and tectonic effects, complicate these "eustatic" signals. For example, the recovery of middle Miocene debris flows in the Straits of Florida, north of Little Bahama Bank and in the abyssal Blake Bahama Basin suggests a regional, presumably tectonic, event which triggered a sedimentologic response felt in all water depths. A coeval catastrophic collapse of part of the west Florida carbonate platform margin may have the same cause (Mullins and others, 1986). Furthermore, the incomplete correlation of well-sampled Tertiary sediment records at Sites 627 and 628 only 10 km apart (Fig. 13) is ample testimony to the complexity of depositional systems near the axes of meandering currents like the Gulf Steam/Antilles Current. Clearly additional work is required to understand not only the depositional evolution of continental margins, particularly where these margins receive mixed carbonate/clastic input, but the nature of the transfer mechanisms affecting the movement of margin sediments across slopes and rises to the deep-sea.

Sediment record. Leg 101 spent considerable effort attempting to close a gap between studies on recent carbonate slopes and those on their ancient counterparts. Of modern slopes, we already knew the nature of the surficial sediment cover, topography, and, to some extent, the formative processes. Windward-leeward orientations, setting in an open ocean vs. a restricted embayment, and other factors such as slope angle and height were all understood to influence recent sedimentation on Bahamian slopes (Mullins and Neumann, 1979; Schlager and Ginsburg, 1981; and others). However, while outcrop/piston coring studies normally concentrated on slope cross-sections, i.e. the surficial change through time, Leg 101 drilling allowed the recovery of complete sediment records and therefore the construction of comprehensive Neogene geologic histories of slope development.

Leg 101 concentrated on a comparison of a gentle, relatively low slope in an open-ocean setting and a steeper, higher slope within a reentrant. The results suggest some modifications of our original ideas concerning carbonate platform flank development. In both Exuma Sound and north of Little Bahama Bank, the slope proper is a zone of mud accumulation. Coarser debris bypasses the slope in turbidity currents, forming graded beds on the lower slope apron and basin floor. As expected, the steep southeastern slope of Exuma Sound is more efficient than the gentle northern slope of Little Bahama Bank in funneling sediment offshore. In Exuma Sound, sedimentation rates in the basin are higher than those on the slope (Fig. 15). In contrast, north of Little Bahama Bank sedimentation rates are highest on the slope and decrease towards the Blake Plateau (Fig. 15; Austin, Schlager, Palmer and others, in press). This confirms part of the evolutionary trend suggested by Schlager and Ginsburg (1981). However, sedimentation rates in Exuma Sound were much higher than expected, and there were none of the expected signs of intermittent erosion and sediment starvation that would herald the transition from "accretionary" to "erosional" slope regimes. The slopes up to 12° explored during Leg 101 are all still accreting rapidly, further substantiating the hypothesis that carbonate bank edges migrate laterally many km through geologic time, with perhaps only limited control exerted by tectonic influences, e.g. regional tilting, faulting.

Geochemistry. Leg 101 also made clear the importance of high depositional rates and local stratigraphy to the pore water geochemistry of carbonate slopes. Elemental abundances of calcium, strontium, and magnesium, and by implication the associated processes of aragonite/high-magnesium calcite dissolution and consequent dolomitization, appeared related either to bacterial sulfate reduction and the production of CO_2 (thereby increasing alkalinities) where sufficient organic material was present and quickly buried (Exuma Sound) or to the presence of underlying terrigenous sediments (Little Bahama Bank). These reactions were further complicated by the presence of migrating hydrocarbons in both slope sections.

CONCLUSIONS

Leg 101 proved that a prominent acoustic unconformity identified beneath the southern Blake Plateau correlates with the top of a drowned, shallow-water carbonate platform complex. Extrapolation of these results to both the Great Isaac-1 well and Site 626 suggests that such a platform underlies all of the northwestern Bahamas. Platform drowning occurred in steps during the mid-Cretaceous, and this segmentation can be explained by differential subsidence patterns characteristic of passive margin environments. However, faulting and/or regional tilting perhaps associated with the collision of the Bahamas and the Greater Antilles during the Late Cretaceous-Paleogene are other possible mechanisms controlling the long-term platform-basin pattern. In the south and southeast, this mid-Cretaceous "megaplatform" may have had deep-water reentrants of its own. However, during the Late Cretaceous and Tertiary, north- and west-facing platform flanks have prograded tens of kilometers.

In terms of carbonate slope evolution, Leg 101 drilling lends support to the concept of highstand shedding, a depositional response to sea level fluctuations generally opposite to that of siliciclastic systems. Slopes themselves are generally covered by muddy sediments, whereas graded sand and rubble characterize the turbidite aprons at the toe-of-slope and on the basin floors. Bypassing of the slopes by turbidity currents and slumps is more efficient on steeper slopes, but all slopes drilled during Leg 101 accrete rapidly and the transition to erosional slopes must occur at declivities over 12°.

By encountering migrating hydrocarbons at Sites 627 and 632, Leg 101 illustrated emphatically (although without prior intent) that the Bahamas is a prospective region for oil and gas exploration, much like its ancient counterparts.

In conclusion, Leg 101 set a reasonable standard to achievement for the new Ocean Drilling Program. Eleven sites and nineteen holes were occupied in only 36 days of operations, and almost 1.5 km of core was retrieved (46.2% recovery). A commercial drilling vessel was converted and used for deep-ocean operations, and advanced technology was successful both in sampling and logging the first boreholes attempted in the Bahamian archipelago in fourteen years.

ACKNOWLEDGMENTS

The Scientific Party of Leg 101, the inaugural international expedition of the Ocean Program (ODP), wishes to express its profound appreciation to Captain Gerard Kuster and the crew of the *JOIDES Resoution* (SEDCO BP-471) for their diligence and skill in helping us to achieve so many of our scientific objectives. A special thanks goes to "Doc" Knotts for making all of those ham radio telephone patches that kept us in touch with families and friends back on *terra firma*. We also thank the Texas A&M University/ODP seagoing technical staff for their competence, enthusiasm and good humor as we all literally and figuratively broke new ground.

We thank Pamela Vesterby, who turned almost unintelligible scratchwork into scientific art of high quality.

We formally acknowledge and thank the

government of the Commonwealth of the Bahamas for granting us permission both to conduct geophysical site surveys and carry out subsequent drilling operations in their territorial waters. Tom Cocke and Bill Erb at the U.S. Department of State were indefatigable in their efforts to secure that permission for us.

Our appreciation goes also to the captain and crew of the University of Texas Institute for Geophysics vessel *Fred H. Moore* for their help in making the seismic surveys of potential Bahamas drilling sites a success. Joint Oceanographic Institutions, Inc. funded these surveys under Subcontract No. 62-84 as part of their continuing mandate to fund site-surveys for ODP on behalf of the National Science Foundation. We also want to thank our scientific partners in that site-survey effort who were not subsequently part of the Leg 101 Scientific Party: John Ladd of Lamont-Doherty Geological Observatory, Robert Sheridan of the University of Delaware, and John Ewing and Mike Purdy of Woods Hole Oceanographic Institution.

Finally, we thank both the JOIDES Planning Committee and associated advisory panels for their support of Leg 101, and the people and governments of the JOIDES member nations for their continuing financial support of and scientific input to ODP.

University of Texas Institute for Geophysics Contribution No. 690

REFERENCES CITED

Andrews, J.E., Shepard, F.P., and Hurley, R.J., 1970, Great Bahama Canyon: Geological Society of American Bulletin, v. 81, p. 1061-1078.

Angstadt, D.M., Austin, J.A., Jr., and Buffler, R.T., 1985, Early Late Cretaceous to Holocene seismic stratigraphy and geologic history of southeastern Gulf of Mexico: American Association of Petroleum Geologist Bulletin, v. 69, p. 977-995.

Austin, J.A., Jr., 1983, OBC 5-A: Overthrusting in a deep-water carbonate terrane in Bally, A.W., ed., American Association of Petroleum Geologists Studies in Geology, v. 3, no. 15, p.3.4.2, 167-172.

Schlager, W., and others, in press, Initial Reports of the Ocean Drilling Program, Leg 101, pt. A, Texas A&M University, College Station.

Ball, M.M., Martin, R.G., Bock, W.D., Sylvester, R.E., Bowles, R.M., Taylor, D., Coward, E.L., Dodd, J.E., and Gilbert, L., 1985, Seismic stratigraphy and structure of norther edge of Bahaman-Cuban collision zone: American Association of Petroleum Geologists Bulletin, v. 69, p.1275-1294.

Beach, D., 1982, Depositional and diagenetic history of Pliocene-Pleistocene carbonates of northwestern Bahama Bank; evolution of a carbonate platform (Ph.D. thesis): Coral Gables, Florida, University of Miami, 447 p.

Benson, W.E., Sheridan, R.E., and others, 1978, Initial reports of the Deep Sea Drilling Project, Volume 44: Washington, D.C., U.S. Government Printing Office, p. 1-1005.

Bliefnick, D.M., Robertson, A.H.F., and Sheridan, R.E., 1983, Deposition and provenance of Miocene intraclastic chalks, Blake-Bahama Basin, western North Atlantic, in Sheridan, R.E., Gradstein, F.M., and others, Initial reports of the Deep Sea Drilling Project, Volume 76: Washington, D.C., U.S. Government Printing Office, p. 727-748.

Boardman, M.R., and Neumann, A.C., 1984, Sources of periplatform sediment to Northwest Providence Channel, Bahamas: Journal of Sedimentary Petrology, v. 54, p.1110-1123.

Neumann, A.C., Baker, P.A., Dulin, L.A., Kenter, R.J., Hunter, G. E., and Kiefer, K.B., 1986, Banktop responses to Quaternary fluctuations in sea level recorded inperiplatform sediments: Geology, v. 14, p. 28-31.

Buffler, R.T., Schlager, W., and others, 1984, Initial reports of the Deep Sea Drilling Project, Volume 77: Washington, D.C., U.S. Government Printing Office, p. 1-747.

Cook, H.E., and Enos, P., 1977, Deep-water carbonate environments-an introduction, in Cook, H.E., and Enos, P., eds., Deep-water carbonate environments: Society of Economic Paleontologists and Mineralogists Special Publication No. 25, p. 1-3.

Corso, W., Schlager, W., Flugel, E., and Buffler, R.T., 1985, A reinterpretation of an Early Cretaceous carbonate platform on Abaco Knoll, northwestern Bahamas: Gulf Coast Association of Geological Societies Transactions, v. 35, p. 29-38.

COSOD, 1981, Report of the Conference on Scientific Ocean Drilling: Joint Oceanographic Institutions for Deep Earth Sampling, Washington, D.C., 112 p.

Droxler, A.W., 1984, Late Quaternary glacial cycles in the Bahamian deep basins and in the adjacent Atlantic Ocean (Ph.D. thesis): Coral Gables, Florida, University of Miami, 120 p.

_______________ Schlager, W., and Whallon, C.C., 1983, Quaternary aragonite cycles and oxygen-isotope record in Bahamian carbonate ooze: Geology, v. 11, p. 235-239.

_______________ Schlager, 1985, Glacial versus interglacial sedimentation rates and turbidite frequency in the Bahamas: Geology, v. 13, p. 799-802.

Eberli, G.P., and Ginsburg, R.N., in press, Segmentation and coalescence of Cenozoic carbonate platforms, northwestern Great Bahama Bank: Geology.

Enos, P., 1977, Tamabra Limestone of the Poza Rica trend, Cretaceous, Mexico, in Cook, H.E., and Enos, P., eds., deep-water carbonate environments: Society of Economic Paleontologists and Mineralogists Special Publication No.25, p. 273-314.

Gieskes, J.M., 1981, Deep-sea drilling interstitial water studies: Implications for chemical alteration of the oceanic crust, Layers I and II, in Warme, J.E., Douglas, R.G., and Winterer, E.L., eds., The Deep Sea Drilling Project: A Decade of Progress: Society of Economic Paleontologists and Mineralogists Special Publication No. 32, p. 149-167.

Goreau, P.D.E., 1981, The tectonic evolution of the north central Caribbean plate margin (Ph.D. Thesis): Woods Hole, Massachusetts, Massachusetts Insitute of Technology-Woods Hole Oceanographic Institution, 245p.

Haq, B.U., Hardenbol, J., and Vail, P.R., in press, Chronology of fluctuating sea levels since the triassic (250 million years ago to Present): Science.

Heezen, B.C., and Sheridan, R.E., 1966, Lower Cretaceous Rocks (Neocomian-Albian dredged from Blake Escarpment: Science, v. 154, p. 1644-1647.

Hollister, C.D., Ewing, J.I., and others, 1972, Initial reports of the Deep Sea Drilling Project, Volume 11: Washington, D.C., U.S. Government Printing Office, 1077 p.

Kier, J.S., and Pilkey, O.H., 1971, The influence of sea-level changes on sediment carbonate mineralogy, Tongue of the Ocean, Bahamas: Marine Geology, v. 11, p. 189-200.

Klitgord, K.D., Popenoe, P., and Schouten, H., 1984, Florida: A Jurassic transform plate boundary: Journal of Geophysical Research, v. 89, p. 7753-7772.

Ladd, J.W., and Sheridan, R.E., in press, Seismic Stratigraphy of the Bahamas: American Association of Petroleum Geologists Bulletin.

Leg 100 Scientific Party, 1985, Ocean drilling program launches first cruise: Geotimes, v. 30, no. 7, p. 12-14.

Leg 101 Scientific Party, 1985a, Rise and fall of carbonate platforms in the Bahamas: Nature, v. 30, no. 6021, p. 632-633.

_______________ 1985b, Megabank found? Flanks record sea level: Geotimes, v. 30, no. 11, p. 12-15.

Malfait, B.T., and Dinkelman, M.G., 1972, Circum-Caribbean tectonics and igneous activity and the evolution of the Caribbean plate: Geological Society of America Bulletin, v. 83, p. 251-272.

Meyerhoff, A.A., and Hatten, C.W., 1974, Bahamas salient of North America, in Burk, C.A., and Drake, C.L., eds., The geology of continental margins: New York, Spring-Verlag,p. 429-446.

Mullins, H.T., 1983, Eustatic control of turbidites and winnowed turbidites: comment: Geology, v. 11, P. 57-60.

_______________ and Lynts, G.W., 1977, Origin of the Northwestern Bahama Platform: review and reinterpretations: Geological Society of American Bulletin, v. 88, p. 1447-1461.

_______________ and Neumann, A.C., 1979, Deep carbonate bank margin struction and sedimentation in the northern Bahamas, in Doyle, L.J., and Pilkey, O.H., eds., Geology of carbonate slopes: Society of Economic Paleontologists and Mineralogists special Publication No. 27, p. 165-192.

_______________ and Sheridan, R.E., 1983, Wrench tectonic origin for the northern Bahama platform (abs.): Geological Society of America Abstracts with Programs, v. 15, no. 6, p. 648-649.

_______________ Neumann, A.C., Wilber, R.J., Hine, A.C., and Chinburg, S.J., 1980, Carbonate sediment drifts in northern Straits of Florida: American Association of Petroleum Geologists Bulletin: v. 64, p. 1701-1717.

_______________ Keller, G.H., Kofoed, J.W., Lambert, D.N., Stubblefield, W.L., and Warme, J.E., 1982, Geology of Great Abaco Submarine Canyon (Blake Plateau): Observations from the research submersible "Alvin": Marine Geology, v. 48, p. 239-257.

_______________ Heath, K.C., Van Buren, H.M., and Newton, C.R., 1984, Anatomy of a modern open-ocean carbonate slope: northern Little Bahama Bank: Sedimentology, v. 31, p. 141-168.

_______________ Wise, S.W., Jr., Land, L.S., Siegel, D.I., Masters, P.M., Hinchey, E.J., and Price, K.R., 1985, Authigenic dolomite in Bahamian peri-platform slope sediment: Geology, v. 13, p. 292-295.

_______________ Gardulski, A.F., and Hine, A.C., 1986, Catastrophic collapse of the west Florida carbonate margin: Geology, v. 14, p. 167-170.

Murris, R.J., 1980, Middle East stratigraphic evolution and oil habitat: American Association of Petroleum Geologists Bulletin, v. 64, p. 597-618.

Olsson, R.K., Miller, K.G., and Ungrady, T.E., 1980, Late Oligocene transgression of middle Atlantic coastal plain: Geology, v. 8, p. 549-554.

Paulus, F.J., 1972, The geology of Site 98 and the Bahama Platform, in Hollister, C.D., Ewing, J.I., and others, Initial reports of the Deep Sea Drilling Project, Volume 11, Washington, D.C., U.S. Government Printing Office, p. 877-897.

Pinet, P.R., and Popenoe, P., 1985a, A scenario of Mesozoic-Cenozoic ocean circulation over the Blake Plateau and its environs: Geological Society of America Bulletin, v. 96, p. 663-675.

_______________ 1985b, Shallow seismic stratigraphy and post-Albian geologic history of the northern and central Blake Plateau: Geological Society of America Bulletin, v. 96, p. 676-690.

Poag, C.W., ed., 1985, Geologic evolution of the United States Atlantic margin: New York, Van Nostrand Reinhold Company, 383 p.

Schlager, W., 1981, The Paradox of drowned reefs and carbonate platforms: Geological Society of America Bulletin, v. 92, p. 197-211.

_______________ and James, N.P., 1978, Low-magnesian calcite limestones forming at the deep-sea floor, Tongue of the Ocean, Bahamas: Sedimentology, v. 25, p. 675-702.

_______________ and Chermak, A., 1979,

Sediment facies of platform-basin transition, Tongue of the Ocean, Bahamas, in Doyle, L.J., and Pilkey, O.H., eds., Geology of continental slopes: Society of Economic Paleontologists and Mineralogists Special Publication No. 27, p. 193-208.

______________ and Ginsburg, R.N., 1981, Bahama carbonate platforms - the deep and the past: Marine Geology, v. 44, p. 1-24.

______________ Austin, J.A., Jr., Corso, W., McNulty, C.L., Fluegel, E., Renz, O., and Steinmetz, J.C., 1984, Early Cretaceous platform reentrant and excarpment erosion in the Bahamas: Geology, v. 12, 147-150.

______________ Buffler, R.T., and others, 1984, Deep Sea Drilling Project, Leg 77, southeastern Gulf of Mexico: Geological Society of America Bulletin, v. 95, p. 226-236.

Sheridan, R.E., Drake, C.L., Nafe, J.E., and Hennion, J., 1966, Seismic-refraction study of continental margin east of Florida: American Association of Petroleum Geologists Bulletin, v. 50, p. 1972-1991.

______________ Smith, J.D., and Gardner, J., 1969, Rock dredges from Blake escarpment near Great Abaco Canyon: American Association of Petroleum Geologists Bulletin, v. 53, p. 2551-2558.

______________ Crosby, J.T., Bryan, G.M., and Stoffa, P.L., 1981, Stratigraphy and structure of southern Blake Plateau, northern Florida Straits, and northern Bahama Platform from multichannel seismic reflection data: American Association of Petroleum Geologists Bulletin, v. 65, p. 2571-2593.

______________ Gradstein, F.M., and others, 1983, Initial reports of the Deep Sea Drilling Project, Volume 76: Washington, D.C., U.S. Government Printing Office, 947 p.

______________ Mullins, H.T., Austin, J.A., Jr., Ball., M.M., and Lass, J.W., in press, Geology and geophysics of the Bahamas: Decade of North American Geology, Geological Society of America.

Talwani, M., Worzel, J.L., and Ewing, M., 1960, Gravity anomalies and structure of the Bahamas: 2nd Caribbean Geological Conference, Mayaquez, Puerto Rico, 1959, Transactions, p. 159-161.

Tator, B.A., and Hatfield, L.E., Bahamas present complex geology: Oil and Gas Journal, v. 73, no. 43, p. 172-176; no. 44, p. 120-122.

Tucholke, B.E., Vogt, P.R., and others, 1979, Initial reports of the Deep Sea Drilling Project, Volume 43: Washington, D.C., U.S. Government Printing Office, 1115 p.

Tyler, N. Galloway, W.E., Garrett, C.M., Jr., Ewing, T.E., 1985, Oil accumulation, production characteristics, targets for added recovery in Texas reservoirs: Oil and Gas Journal, v. 83, no. 8, p. 123-132; no. 9, p. 133-141.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III., Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level, in Payton, C.E., ed., Seismic stratigraphy - applications to hydrocarbon explorations: American Association of Petroleum Geologists Memoir 26, p. 49-212.

______________ and Hardenbol, J., 1979, Sea-level changes during the Tertiary: Oceanus, v. 22, no. 3, p. 71-79.

Van Buren, H.M., and Mullins, H.T., 1981, Seismic stratigraphy of a modern carbonate slope (abs): American Association of Petroleum Geologists Bulletin, v. 65, p. 1004.

______________ 1983, Seismic stratigraphy and geologic development of an open-ocean carbonate slope: the northern margin of Little Bahama Bank, in Sheridan, R.E., Gradstein, F.M., and others: Initial reports of the Deep Sea Drilling Project, volume 76, Washington, D.C., U.S. Government Printing Office, p. 749-762.

Watts, A.B., and Steckler, M.S., 1981, Subsidence and tectonics of Atlantic-type continental margins in Geology of continental margins symposium, Proceedings of the 26th International Congress, Paris: Oceanologica Acta, v. 4, p. 143-153.

Williams, S.C., 1985, Stratigraphy, facies evolution and diagenesis of late Cenozoic limestones and dolomites, Little Bahama Bank, Bahamas (Ph.D. thesis): Coral Gables, Florida, University of Miami, 215 p.