Testing a Seismic Interpretation of Great Bahama Bank with a Computer Simulation[1]

Gregor P. Eberli,[2] Christopher G. St. C. Kendall,[3] Phil Moore,[3] Gregory L. Whittle,[3] and Robert Cannon[4]

ABSTRACT

Sixty million years of carbonate deposition were simulated to test an interpretation of platform development based on seismic data and limited well control from northwestern Great Bahama Bank. Seismic profiles of the northwestern Great Bahama Bank document the lateral growth potential of isolated platforms that were welded together by progradation to form the modern bank. The mechanism we proposed responsible for an evolution from aggradation to progradation was sediment overproduction on the platform, the excess of which was transported offbank and which caused a decrease in accommodation space on the marginal slope. Progradation occurred in pulses that were interpreted to be the result of third-order sea level fluctuations. To evaluate the proposed mechanism, 15 input parameters were used to model the platform evolution.

The simulation program, which uses empirical relationships to model basin fill, successfully reproduced the geometries seen on the seismic lines, indicating that the proposed interplay of mechanisms could have built the observed platform architecture. The simulation demonstrated, in particular, that in a setting like the Bahamas, a basin must be substantially filled before progradation can take place, and that sea level changes can drive the pulses of progradation. This implies that laterally stacked sequences often contain the record of sea level changes, and therefore have potential use in sequence stratigraphy.

The simulation can also be used to estimate the quantitative importance of individual factors controlling aggradation and progradation in the Bahamas. We show how close the balance between aggradation and progradation is, and how small changes in the rate of subsidence or accumulation can cause immediate switches from aggradation to progradation. In particular, we show that the rate of subsidence exerts the major control on the timing of progradation, more so than basin width. Carbonate production rates similar to modern rates were required to produce the necessary sediment input for progradation, which suggests that carbonate production has been consistently high since the early Tertiary. Repeated exposure and erosion, however, have decreased the overall accumulation rate. The simulation also suggests that the asymmetric progradation in the Bahamas was only possible where there were extreme differences between windward and leeward conditions, with a maximum sediment input of 10% from the windward side.

INTRODUCTION

Data from seismic surveys are usually the best sources of information for a frontier region, but are often poorly constrained stratigraphically by sparse well and/or outcrop data. For this reason, the initial interpretation of a frontier region is often speculative. The usual test of the interpretation is costly drilling, but now computer simulations offer an alternative test for the interpretation of the nature of basin fill. Such simulations can help to better site the exploration wells and thus potentially increase the success rate in drilling.

A successful sedimentary simulation program should account for all of the relevant parameters

---

[1] Manuscript received, March 12, 1993; revised manuscript received, January 25, 1994; final acceptance, February 16, 1994.

[2] Department of Marine Geology and Geophysics, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Florida 33149.

[3] Department of Geological Science, University of South Carolina, Columbia, South Carolina 29208.

[4] Department of Computer Science, University of South Carolina, Columbia, South Carolina 29208.

Part of the work by G. Eberli was performed during his tenure at the Geological Institute at the Eidgenosische Technische Hochschule, Zürich, Switzerland, with financial support from the Swiss Nationalfonds Grant 20-27 457.89 to Daniel Bernoulli. He thanks Martin Casey for technical assistance with installing the SEDPAK program in Zürich. Work on SEDPAK and its applications was funded by Conoco, JNOC, Mobil, Texaco, Statoil, and British Petroleum. The careful reviews of Mark Longman, Edward Purdy, and Wolfgang Schlager improved the manuscript. In addition, discussion with Wolfgang Schlager helped clarify several points of the manuscript.

responsible for the observed stratal geometries. In particular, input parameters for a simulation program should include assumptions about the sedimentation processes and the tectonic evolution of the study area. These assumptions should be based upon currently accepted sedimentological, tectonic, and eustatic models (Scaturo et al., 1989; Boscence and Waltham, 1990; Kendall et al., 1990; Lawrence et al., 1990; Bosscher and Southam, 1992) and not be blind creations of the users. These parameters should be weighted by the interpretation of the sedimentary history of the basin. When this is done and the simulated geometries match with the observed seismic geometries, the simulation parameters can be assumed to be more likely those that produced the observed geometries. At the same time, it should be recognized that a simulation success does not represent the absolute truth of a particular interpretation, but almost invariably will provide constraints to boundary conditions.

This paper reports on the use of the simulation program, SEDPAK, developed at the University of South Carolina, which was used to test the interpretation of the first multichannel seismic lines from the top of Great Bahama Bank. In using the simulation, we hoped to (1) gain feedback on how such a procedure affects our understanding of the sedimentary models which are programmed into the simulation, and (2) display the strengths and weaknesses of such a simulation.

The sequence stratigraphic model we simulated was based upon a grid of multichannel seismic lines from northwestern Great Bahama Bank, which reveals the internal structure of the bank (Eberli and Ginsburg, 1987, 1988). Sources of information for the timing and facies of the sedimentary packages came from the cuttings of only one well, the Great Isaac well, at the northern end of the grid. Based upon these sparse data and current carbonate depositional models, an interpretation that related pulses of progradation to third-order variations of sea level was made for the platform (Eberli and Ginsburg, 1989). In this and similar cases, an interpretation from such a limited data base inevitably requires acceptance of the assumptions of the models applied.

In the Bahamian examples, Eberli and Ginsburg (1989) proposed that variations in eustatic sea level exerted an important control on sedimentary sequences, and they related pulses of progradation to these sea level changes. They used a sequence stratigraphic approach to seismic interpretation and a correlation to the global onlap chart (Haq et al., 1987) to tentatively date the seismic reflectors. The goal of the present simulation of the Great Bahama Bank seismic lines is to test this interpretation; thus, the sea level curve of Haq et al. (1987) was used as given, but other parameters were varied. Those parameters included subsidence as a function of time, pelagic deposition as a function of time, depth-dependent carbonate accumulation, and damping of carbonate accumulation by windward wave activity. All these parameters are known to influence carbonate platform evolution. Not all of them are quantitatively determined, however. The interactions of these parameters and the assumptions as to their size were evaluated by using the simulation. Sixty million years of carbonate deposition were modeled to reproduce the sequence geometries seen on the seismic section and to test the proposed sequence stratigraphic model of Eberli and Ginsburg (1989).

BAHAMAS DATA SET

The seismic data set used in this experiment consists of a cross-bank profile that was part of a study of an approximately 700-km-long grid of unmigrated, multichannel seismic profiles. The top 1.7 s (two-way traveltime) were accessible for the initial study of a cross-bank profile located on the southern side of the grid. For the rest of this northern grid, the top 1.1 s (two-way traveltime) of the profile were available. These seismic profiles are tied to the industrial Great Isaac well at the northwestern edge of the Great Bahama Bank (Figure 1). The time-to-depth conversion from the Great Isaac well indicates that the entire Cenozoic history is recorded in these upper sections (Tator and Hatfield, 1975; Schlager et al., 1988). The cuttings from this well gave some of the initial information on the lithology and age of the reflectors (Schlager et al., 1988; Eberli and Ginsburg, 1987, 1989). More recently (1990), two continuously cored wells positioned on the cross-bank profile were drilled with an overall recovery of nearly 80%, and provided us with further information on the age and lithology of the uppermost 442 and 660 m, respectively, of the western margin of Great Bahama Bank (Kenter et al., 1991). The recovered sediment records the late Miocene–Holocene progradation of the margin, and it can be compared with the results of the simulation and the initial interpretation.

Seismic Interpretation of Bahamas Lines

The analysis of the seismic profiles for the northwestern Great Bahama Bank revealed a complicated internal architecture that is the result of extensive lateral expansion of smaller nuclear banks and their coalescence to form the large modern bank (Eberli and Ginsburg, 1987). In the Late Cretaceous, the present northwestern Great Bahama Bank consisted of two small banks separated by a seaway, the Straits of Andros (Figures 1, 2). Since then, these platforms have grown vertically about 1500 m, and their margins have prograded as much as 25 km. In the middle Miocene(?) another seaway, the Bimini Embay-

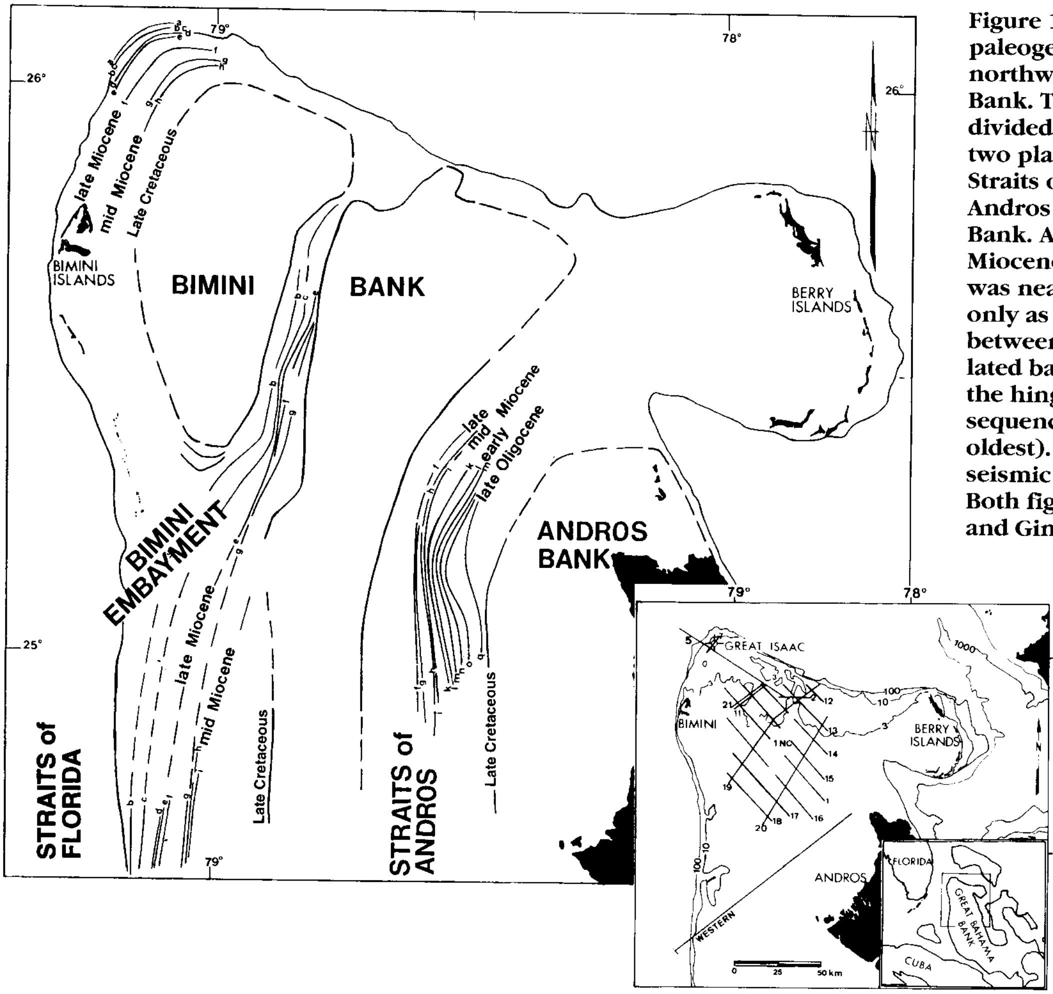


Figure 1—Map displaying paleogeographic evolution of northwestern Great Bahama Bank. The Bimini Embayment divided the Bimini Bank into two platforms, while the Straits of Andros separated Andros Bank from Bimini Bank. At the end of the Miocene, the Straits of Andros was nearly filled and existed only as a deep lagoon between the two formerly isolated banks. Small letters label the hinge line of prograding sequences (a = youngest, q = oldest). Inset: Location map of seismic lines and drill holes. Both figures are from Eberli and Ginsburg (1989).

ment, formed within the western of these banks, the Bimini Bank (Figure 1). Subsequent lateral progradation of the western margins filled the embayment and, farther south, shifted the bank margin approximately 25 km westward to its present position (Figure 2). The recognition of the extensive lateral expansion of these isolated platforms contrasts with the commonly believed idea that the banks had grown upward with only a minor change in the positions of their margins (Kendall and Schlager, 1981; Schlager and Ginsburg, 1981). In addition, this finding emphasizes the role of segmentation in the development of carbonate platforms and the impressive lateral growth potential of isolated platforms (Eberli and Ginsburg, 1987, 1988, 1989).

Coalescence of smaller banks, which produced the modern Great Bahama Bank, is the combined result of basinal aggradation and bank-margin progradation. From the data available, Eberli and Ginsburg (1989) interpreted the fundamental processes responsible for the transition from aggradation to progradation and the mode of progradation to have occurred as follows.

(1) Seismic data documents that in both the Straits of Andros and the Straits of Florida, a phase of basin and slope aggradation preceded progradation. Seismically, this basin and slope fill is expressed as wedges with various slope angles. The initial basin asymmetry was filled by a wedge-shaped body with a horizontal upper boundary. Over this nearly flat basin surface, a wedge-shaped prism with a declivity of approximately 10° was deposited on the eastern side of the straits. Slightly higher sedimentation rates in the basin axis resulted in a decrease of the slope angle and a shoaling of the basin. It is over the top of the resulting accretionary slope that progradation eventually took place (Figure 2). Obviously, the space on the upper slope had to be reduced before the sediment transported offbank filled the remaining space and extended the platform margin farther basinward.

(2) Progradation occurred in pulses which are recorded on the seismic lines as a succession of pro-

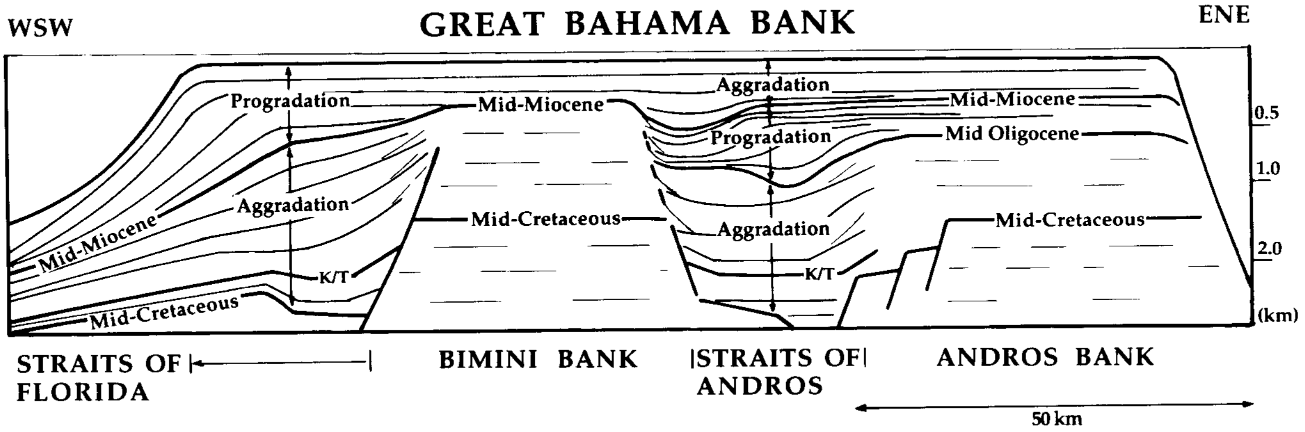


Figure 2—Schematic cross section through northwestern Great Bahama Bank displaying the two nuclear banks, Andros and Bimini, the filled seaway Straits of Andros, and the prograding western margin. In the Straits of Andros, ages of the prograding events were interpreted by jump correlation from the Straits of Florida, but were confirmed by drilling along the western margin.

grading and sigmoidal sequences, with each sigmoid believed to have been formed as the result of a single cycle of sea level fall and rise (Figure 3) (Eberli and Ginsburg, 1989). Each prograding sequence is up to 500 m thick and probably consisted of an offlapping complex of reefal carbonates covered by calcareous sand. Eberli and Ginsburg (1989) thought that during the transgressive stages, marginal reefs were established and then buried during the subsequent highstand, when abundant sediment was produced on the flooded bank and transported to and off the leeside of the bank. This interpretation was based on findings from the leeside of the modern bank where early Holocene reefs are covered by offbank transported sand (Hine et al., 1981). Two recent core borings (Unda and Clino) on the western margin of the Great Bahama Bank confirmed this interpretation. The Unda hole penetrated the proximal part of the sequences, whereas the Clino hole was positioned

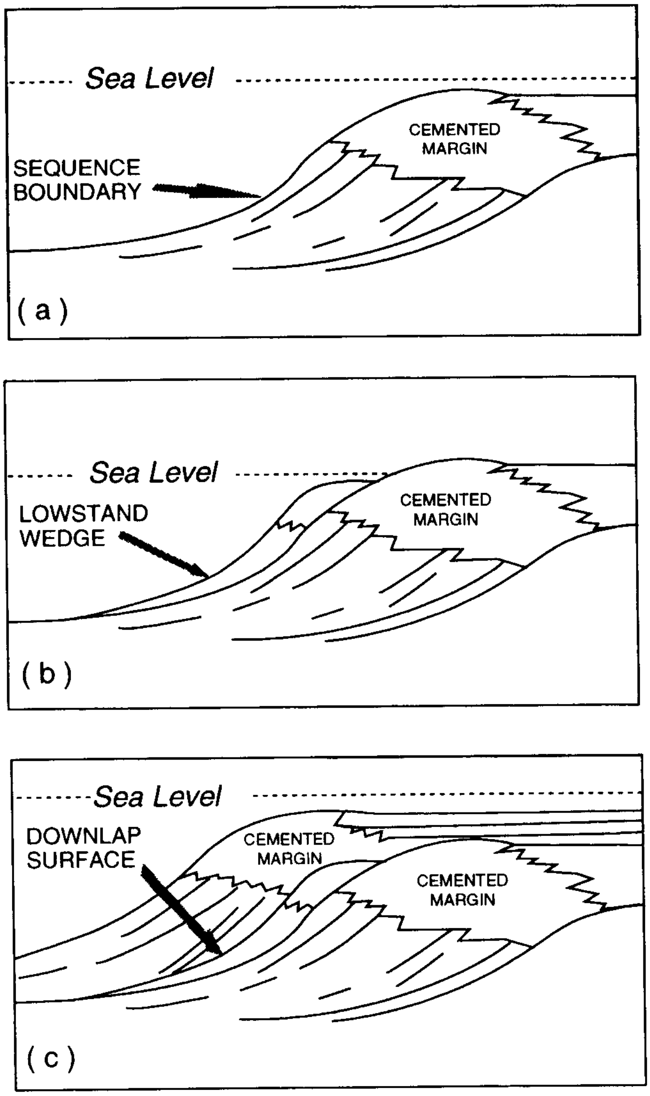


Figure 3—Model for platform progradation in which each cycle of sea level fall and rise produces one pulse of progradation. (a) A flooded carbonate platform produces enough sediment to have its surface match sea level and to shed excess sediment offbank. (b) A relative sea level fall exposes the platform and dramatically decreases sediment production, which is now limited to the rim of the platform. As a consequence, little sediment accumulation occurs on the slopes, resulting in a thin lowstand deposit. (c) After a relative sea level rise, carbonate production is re-established on the platform. Along the leeside margins of the platform, reefs that might have been established during the transgression are being covered by offbank transported calcareous sand and mud. This process leads to the progradation of the platform edge. Modified from Eberli and Ginsburg (1989).

on more distal, inclined parts of the sequences. Upper Miocene–Pleistocene sediments in the Unda hole consist of three successions of shallow-water and reefal deposits that alternate with two intervals of deeper marginal sediments that reflect periods of rapid sea level rise and backstepping of the platform margin. Upper Miocene–Pleistocene sediments recovered in the Clino hole were a single unit of platform and reefal sediments overlying a thick succession of slope sediments. The reefal unit is the basal part of a prograding pulse and is covered by offbank transported shallow-water carbonates (Ginsburg et al. 1991; Kenter et al. 1991).

During relative sea level lowstands, most of the shallow bank was exposed, and the sediment production zone was reduced to a narrow rim flanking the margin. As a result, little sediment was shed into the adjacent basin. On the seismic line, thin units overlying proposed sequence boundaries were interpreted to represent these lowstand deposits (Figure 3).

(3) In northwestern Great Bahama Bank, lateral expansion is toward the west. This growth pattern is probably the result of the influence of the prevailing easterly trade winds in the region, causing excess sediment to be transported in this direction (Hine et al., 1981; Wilber et al., 1990). The asymmetry emphasizes the importance of the direction of the energy flux for the redistribution of sediments on shallow-water platforms and the importance of offbank transport as a major mechanism for platform expansion.

(4) Although the mode of progradation was the same in both straits, the timing was not. Progradation started earlier in the Straits of Andros than in the Straits of Florida. The ages of the reflectors were inferred from the correlation between the scarce biostratigraphic data of the Great Isaac well and the seismic reflectors in a northern line and the correlation with apparently similar events on the cross-bank profile (Eberli and Ginsburg, 1989). From this correlation, we interpret the progradation in the Straits of Andros to have probably begun during the sea level rise in the earliest late Oligocene, whereas the progradation of the western margin into the Straits of Florida did not begin until the middle Miocene. The different timing of the progradation is thought to result from the different widths and depths of the two straits, with the narrower Straits of Andros being filled earlier with basinal sediments, enabling the adjacent eastern platform to prograde. Additionally, in the deeper Straits of Florida, the Florida current is thought to have removed part of the sediment from the slopes of the western Great Bahama Bank (Mullins et al., 1980; Austin et al., 1986), thus slowing the filling of the already wider straits.

(5) If their ages have been determined correctly, the number of prograding sequences in the time interval from the middle Oligocene to the Holocene nearly matches the third-order sea level fluctuations on the global cycle chart (Haq et al., 1987). Because Eberli and Ginsburg (1989) assumed that a pulse of progradation coincides with one cycle of sea level fall and rise, the prograding sequences were interpreted by them to be the record of third-order sea level fluctuations. As a consequence, sequence stratigraphy was used to date the sigmoids and enabled tentative ages to be assigned to the individual sequence boundaries (Eberli and Ginsburg, 1989).

TEST WITH SIMULATION

A computer simulation represents a means to test and interpret sequence stratigraphy before drilling. Before the simulation can be run, a calibration of the ages and identification of the lithology of the individual sigmoid packages seen on the seismic lines is required. The output from the simulation can then verify the sedimentological models used to explain the pulses of progradation and their timing as interpreted on the seismic line.

Boundary conditions for the simulation program are a stratigraphic data base and the assumptions that derive from commonly accepted models which explain these data. In the case of the northwestern Great Bahama Bank, these basic assumptions are: (1) carbonate production is highest in the photic zone (Schlager, 1981) and did not change with respect to depth within the last thirty million years; (2) pulses of progradation coincide with third-order sea level fluctuations; (3) offbank transport is the mechanism that supplies the sediment to the slopes (Hine et al., 1981); (4) offbank transport is from east to west on the leeside of the platform (Hine et al., 1981); (5) reduction of the space on the slope is a prerequisite for progradation; and (6) different basin widths and depths result in different timings for the fulfillment of the prerequisite of reduced space.

The test of a stratigraphic model through the use of a computer simulation can be considered positive when, after taking all these assumptions into consideration, the simulation produces a geometry similar to that seen on the seismic line. Unfortunately, a positive result means only that the proposed model or interpretation represents one possible solution or one reasonable way to interpret the geometries observed.

The comparison of geometries from the simulation and those observed on seismic lines also assumes that the seismic reflectors are indeed following depositional surfaces, thus imaging depositional geometries. Indications that this crucial assumption is correct are provided by the results of the correlation between the two core borings (Unda and Clino) and the seismic data through the prograding sequences of western Great Bahama Bank. The lithologies of the two cores through these sequences show sedimentary successions that are arranged in a repetitive pattern. Based on the changes in sedimentation rate and composition, these successions can be related to changes in relative sea level (Kenter et al., 1991). There is also a strong correlation between the early diagenesis and the seismic sequences. Seismic sequence boundaries coincide with boundaries of diagenetic zones and horizons (e.g., hardgrounds) (Eberli et al., 1992). This surface-bounded diagenesis dramatically influences the petrophysical behavior of the rocks. In particular, sonic velocity is greatly influenced by the pore types that develop during diagenesis (Anselmetti and Eberli, 1993). These diagenetically induced petrophysical alterations in combination with changes in lithology are the reason why seismic reflectors image the depositional surfaces and record depositional geometries.

SEDPAK Simulation Program

The simulation program, SEDPAK, uses empirical relationships to simulate basin evolution. Like other empirical simulations, it uses linear differential equations to represent geological assumptions rather than the non-linear differential equations that model the dynamic depositional system with more fidelity but lack the control of the empirical approach.

The simulation starts with a hole to be filled; this space has an area and shape and is related to the earlier history of the basin. For example, in the simulation of the northwestern Great Bahama Bank, we started with the 60-Ma seismic reflector, which already draped an older basin topography. This initial basin shape is filled by sedimentary bodies whose changing geometries reflect the sum of the dynamic processes affecting basin evolution. SEDPAK models the evolving geometry of a basin and the sediments that fill it as they respond to the interaction between the following major variables: (1) eustatic sea level; (2) tectonic movement (i.e., subsidence); and (3) sediment accumulation. The simulation generates two-dimensional sedimentary geometries by the infilling of a basin from one or both sides, with a combination of redeposited siliciclastic and carbonate sediment and in-situ carbonate growth (Strobel et al., 1989a, b; Kendall et al., 1990, 1993). In the pure carbonate environment of the Bahamas, no siliciclastics are deposited. Instead the source of sediments is almost exclusively the shallow banks, with smaller amounts of carbonate coming from the water column itself, in the form of biogenic production and chemical precipitation. The resulting carbonate geometries are, therefore, mainly influenced by the amount of in-situ carbonate accumulation and the amount of transported carbonate that accumulated over the same time interval.

Table 1. Input parameters Used in SEDPAK Program

1	Time interval and time steps
2	Basin surface
3	Sea level
4	Subsidence
5	Clastic supply
6	Depositional distance
7	Winnowing
8	Erosion and angle of repose
9	Carbonate accumulation rate
10	Depositional lag time
11	Lagoonal damping
12	Wave damping
13	Pelagic deposition
14	Carbonate parameters
15	Overburden

Input Parameters

Carbonate modeling includes consideration of progradation, downslope aprons, keep up, catch up, backstep, and drowned settings, as well as lagoonal settings. Particularly important to the simulation of the Great Bahama Bank are carbonate depositional phenomena that respond to the influence of fluctuations of sea level upon the rates of accumulation, thus producing the progradation or retreat of carbonates described by Bice (1988), Scaturo et al. (1989), and Strobel et al. (1989a, b). SEDPAK invokes fifteen combined input parameters that influence basin evolution and sediment accumulation for the specified time interval set by the user (Table 1). Information for each of the various parameters that affect each of the major process variables in the model must be specified. In the simulation for the Great Bahama Bank, all parameters associated with clastic sedimentation were turned off, but parameters regulating carbonate accumulation were defined. For the simulation of the Great Bahama Bank geometries, we used the following parameters.

Time Interval

The simulation program is iterative and deposits sediments layer-by-layer for a specified number of time steps. Each time step corresponds to a user-defined number of real years. For the Great Bahama Bank, the last 60 m.y. of platform evolution were modeled using time steps of 300,000 yr. The 300,000-yr time step divides a third-order sea level cycle into 3-5 intervals, displaying each prograding pulse over 5-7 steps.

Initial Basin Surface

For the northwestern Great Bahama Bank, the initial deposition surface for the simulation was derived from the seismic lines using the reflector with the interpolated 60-m.y. age. The velocity profile of the Great Isaac well was used for time-to-depth conversion.

The subject basins (Straits of Florida and Straits of Andros) differ in size. The Straits of Andros initially formed as an asymmetric trough approximately 25 km wide. At the end of the Cretaceous, this asymmetry was filled, and the nearly flat basin floor was bordered on both sides by steep slopes with a depth of approximately 300 m. The eastern slope had an angle of approximately 10°, the western side had a slope of more than 30°.

In contrast, the Straits of Florida is today approximately 100 km wide, whereas at 60 Ma, the eastern margin was 25 km farther east. At that time, the basin topography matched a nearly flat seismic reflector which underlies the Straits of Florida (Sheridan et al. 1981; Shipboard Party, 1988), but at the eastern side, the reflectors indicate an approximately 10-km-wide depression reminiscent of a partly filled extensional half graben. A steep slope, probably fault controlled, separated the straits from the Bimini Bank (Figure 2). For the western Great Bahama Bank, we assumed an initial surface that started deep to the west and then climbed gently upwards to a small graben. East of the graben, we placed a platform-bounding fault that was located 49 km from the west end of the cross section.

For the purpose of simulation by SEDPAK, the cross sections of these two straits are subdivided into evenly spaced vertical columns. The simulation models sediment deposition column-by-column. The initial basin surface is specified by providing an initial height for each column or providing the heights for some of the columns, so that SEDPAK computes the initial heights of the remaining columns by linear interpolation. There are several important considerations about the way the simulation treats the initial basin surface. In particular, the simulation does not allow for erosion below this surface. Furthermore, sediments that may exist underneath this surface do not compact from the deposition of sediments. The surface may move up or down, however, in response to sediment loading, erosion of sediment on its surface, faulting, regional uplift, and hinged and/or regional subsidence.

Eustatic Sea Level

Whereas fluctuating sea level is one of the major controlling factors for sediment production, distribution and accumulation in a specific basin and the timing and amplitude of relative changes in sea level are the combined result of regional tectonic movements, eustasy, and their feedback mechanisms (Pitman and Golovchenko, 1983; Watts and Thorne, 1984; Haq et al., 1987; Christie-Blick et al., 1990). Because the signal produced by eustasy is hidden in the joint product of tectonics, compaction, and eustasy, an independent measurement of eustasy is not possible (Kendall and Lerche, 1988) and, consequently, no completely correct eustatic sea level curve exists. It is left to the user to define or choose the eustatic sea level curve to be used. Because one aim of the simulation was a test of our interpretation that pulses of progradation are the result of sea level changes with a frequency of approximately 1 m.y., we selected the Haq et al. curve (1987) as an approximation of the history of sea level positions with respect to the present day sea level. Using the Haq et al. curve (1987), sea level positions were determined for each depositional time step of the simulation. Since we planned to model the deposition of sediments every 300,000 yr, we entered a sea level position for every 300,000-yr period, beginning at 60 Ma and working up to the present.

Tectonic Movement

SEDPAK models the tectonic behavior of the basin by varying the rate of subsidence of each of the columns that define the basin. The regional subsidence values are externally derived from subsidence history (i.e., backstripped subsidence curves or burial history calculations; Strobel et al., 1989b). Faulting is handled by subsiding two neighboring columns at different rates over a certain time interval, mimicking fault displacement.

Subsidence due to overburden is calculated in each time step after deposition of the sediment. This calculation also includes the determination of the compaction, which is assumed to be a function of the height of sediment residing over the sediment type under consideration. The equations of Baldwin and Butler (1985) are used to calculate compaction. Subsidence is modeled by assuming isostatic compensation for the sediments at some depth beneath the boundaries of the simulation. The weight of the newly deposited or eroded sediment is calculated, and the elevations of the sediments are adjusted according to the formula,

$$dz = ([\mathit{density\ of\ sediment} \times S \times \mathbf{\mathit{height}}] + [D_{pf} \times (1 - S) \times \mathbf{\mathit{height}}])/D_m,$$

where dz is the change in elevation due to either sediment deposition or erosion, S is the sediment's solidity, ***height*** is the height of sediment in each column, D_{pf} is the density of the pore fluid, and D_m is the density of the mantle.

When setting up the Bahamas simulation, we determined the subsidence history directly from the seismic section, using the thickness of the sediment on the platform as a first approximation for changes in the rate of subsidence. On this basis, it can be seen that these rates changed several times throughout the 60-m.y. period, reflecting changes in accommodation space at different time intervals. In addition, subsidence differed between the platform in the east and

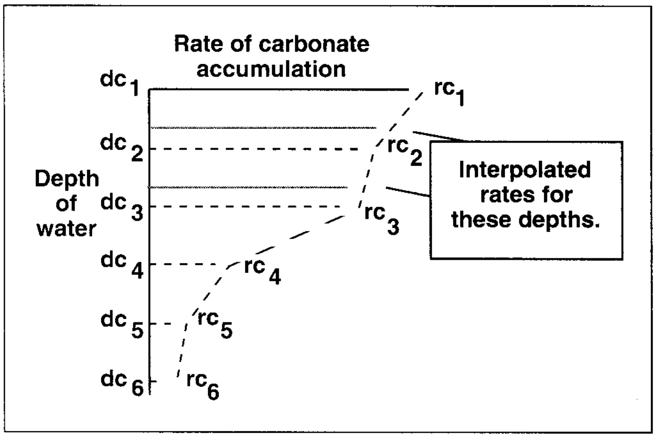


Figure 4—Curve of carbonate production and accumulation curve vs. water depth. Neritic carbonate accumulation (rc) is modeled as a function of depth (dc), thus mimicking the response to photosynthesis of the most important carbonate-producing organisms. The shape of the curve is determined by the user.

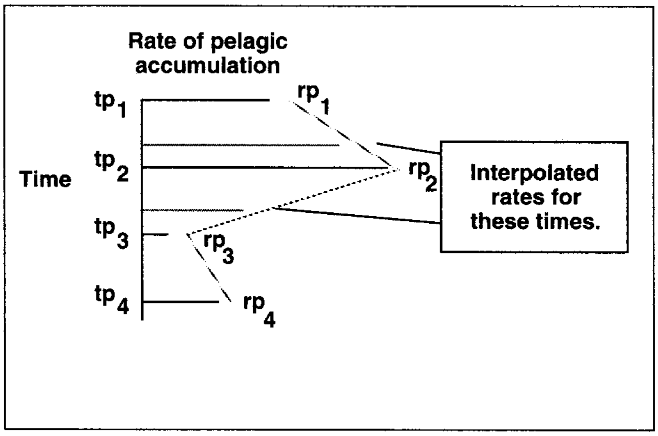


Figure 5—The rate of pelagic carbonate accumulation (rp) is modeled to vary through time (tp). Pelagic carbonate accumulation includes the sediment produced by planktonic organisms and offbank transported lime mud.

the basinal areas in the west, thus mimicking an active fault between the Bimini Bank and the Straits of Florida. Differential subsidence, and the resulting fault movement, was kept active from 60 to 30 Ma. We varied subsidence rates, their timing, and location for a number of simulation runs to ensure that there was enough space available to accommodate the carbonates as they were generated.

Subsidence, together with eustasy, controls water depths, which in turn control rates of carbonate accumulation as a function of water depth. The subsidence history was therefore critical to the sedimentation history of the carbonate and the thickness seen on the seismic section. The simulation corroborated the notion that subsidence primarily controls the accommodation space, whereas eustatic sea level controls how accommodation space is filled (Vail et al., 1991).

Sediment Production and Accumulation

The northwestern Great Bahama Bank is a setting for pure carbonate deposition. In SEDPAK, the source for carbonate sediments is assumed to be located within the boundaries of the simulation. The depositional geometries are a function of in-situ carbonate production and accumulation as well as the amount of transported carbonate that accumulated during the same time interval. For both production and redeposition, carbonates display specific phenomena that need to be considered when simulating the system.

Production

Carbonate production is highest in well-oxygenated tropical seas where sediment is generated by carbonate-secreting organisms and/or chemical precipitation. Because most of the sediment is produced by organisms that are dependent upon light, production rates decrease rapidly with increasing water depth (Schlager, 1981). In the simulation, it is assumed that all the produced carbonate accumulates at the location of production. Thus in a strict sense, the simulation models accumulation, not production. Accumulation is modeled as a function of water depth, however, thus mimicking the photosynthetic response of carbonate-producing organisms (Figure 4). The user defines the depth-dependent production and accumulation curve. In our simulation, the importance of this input parameter became clear as small changes in the production curve resulted in dramatic changes in progradation.

A second source of sediment is the water column. This pelagic rain varies as a function of time (Figure 5). It includes the mud-size carbonate that is transported offbank on the Great Bahama Bank. This mud consists mainly of aragonite needles that probably formed during highstands of sea level on the bank top (Wilber et al., 1990).

Damping

Carbonate production is highest in areas of open circulation at the shelf margin and decreases towards the more restricted environments of the lagoon (Stockman et al., 1967; Neuman and Land, 1975). Several mechanisms damp carbonate production. Their effects are modeled in the simulation by classifying each segment of the basin as open basin, carbonate buildup crest (or reef), lagoon (or epeiric shelf), or subaerial surface. Locations of the buildup crests or reefs are determined by finding, from deep to shallow water, the location at which carbonate growth reaches sea level. The points which reach sea level first are considered "reefs." After these locations are determined, the areas between them are examined. If the depth of the sea is below a critical value, then the area is considered a lagoon, and accumulation is damped accordingly. In the Bahamas-Florida region, quantitative studies demonstrated that carbonate production in the bank lagoons is high, despite lagoonal damping. Commonly, biogenic carbonate production can account for all the sediment found in an area; typically 1.5–3 times more sediment is produced than can be accommodated (Neuman and Land, 1975; Nelsen and Ginsburg, 1986; Bosence, 1989). For this reason, lagoonal damping was turned off in our simulation.

At the platform margins, rapid sea level rises suppress carbonate production. This decrease in sediment production results in a lag time before the platform resumes full production. In the Holocene, this lag time is in the order of 2000–5000 yr (Schlager, 1981, 1991). It can be argued that the lag time is of the same duration in third-order sea level cycles and thus has a negligible effect (Schlager, 1991). Backstepping of margins, as observed in many ancient examples, suggests, however, that a suppression of carbonate production is also occurring during third-order sea level rises. SEDPAK models such suppression by multiplying the carbonate growth potential at any particular depth by the size of the sea level change. This modeled long-term suppression is somewhat speculative as no quantitative estimate exists on such long-term lag effects. The net result of using this function is that carbonate accumulation is slowed during rapid large rises and resumes its nor-

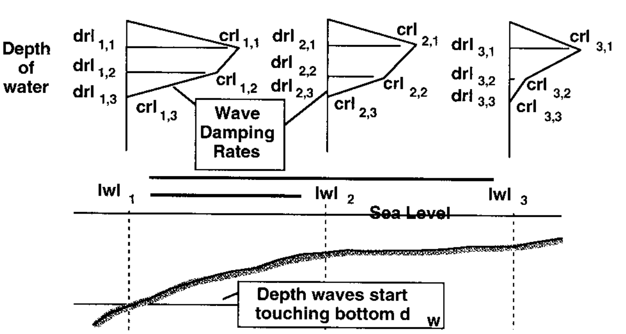


Figure 6—Wave damping of carbonate production following sea level rise. Carbonate accumulation (crl) is suppressed by the effects of wave energy over a specific range of depths some distance below the water surface (drl). At any point bankward of the location at which waves touch bottom, carbonate accumulation at depth d is reduced at a rate of r m/1000 yr.

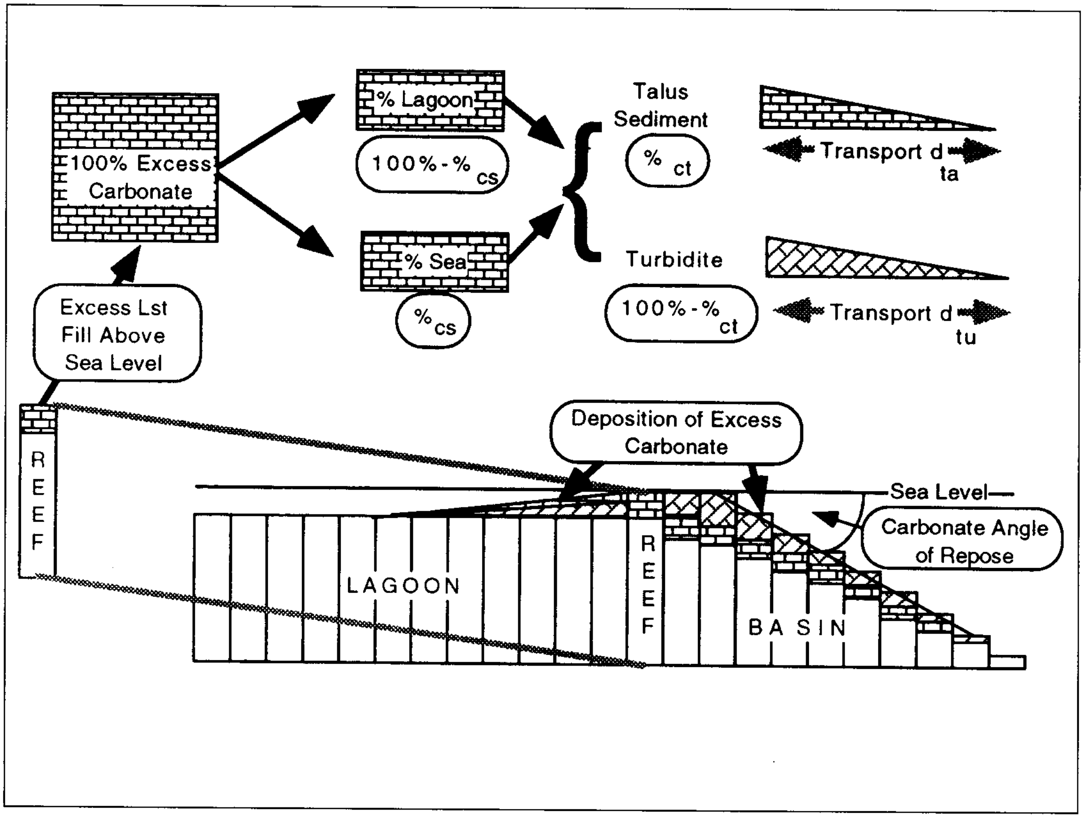


Figure 7—Schematic illustration of the modeling of redeposition of carbonates. The column that reaches sea level first is labeled "REEF." Excess carbonate that accumulates on this column and which would cause the column to rise above sea level in the simulation is deposited into the lagoon or basin as talus or turbidites. The user defines the respective amounts for talus and turbidites, the depth of basin penetration of the turbidites, and the repose angle of the slope.

mal rate at sea level stillstands and highs. The purpose of using this input parameter is to model the development of hardgrounds in conjunction with the lag time that follows a rapid sea level rise.

The growth potential of the reef crest is not suppressed by clastics in the water column of the Great Bahama Bank, but suppression of carbonate accumulation in response to the effects of wave energy does occur and is simulated. In this case, the location at which waves start affecting carbonate accumulation is defined by indicating the depth above which waves begin to break. From this point bankward, carbonate accumulation is reduced at defined distances by a user-defined rate (Figure 6). Wave damping can be modeled from the left and/or from the right, thus modeling the effect of wave action on the windward or leeward sides of the margin. For the northwestern Great Bahama Bank, there is a big difference between windward and leeward accumulation rates of carbonate. Easterly trade winds damp most of the accumulation on the marginal slopes on the eastern side of the banks, whereas an uninhibited offbank transport exists on the leeward side (Hine et al., 1981; Eberli and Ginsburg, 1987, Wilber et al., 1990).

Redeposition

On the modern Great Bahama Bank, more sediment is produced than can be accommodated on the bank top. This excess sediment is exported into the deep water areas, where it accumulates either as a pelagic rain or is transported downslope in mass gravity flows. Carbonate accumulation varies greatly in relation to the energy flux on the platform; little sediment accumulates on the windward side of the platforms, but it is transported to the leeside, where it buries reefs and forms a thick wedge of sediment on the slopes (Hine et al., 1981; Wilber et al., 1990).

For the redistribution of excess sediment from the bank top, the program takes several factors into account (Figure 7). It limits carbonate growth of the buildup crests to sea level. Excess carbonate production, which would cause the buildups to rise above sea level, is transported off the buildup and is redeposited (Figure 7). For our simulation, SEDPAK assumes that all the carbonate talus of the margin comes from the column that makes the "reef" crest. Thus, while the slope produces carbonate, much of the sediment transported downslope on the clinoform slope is assumed to come from this "reef" crest. The user determines what percentage of the talus is to be transported downslope off the carbonate platform into the basin with the remnants transported as back-reef facies into lagoons or over an epeiric shelf. By determining the respective amounts of back-reef and talus deposition, windward vs. leeward effects can be modeled.

Sediment transported downslope is deposited as apron sediments and turbidites. The respective amount and the maximum distance that turbidites flow into the basin are determined by the user. The angle of repose is important for deposition of these mass gravity flows. Carbonates have a high angle of repose, which is controlled by the cohesiveness of the sediment (Kenter, 1990; Kenter and Schlager, 1990). In SEDPAK, the user specifies this parameter. Parameters for carbonate production and distribution used in the simulation are given in Tables 2–4.

Table 2. Carbonate Rates

Depth (m)	Rate (m/1000 yr)	
	Straits of Andros	Straits of Florida
0	0.635	0.64
10	0.32	0.32
50	0.18	0.18
200	0.012	0.012
300	0.0	0.0

Table 3. Pelagic Deposition

Time (Ma)	Rate (m/1000 yr)	
	Straits of Andros	Straits of Florida
60	0.030	0.010
30	0.017	0.015
29	0.029	0.030
10	0.029	0.030

Table 4. Carbonate Parameters

	Straits of Andros	Straits of Florida
Carbonate repose angle	20°	20°
Percent to sea	100	100
Percent to talus	30	30
Talus penetration distance (km)	9.0	9.0
Turbidite penetration distance (km)	25.0	25.0

OUTPUT AND RESULTS

The results of two simulations are used to present our model of the western Great Bahama Bank (Figures 8, 9). They trace Danian through Holocene sedimentary accumulation of this carbonate platform system and test the model proposed for the 60 m.y. of carbonate deposition with SEDPAK. These simulations reproduce sequence geometries seen on seismic cross sections for the western Great Bahama Bank at its prograded margin and across the infilled reentrant known as the Straits of Andros (Eberli and

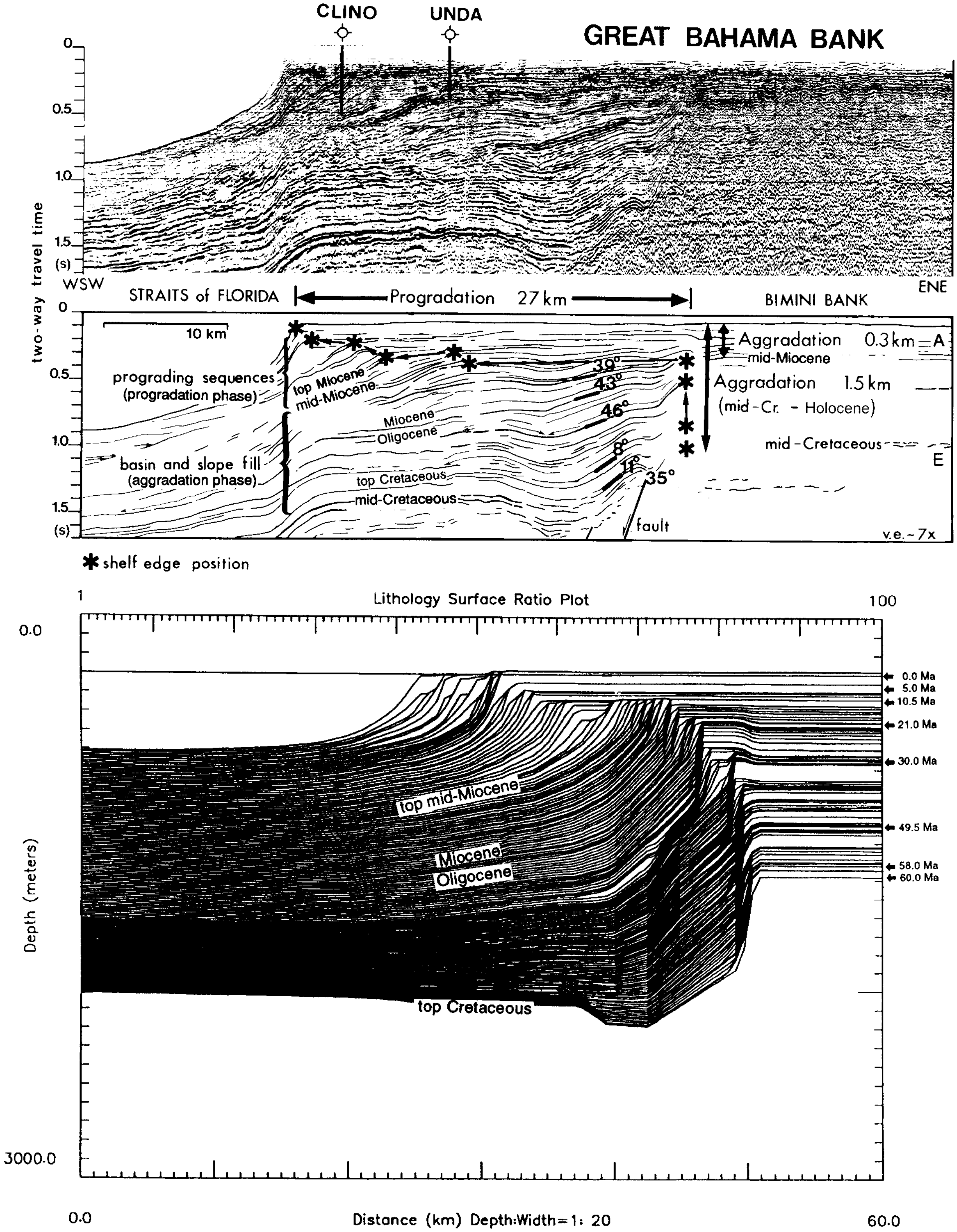


Figure 8—Comparison of seismic line, line drawing, and SEDPAK output from western Great Bahama Bank. This simulation is able to reproduce the decrease of slope angle prior to progradation; furthermore, distance and timing of the main progradation pulse coincide on the seismic line and in the simulation (seismic line and line drawing from Eberli and Ginsburg, 1989). SEDPAK width 100 columns, 200 time steps.

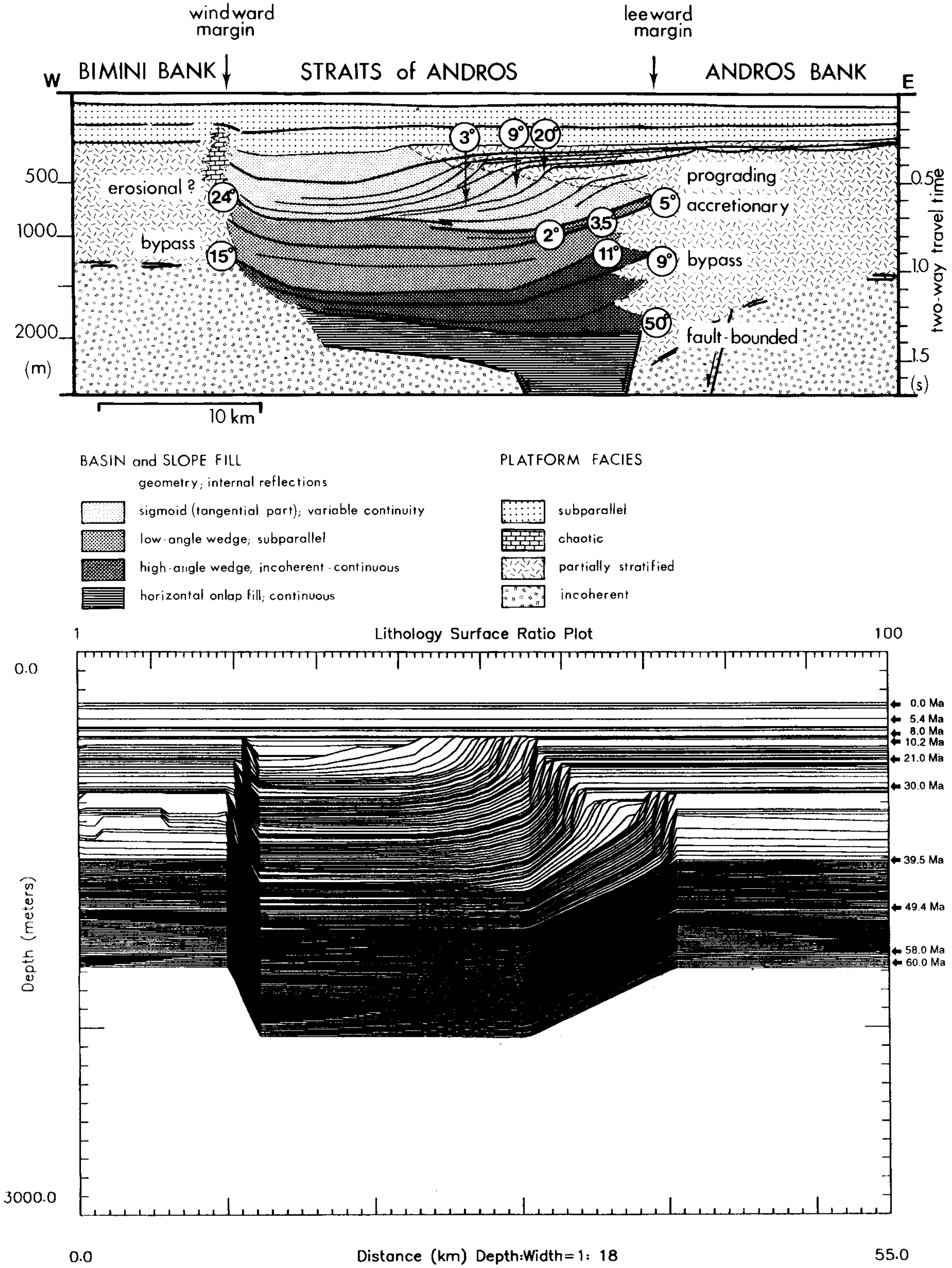


Figure 9—Simulation output of Straits of Andros in comparison with the schematic presentation of basin fill. Geometry and timing of basin fill is nearly identically mimicked in the simulation (line drawing of Straits from Eberli and Ginsburg, 1989). SEDPAK width 100 columns, 200 time steps.

Ginsburg, 1987, 1989). The major geological difference between these two adjacent carbonate seaways is that the sediments of the western margin of Great Bahama Bank aggraded for much of the early Tertiary and do not prograde until the middle Miocene. In contrast, the Straits of Andros sediments aggraded until the Oligocene and then prograde and fill the reentrant area through to the late Miocene. Achieving this difference in the timing of the respective progradational events while maintaining the relatively similar geological histories lends credence to our hope that simulations can be of use in testing stratigraphic models.

The beginning of each simulations was set at the early Tertiary on a Danian surface, and both were carried through to the end of the Holocene. The western Great Bahama Bank has a width of about 60 km (Figure 8), whereas the Straits of Andros was about 55 km wide (Figure 9). Using the Haq et al. (1987) chart, we input identical sea level data for both areas and modeled the deposition of sediments every 300,000 yr through 200 time steps. The curve defining carbonate accumulation as a function of depth was identical in both simulations (see Table 2), as were the parameters controlling carbonate redeposition: angle of repose, distance of transportation of turbidites, and amount of sediment deposited as talus vs. turbidite deposition (Table 4). By keeping these parameters constant, we were able to evaluate the influence of the basin morphology on the depositional pattern and especially on timing of the prograding events.

A simulation with the foregoing assumptions enabled us to reproduce the two-stage evolution of the platform with aggradation prior to progradation. Basinal fill and platform aggradation is the normal sedimentation pattern during most of a platform's history, whereas progradation occurs only at certain intervals. The Straits of Andros was simulated to aggrade both at its margins and at its center until the middle Oligocene (Figure 10d); a sea level drop at this time brought the sediment-water interface higher into the photic zone. Simulation results show how rapid progradation was initiated from the west, while on the steep eastern margin sedimentation was damped by intense wave action (Figure 10e). The simulation of the seismic image of the western margin of the Great Bahama Bank successfully reproduced the seismic geometries through the application of a slightly different subsidence history than in the Straits of Andros (Figures 8, 10a–c; Tables 5, 6). The combination of differences in morphology and subsidence are the major controls on the different geometries.

In contrast to the Straits of Andros, the Straits of Florida was simulated to continue aggrading through the middle Oligocene (Figure 10a; compare with Figure 10d) up until the middle Miocene (Figure 10b; compare with Figure 10e). At this time, a sea level drop reduced accommodation and caused the progradation of the margin through to the present (Figure 10b, c). The simulated prograding pulses are somewhat more regular in thickness than the prograding seismic sequences (Figure 9). This is probably due to the fact that SEDPAK generates and distributes sediment within the area displayed, whereas in nature sediment can be transported out of this plain.

Test of the Mechanism of Progradation

One goal of the simulation was to test the interpretation that (1) pulses of progradation were generated by fluctuations in sea level and (2) that an aggradational phase on the marginal slope preceded progradation (Eberli and Ginsburg, 1989). The simulation is compatible with both hypotheses, especially for pulses of progradation which appear to be related to sea level fluctuations. Simulation indicates, however, that there is a fine balance between aggradation and progradation. For example, a slight decrease in the rate of accumulation or increase in the rate of subsidence often terminated progradation and resulted in vertical aggradation of the platform only. In such cases, accommodation space on the bank top becomes great enough to store much of the sediment produced and, as a result, the basinal areas received less sediment and remained deep troughs. For this reason, the simulation supported the interpretation that basinal aggradation is a prerequisite for progradation. The timing, amount, and mode of progradation and the geometries of the prograding units are controlled by several factors. In the following we describe and discuss each of these factors and its influence on progradation.

Sea Level

Sea level change is responsible for the pulsed progradation and erosional and onlap patterns within the sequences. The fluctuation of sea level has a major control on carbonate production. Simulation assumes full sediment production during a sea level highstand with sediment distribution to the lagoon and the slope (Figure 7). When sea level falls below a platform edge, production is restricted to a narrow rim on the slope, and the produced sediment is exported exclusively downslope. SEDPAK simulates this process by shifting the location of sediment production and accumulation in concert with sea level. The result is a fluctuating rate of sediment accumulation, although the rate of sediment production itself (Figure 4) is not changed. Changing sediment production resulted in variations of the rate of progradation, but the sequences still displayed the pulsed character.

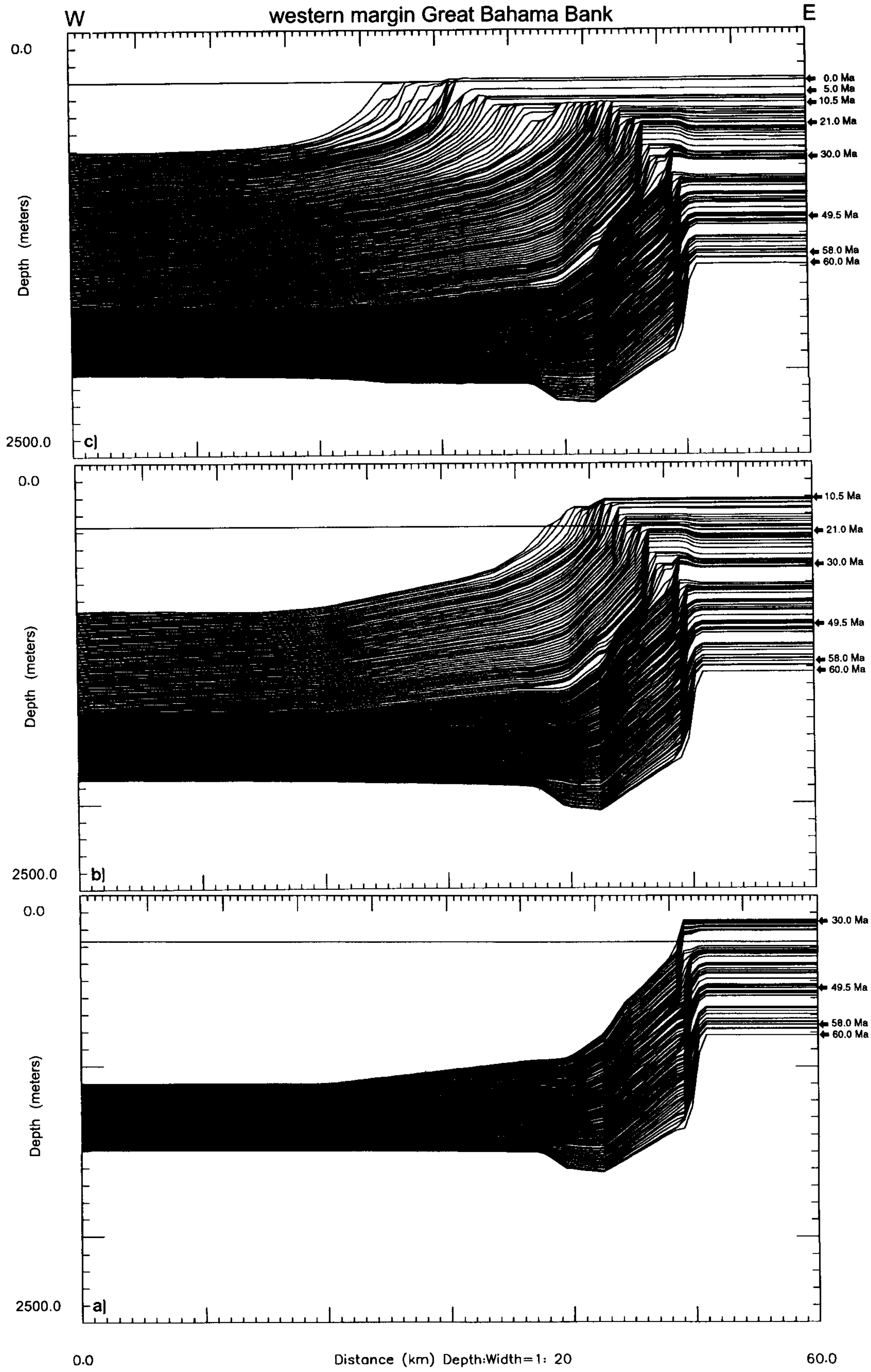


Figure 10—Simulation of western Great Bahama Bank: (a–c) western margin of Great Bahama Bank, (d–f) Straits of Andros. Time steps coincide with supercycle boundaries of Haq et al. (1987). Horizontal scale at the top of the output shows columns across basin (100); horizontal scale at the bottom displays the basin length in kilometers; vertical scale at the left shows depth in meters; vertical scale at the right shows the age of the depositional surfaces.

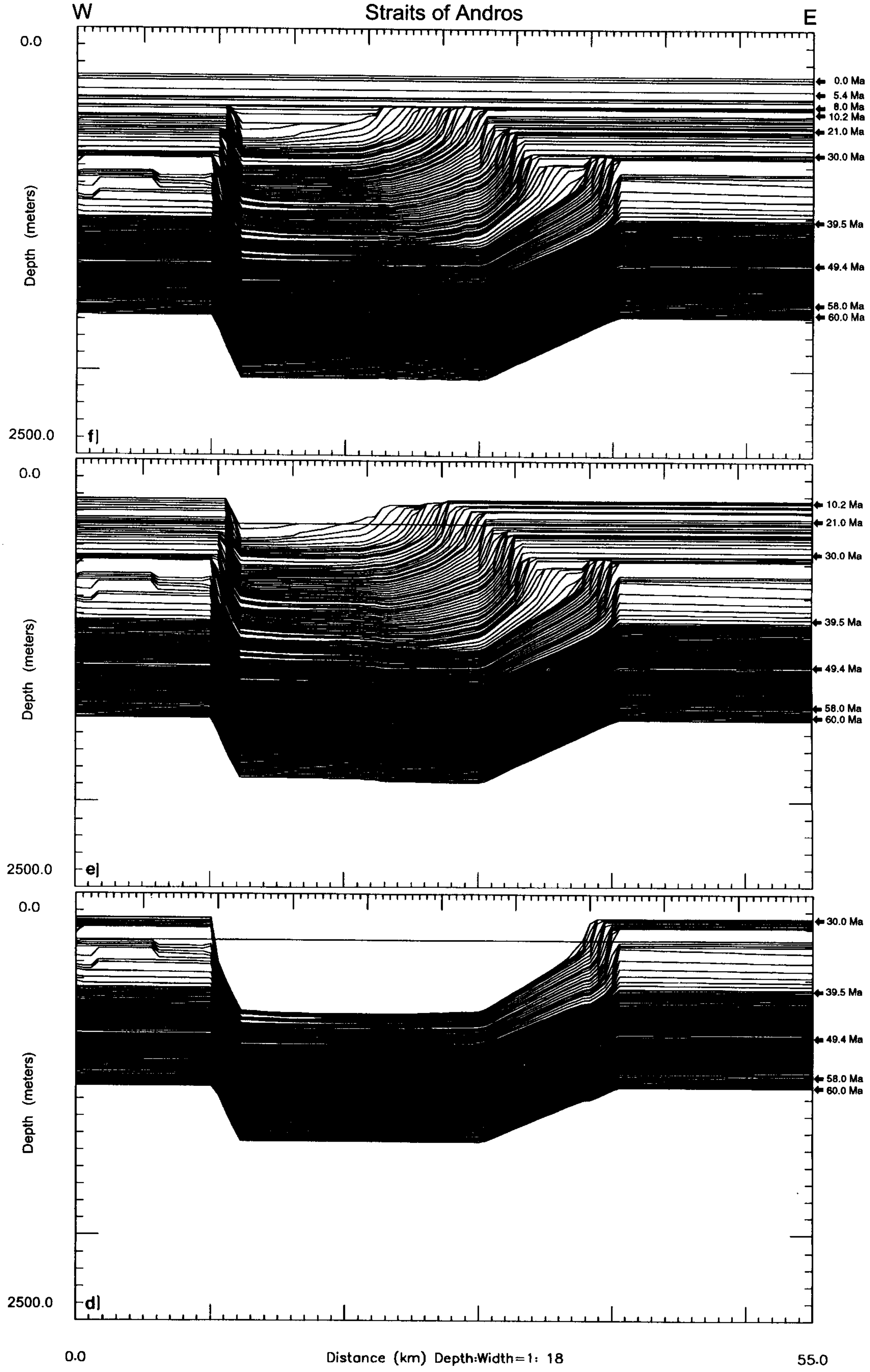


Figure 10—Continued.

Table 5. Subsidence in Straits of Andros

Time (Ma)	Rate (m/1000 yr) 1.0 km	55.0 km
60	0.018	0.0185
30	0.016	0.016
18.5	0.257	0.260
10	0.0171	0.0171
0	0.121	0.121

Table 6. Subsidence in Straits of Florida

Time (Ma)	Rate (m/1000 yr) 1.0 km	49.0 km	50.0 km	60.0 km
60	0.027	0.034	0.019	0.019
30	0.015	0.019	0.0185	0.0185
18.4	0.018	0.018	0.024	0.024
10.8	0.010	0.010	0.010	0.010
10.6	0.014	0.016	0.016	0.016
0	0.010	0.010	0.012	0.0125

In the simulation, the onset of progradation is commonly during a sea level rise which has a lower amplitude than the preceding fall (i.e., when little or no new accommodation space is created on the platform). For example, in the Straits of Andros the first pulse of progradation occurred during a sea level high after the major sea level drop in the middle Oligocene (Figure 10e). After this major sea level fall, little accommodation space is created during the subsequent rise and highstand of sea level. Thus, excess sediment is transported offbank and deposited on the marginal low-angle slope, where accommodation space is also small. Consequently, all the accommodation space is easily filled and the platform margin starts to prograde.

Subsidence

Subsidence proved to be an important factor as small changes in the subsidence rate were sufficient to trigger or terminate progradation. In order to achieve the correct timing for progradation in the western Great Bahama Bank, the simulation required that subsidence be more rapid in the Straits of Florida than in the Straits of Andros from the early Tertiary into the Miocene. This differential subsidence required the introduction of a "fault" between the Straits of Florida and the western margin of Bimini Bank (Figure 8). This "fault" was active until the middle Oligocene (Figure 10a). In the Straits of Andros, no faulting was modeled, but a slightly higher rate of subsidence was assumed for the more oceanward Andros Bank to the east. The necessity for differential subsidence to force progradation at different times suggests that basin width is less influential on the timing of progradation than previously thought (Eberli and Ginsburg, 1989).

Carbonate Production and Accumulation

Carbonate production rates were chosen to match the light dependency of sediment-producing organisms (i.e., a near exponential decrease with water depth) (Table 2). In addition, pelagic accumulation is simulated to occur, causing the area to be covered with a uniform drape of carbonate (Table 3). In the successful simulation these combined rates are 0.665 m/1000 yr for the top 10 m. This rate is on the lower end of modern accumulation rates for carbonate sands and tidal deposits (i.e., 0.5–1.1 m/1000 yr; Schlager, 1981), but are very close to carbonate lagoonal rates of 0.6 m/1000 yr calculated from modern production rates (Smith and Kinsey, 1976; Bosence, 1989). Due to erosion and redeposition, this accumulation rate is much less when calculated for the 60-m.y. time interval of the simulation, namely 0.025 m/1000 yr on the platform and 0.033 m/1000 yr in the seaways. This rate is comparable to carbonate accumulation rates of ancient carbonate systems (Sarg, 1988). The decrease of the accumulation rate with time is due to several factors, including the availability of accommodation space, compaction, erosion, and redeposition. The simulation suggests that the availability of accommodation space, not erosion, is the most important factor for determining accumulation rate. The high rate of accumulation is valid in times when space can be filled on the platform. Once this space is filled, excess sediment is transported offbank and deposited either as talus or in turbidite beds. This mechanism implies that the Holocene accumulation rate on the platform tops will change after the space created by the last sea level rise is filled. In general, it appears that the periods of high accumulation rates of carbonates on the bank tops are stacked deposits during high sea level, interrupted by long periods of nondeposition and/or erosion at sea level still stands and sea level lows.

In the simulation, the rate of sediment production controls the distance of progradation. For example, small changes in production rates can produce large variations in the distance of progradation. The modeled production rates produce enough sediment for rapid prograding pulses. It appears that, once a threshold value is exceeded, progradation occurs at a rapid rate. This result is in concert with observations that several margins are characterized by the sudden onset of extensive prograding events (i.e., Bosellini, 1984; Eberli and Ginsburg, 1987; Pomar, 1991). The effect of the production rate on the

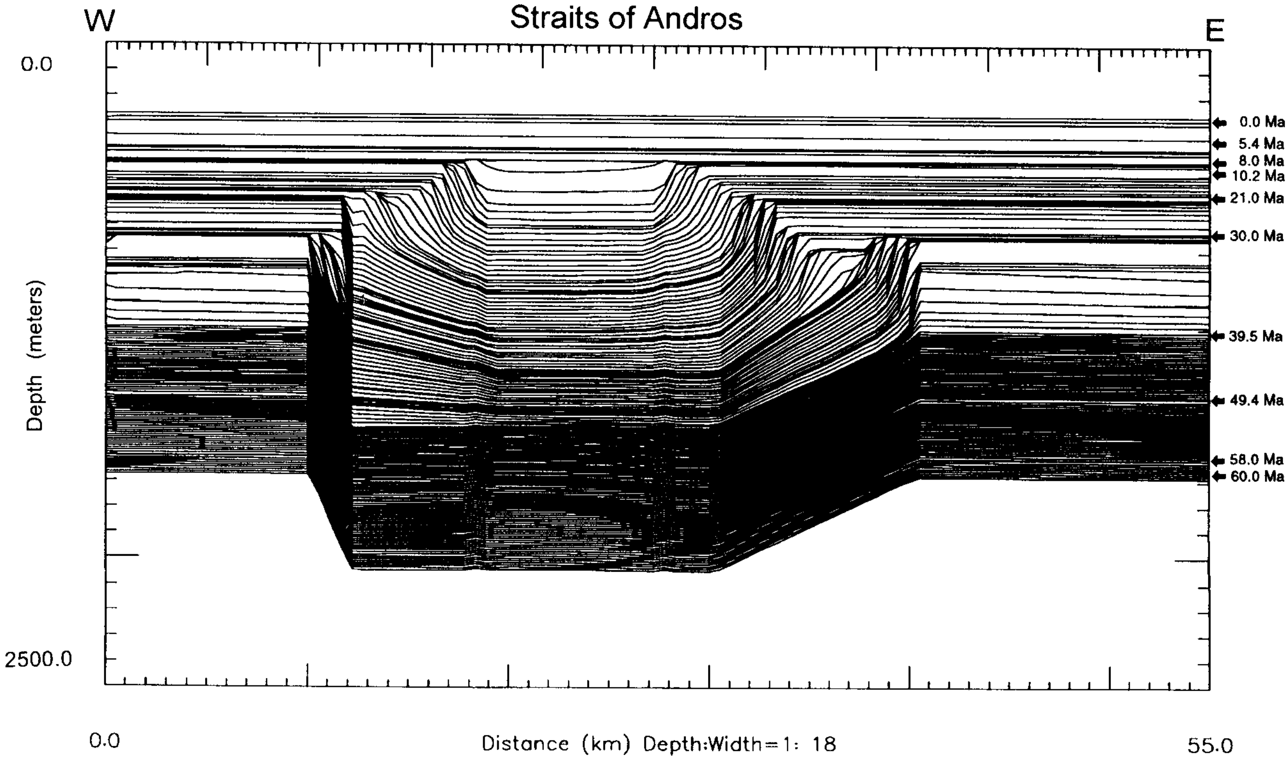


Figure 11—Simulation of the Straits of Andros with wave damping turned down; as a result sedimentation occurs on both the windward and leeward sides of the bank. The Straits of Andros are filled symmetrically from both sides. SEDPAK width 100 columns, 200 time steps.

amount of progradation, however, can be decreased by other factors such as direction of wave-energy, slope angle, and the availability of accommodation space.

Direction of Wave Energy

The unidirectional progradation seen on the seismic lines was interpreted to be the result of wave energy directed across the bank in response to the prevailing east-west direction of the winds (Eberli and Ginsburg, 1987, 1989). As expected, reproduction of this dominant direction of progradation was only possible when sediment accumulation and redistribution was damped on the western side of the Straits of Andros. In order to fill the seaway prior to progradation, however, a small input of sediment from the windward side was needed. Through iterative trial and error, this amount was determined to be about 10% of the amount from the leeward side. When no damping of carbonate production is modeled, the re-entrant is filled by early to middle Miocene (15 Ma) in response to the increased quantity of carbonate available (Figure 11).

Angle of Repose

The angle of repose is important to progradation since it determines how much of the offbank sediment is deposited upon the marginal slope and how much is transported downslope. If the angle of repose is small, more sediment accumulates on the slope, which induces more rapid progradation. Kenter (1990) showed that grainy, noncohesive, mud-free sediments build steeper slopes than muddy, cohesive sediments. The fine-grained packstones recovered in the two bore holes Unda and Clino on Great Bahama Bank, therefore, might have a repose angle of a maximum of 20° (Kenter 1990). In simulation we set the angle of repose at 20°. The relatively low repose angle of muddy carbonate slopes has important implications for the basin filling as a prerequisite for progradation. In the Triassic platforms in the Dolomites, where coarse boulder beds prograde with an angle of approximately 25–35°, basin filling is not a prerequisite for progradation because the boulders are able to maintain very steep slopes (Bosellini 1984). There, basin filling only accelerates progradation (Schlager et al. 1991). In contrast, in the Bahamas, and generally in more mud-rich carbonate slopes, slope height has to be reduced before progradation can occur.

Turbidite Penetration

The distance which turbidites are transported downslope plays an important role in the fill of the basin. It controls the width of the lower slope basin-fill architecture, and sets conditions for progradation. We ran a test simulation with all parameters identical to those in the Straits of Andros simulation except that the turbidite penetration distance was increased to 40 km. Development of the basin was quite similar until the early Miocene (21 Ma), when the basinal fill stretched further across the channel and resulted in a horizontal-layered basin fill (Figure 12; compare with Figure 10f). If this distance is reduced, deposition is concentrated closer to the margin, where the accumulation rate increases and, consequently, accommodation space decreases. In another simulation, the turbidite penetration distance was decreased to 10 km. This shorter distance caused more sediment to be deposited on the slope, thus changing the basinal geometries to low-angle beds instead of horizontal layers (Figure 13; compare with Figure 10f). When we set the distance of penetration at 25 km, which is approximately the length modern turbidites travel in Exuma Sound (Crevello and Schlager, 1980), the combination of this distance and the 20° angle of repose allowed the marginal slopes to retain enough offbank sediment to decrease the water depth and form the proper basin profile for progradation (Figures 9, 10f). The evolution of the slope profile from steep fault bounded to low angle and back to a steeper progradational margin is typical for the Bahamas, but is also known in other platforms (e.g., the Cretaceous-Tertiary platform of the Maiella, Italy; Eberli et. al. 1993). The simulation suggests that this evolution is the product of sedimentation processes acting on and along platforms.

Comparison of the Simulation with the Evolution of Great Bahama Bank

Simulation outputs at different time steps are displayed in Figure 10. They show the evolution of the bank at the end of the supercycle intervals proposed by Haq et al. (1987).

In the early Tertiary evolution of the Great Bahama Bank, both nuclear banks grew vertically with no change in the their lateral dimension. The simulation mimics this growth pattern. In the Straits of Andros, however, a linear decrease in subsidence from 0.018 m/1000 yr at 60 Ma to 0.016 m/1000 yr at 30 Ma was sufficient to change the platform growth from aggradation to progradation. Subsequent sea level changes produced a pulsed progradation which, at the end of the middle Miocene, nearly closed the straits (Figure 10e). With the closure of the seaway at the latest Miocene, the platform again changed to an aggradational style, resulting in both a horizontally layered deposition and seismic reflectors (Figure 10f). At the western margin of the Great Bahama Bank, the transformation from aggradation to progradation occurred in the middle Miocene and is still active today. Slightly increased subsidence and the wider basin profile prevented the platform from prograding earlier. In the middle Miocene, a major sea level drop shifted deposition downslope and progradation started during the subsequent sea level rise (Figure 10b).

The youngest prograding units at the western margin display a very good correlation with the seismic data. The high-amplitude sea level variations of the late Pliocene and Quaternary produced a characteristic stratal pattern, with units onlapping deep in the basin and the shoulders of highstand deposits on the bank top (Figure 14). A very similar pattern is seen on the multichannel line and is documented from the Holocene sediment package (Wilber et al., 1990; Grammer, 1991).

Although there is a good geometrical comparison between simulation and seismic data, there are some features that are not modeled. For example, channel incision or large-scale slope failures that are common erosional processes on the slopes (Harwood and Towers, 1988; Mullins and Hine, 1989) were not modeled by the program though regional prescribed unconformity can be. In SEDPAK, erosion is determined by the angle of repose, and its record is a linear unconformity with a certain declivity. The lack of erosion and redeposition parameters for the slope sediments is probably responsible for the thin slopes on the simulation output compared to the seismic section of the western Great Bahama Bank. Despite this flaw in the program, it still reproduces much of the geometric evolution of the Great Bahama Bank.

Inferences Drawn from Simulation Output on Seismic Data

Numerical modeling in geology has limitations, particularly since not all natural processes have been mathematically defined and, instead, the knowledge is expressed as empirical relationships. The simulation used here (SEDPAK) uses linear differential equations to model the sedimentologic processes. The large number of parameters involved in the simulation produces a buffered system that appears to match natural conditions, which results in good correlation between simulation output and seismic lines. We think that we made reasonable assumptions and, consequently, believe that the simulation

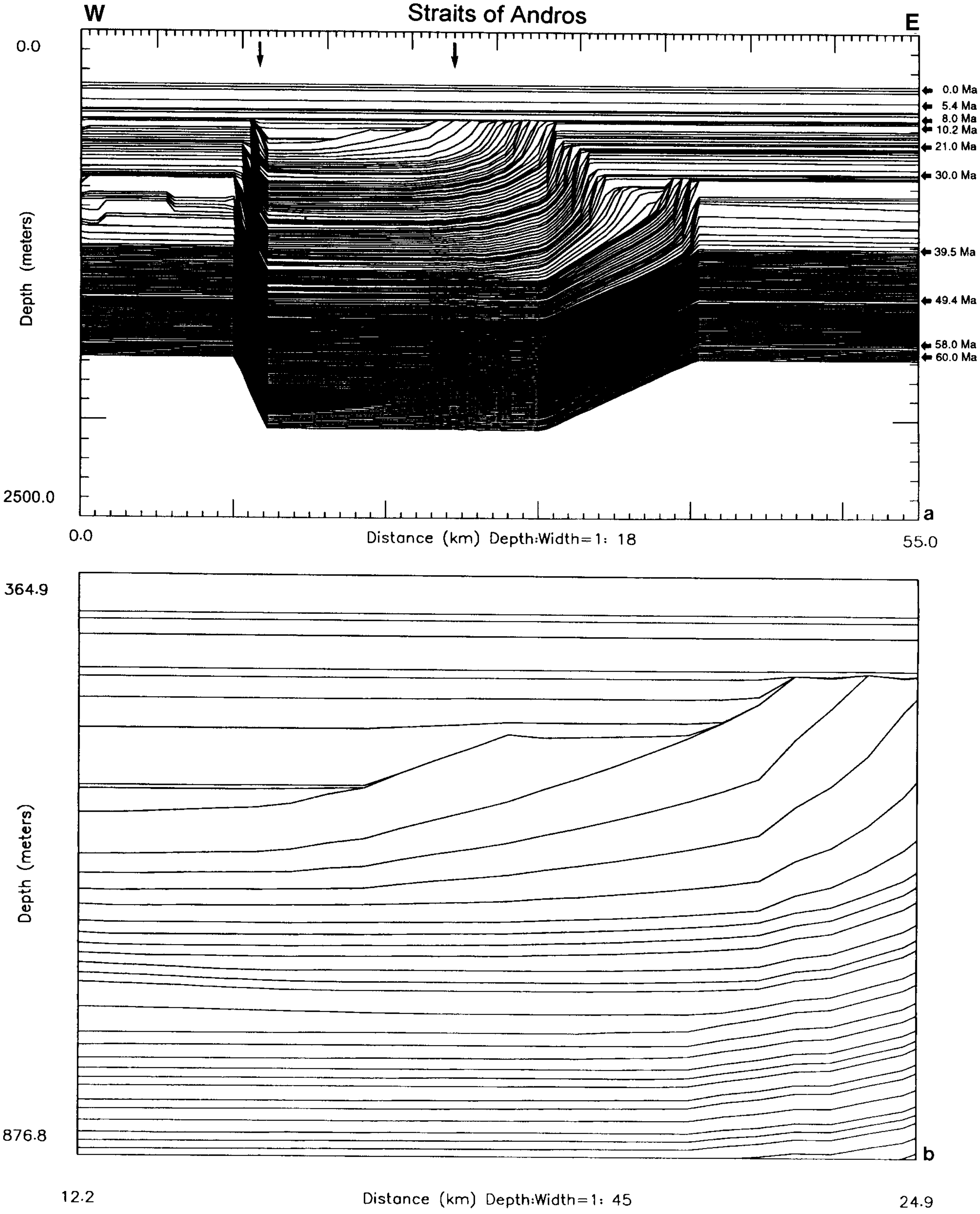


Figure 12—(a) Simulation of the Straits of Andros with the turbidite penetration distance increased from 25 to 40 km. Arrows indicate lateral position of enlarged portion. (b) Enlarged portion of the middle Miocene channel fill. Note the flat basin-fill geometry and the onlap of the basinal turbidites. SEDPAK width 100 columns, 200 time steps.

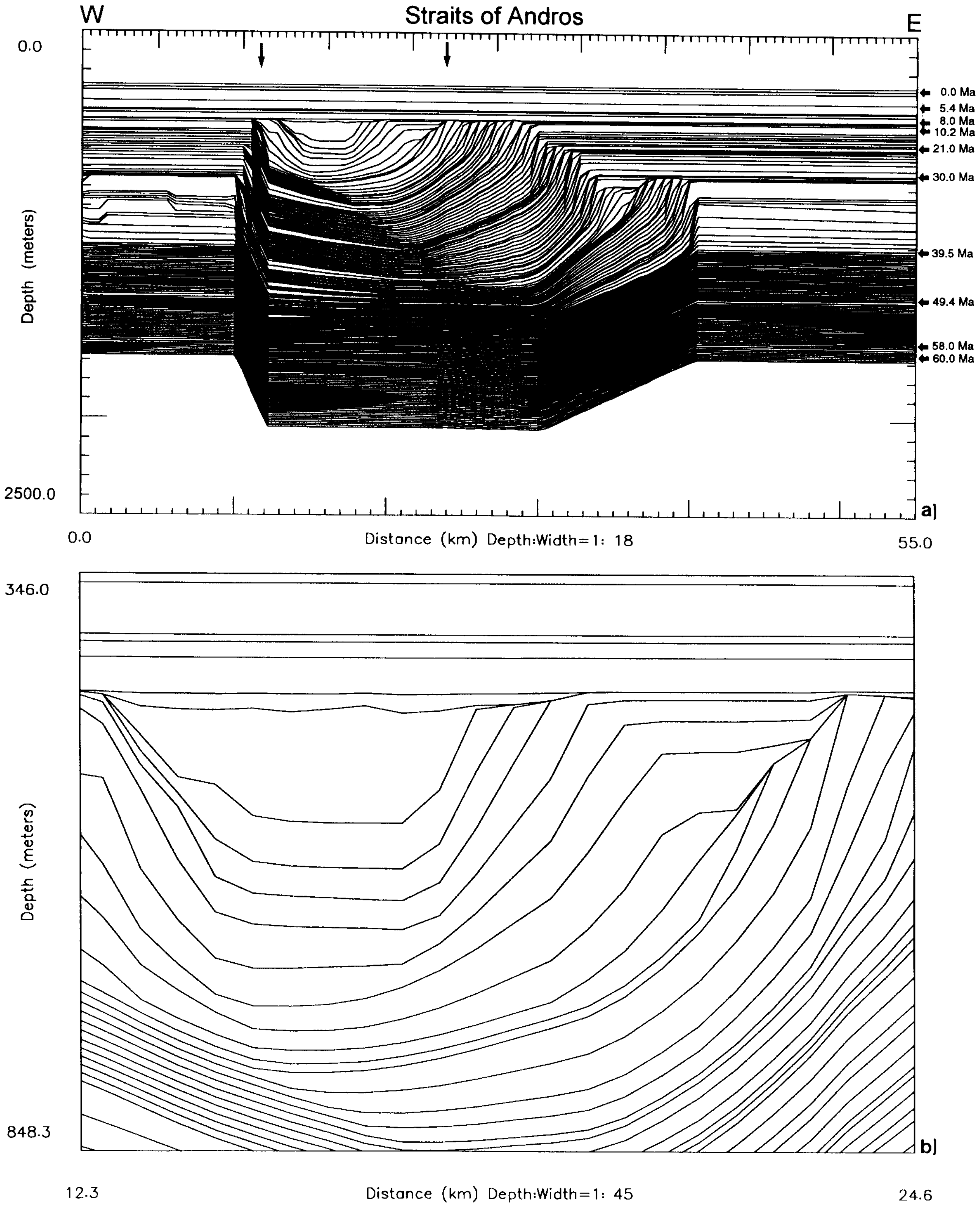


Figure 13—(a) Simulation of the Straits of Andros with turbidite penetration distance decreased from 25 to 10 km. Arrows indicate lateral position of enlarged portion. (b) Enlarged portion of the middle Miocene channel fill illustrating the increased slope sedimentation due to decreased turbidite penetration. SEDPAK width 100 columns, 200 time steps.

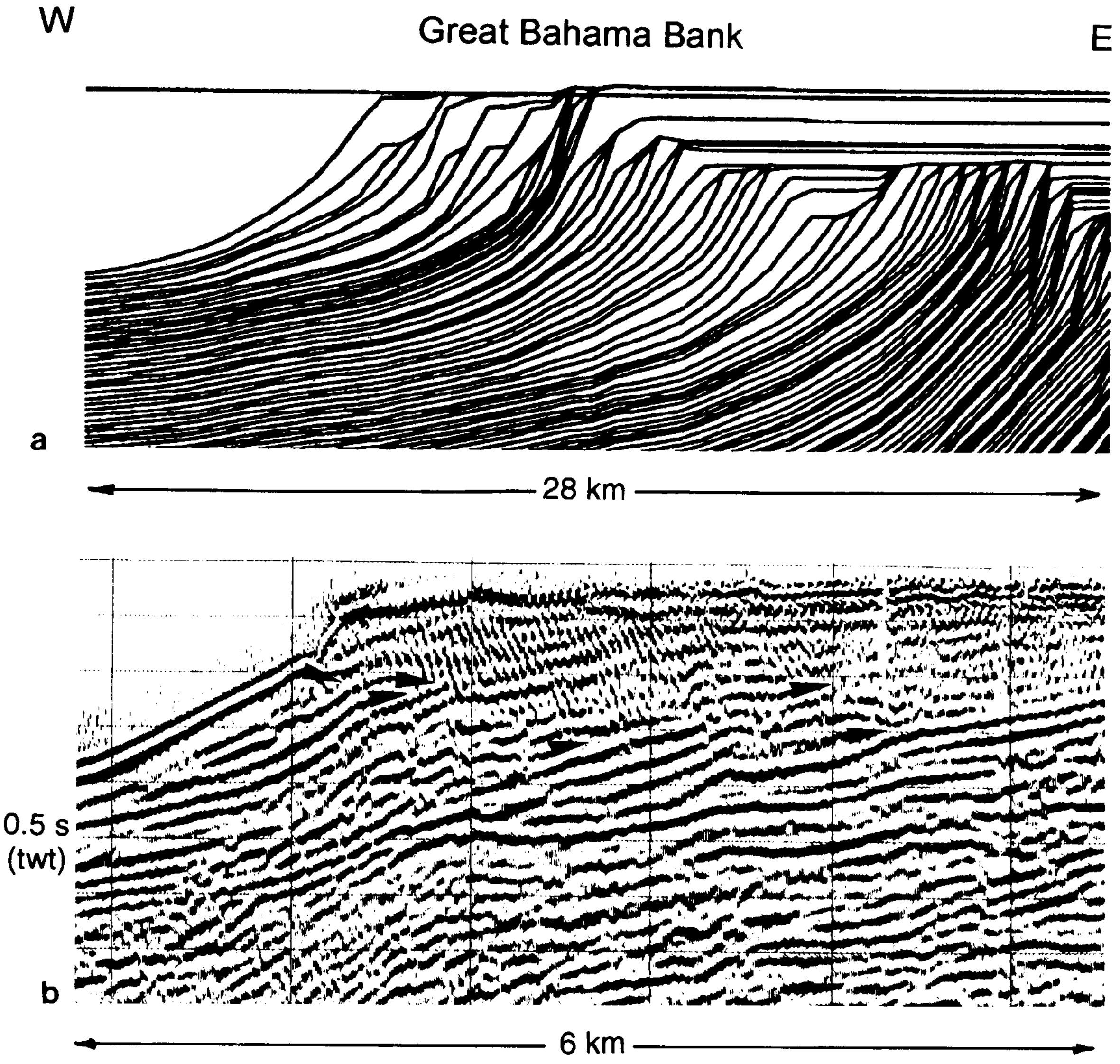


Figure 14—Close up of progradation pattern on western Great Bahama Bank. Pleistocene-Holocene high-amplitude sea level fluctuations produce a characteristic onlap pattern along the steep slopes, which is imaged on the seismic line and mimicked with simulation. (a) Simulation output, (b) seismic line. twt = two-way traveltime.

not only reproduces our seismic data, but also gives some indication as to how the platform grew. These inferences drawn include the following.

(1) There is a delicate balance between aggradation and progradation.

(2) This balance is exceeded by progradation when a sea level drop reduces the accommodation space on the marginal slope. In many cases, the highly productive carbonate environment is not only able to keep up with the subsequent sea level rise, but also produces enough excess sediment to advance the platform margin seaward. Fast rates of sea level rises, however, result in an initial backstep of the margin during the transgression and progradation only during the sea level highstand.

(3) Carbonate production rates might have been constant over the last 60 m.y. It is necessary to extrapolate recent rates of carbonate accumulation into the past to rebuild the edifice of the platform while using the simulation. Exposure and erosion are responsible for the decrease in the overall accumulation rate on the platform to much lower rates than expected when modern rates are extrapolated over the entire time. This suggests that there is more

"gap" than "record" on the platform top. This result is in concert with the findings of a very incomplete stratigraphic record on atolls and platforms by modern dating techniques (Ludwig et al., 1988; McNeill, 1989)

Sedimentary Simulation as a Predictive Tool?

Sedimentary simulation can reproduce the geometries seen on a seismic line, but the question remains as to whether the program models nature or reproduces similar geometries by means of factors other than those expected in nature. Our simulations produced the best results when values of the input parameters were similar to modern measured values. We believe this is strong evidence that the program weighs parameters much as nature does. This implies that the simulation could be pushed further and be used to predict the sedimentary setting at intervals between known stratigraphic tie points.

The simulation reproduces the geometries seen on seismic lines by generating a new sediment surface at each calculated time step. This procedure provides the user with a well-defined time control on the chronology of events that lead to the final stratal pattern. Stratigraphic information from the industrial Great Isaac well enabled us to date some of the reflectors on seismic sections. We used these dated reflectors as checkpoints in our simulation runs. For example, the base of each prograding sequence was dated as middle Oligocene in the Straits of Andros and as middle Miocene on the western margin of the Great Bahama Bank. Parameters were chosen such that the simulation delivers the correct geometry at these checkpoints. It is assumed that the intermediate steps display an approximately accurate geometry as well. Using this assumption, SEDPAK could provide guidance in the dating of horizons between reflectors whose ages are known from biostratigraphy. In addition, observing the evolution with each time step displays the evolution of the basin fill on a time scale that goes beyond the resolution of a seismic sequence. It is also possible to choose finer time steps, which further increases the resolution, potentially at a reservoir level.

CONCLUSIONS

Sixty million years of carbonate deposition can be simulated to reproduce the sequence geometries seen on seismic sections of the Great Bahama Bank. The simulation corroborated that the mechanisms that we proposed controlled platform progradation. We recognize, however, that this is only one possible and reasonable solution. The simulation suggests that the prograding geometries seen on seismic lines can be produced by third-order sea level fluctuations. Additionally, the simulation showed that the timing of progradation depends upon subsidence rate and that this effect is more important than basin width. Furthermore, it indicated that the differential subsidence history at the western margin of the Great Bahama Bank and in the platform interior seaway, the Straits of Andros, is sufficient to cause a difference in the timing of the progradation, while documenting that there is a fine balance between progradation and aggradation.

The simulation also showed that sedimentary processes shape the platform to basin profile and can influence progradation. For example, if a repose angle is reduced, this enables the sediment to accumulate on the marginal slope, inducing progradation. The reduction of sediment accumulation on the windward margin of the Straits of Andros is crucial to unidirectional progradation from the east, with probably only 10% of the allochtonous carbonate coming from the west.

Sea level changes are responsible for the pulsed mode of progradation, and the sequences seen on seismic lines. As a result, these sequences can be used to determine the stratigraphic history of the Great Bahama Bank.

Simulations can be powerful tools to test interpretations that are drawn from limited data sets. In addition, they place constraints upon the chronology of events which fill a basin and can guide further interpretation of seismic data. We used the simulation program SEDPAK to address questions about fundamental processes of platform progradation, and we believe the program can be extended to decipher the basin evolution and facies distribution in other basins as well.

REFERENCES CITED

Anselmetti, F. S., and G. P. Eberli, 1993, Controls on sonic velocity in carbonates, *in* R. C. Liebermann, ed., PAGEOH: Basel, Switzerland, Birkhäuser Verlag, p. 1-37.

Austin, J. A., Jr., et al., 1986, Proceedings of the Ocean Drilling Program, Part A—Initial Reports, v. 101, p. 1-569.

Baldwin, B., and C. Butler, 1985, Compaction curves: AAPG Bulletin, v. 69, p. 622-626.

Bice, D., 1988, Synthetic stratigraphy of carbonate platform and basin systems: Geology, v. 16, p. 703-706.

Bosellini, A., 1984, Progradation geometries of carbonate platforms: examples from the Triassic of the Dolomites, northern Italy: Sedimentology, v. 31, p. 1-24.

Bosence, D., 1989, Biogenic carbonate production in Florida Bay: Bulletin of Marine Sciences, v. 44, p. 419-433.

Bosence, D., and D. Waltham, 1990, Computer modeling the internal architecture of carbonate platforms: Geology, v. 18, p. 26-30.

Bosscher, H., and J. Southam, 1992, CARBPLAT-A computer model to simulate the development of carbonate platforms: Geology, v. 20, p. 235-238.

Christie-Blick, N., G. S. Mountain, and K G. Miller, 1990, Seismic stratigraphic record of sea-level change, *in* Sea-level change: National Academy of Sciences Studies in Geophysics, p. 116-140.

Crevello, P. D., and W. Schlager, 1980, Carbonate debris sheets and turbidites, Exuma Sound, Bahamas: Journal of Sedimentary Petrology, v. 50, p. 1121-1148.

Eberli, G. P., and R. N. Ginsburg, 1987, Segmentation and coalescence of platforms, Tertiary, NW Great Bahama Bank: Geology, v. 15, p. 75-79.

Eberli, G. P., and R. N. Ginsburg, 1988, Aggrading and prograding infill of buried Cenozoic seaways, northwestern Great Bahama Bank. *in* A. W. Bally, ed., Atlas of seismic stratigraphy: AAPG Studies in Geology 27, v. 2., p. 97-103.

Eberli, G. P., and R. N. Ginsburg, 1989, Cenozoic progradation of NW Great Bahama Bank—a record of lateral platform growth and sea level fluctuations, *in* P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Reed, eds., Controls on carbonate platform and basin development: SEPM Special Publication 44, p. 339-355.

Eberli, G. P., R. N. Ginsburg, P. K. Swart, D. F. McNeill, J. A. M. Kenter, R. G. Maliva, C. M. Kievman, and B. Lidz, 1992, Sea-level controlled sedimentation and diagenesis on Great Bahama Bank during the Neogene: International Geological Congress, Kyoto, Abstracts, p. 312.

Eberli, G. P., D. Bernoulli, D. Sanders, and A. Vecsei, 1993, From aggradation to progradation: the Maiella platform (Abruzzi, Italy), *in* J. T. Simo, R. W. Scott, and J.-P. Masse, eds., Cretaceous carbonate platforms: AAPG Memoir 56, p. 213-232.

Ginsburg, R. N., D. F. McNeill, G. P. Eberli, P. K. Swart, and J. A. M. Kenter, 1991, Transformation of morphology and facies of Great Bahama Bank by Plio-Pleistocene progradation (abs.), *in* A. Bosellini, R. Brandner, E. Flügel, B. Purser, W. Schlager, H. Tucker, and D. Zenger, eds., Dolomieu Conference on Carbonate Platforms and Dolomitization Abstracts, p. 88-89.

Grammer, G. M., 1991, Formation and evolution of Quaternary carbonate foreslopes, Tongue of the Ocean, Bahamas: Ph.D. dissertation, University of Miami, Coral Gables, Florida, 314 p.

Haq, B., J. Hardenbol, and P. R. Vail, 1987, Chronology of fluctuating sea level since the Triassic (250 million years to present): Science, v. 235, p. 1156-1167.

Harwood, G. M., and P. A. Towers, 1988, Seismic sedimentologic interpretation of a carbonate slope, north margin of Little Bahama Bank. *in* J. Austin et al., Proceedings of the Ocean Drilling Program, Scientific Results, v. 101, p. 263-278.

Hine, A. C., R. J. Wilber, J. M. Bane, A. C. Neumann, and K. R. Lorenson, 1981, Offbank transport of carbonate sands along open, leeward bank margins: northern Bahamas: Marine Geology, v. 42, p. 327-348.

Kendall, C. G. St. C., and I. Lerche, 1988, The rise and fall of eustasy, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., Sea-level changes—an integrated approach: SEPM Special Publication 42, p. 3-17.

Kendall, C. G. St. C., and W. Schlager, 1981, Carbonates and relative changes in sea level: Marine Geology, v. 44, p. 181-212.

Kendall, C. G. St. C., J. Strobel, R. Cannon, J. Bezdek, and G. Biswas, 1990, The simulation of the sedimentary fill of basins: Journal of Geophysical Research, v. 95, no. 12, p. 6911-6929.

Kendall, C. G. St. C., G. L. Whittle, R. Ehrlich, P. D. Moore, R. L. Cannon, and D. R. Hellmann, 1993, Computer sedimentary simulations models sequence stratigraphy: Oil & Gas Journal, v. 91, no. 17 (April 26), p. 46-51.

Kenter, J. A. M., 1990, Carbonate platform flanks: slope angle and sediment fabric: Sedimentology v. 37, p. 777-794.

Kenter, J. A. M., and W. Schlager, 1990, Comparison of shear strength in calcareous and siliciclastic marine sediments: Marine Geology, v. 88, p. 145-152.

Kenter, J. A. M., R. N. Ginsburg, G. P. Eberli, and D. F. McNeill, 1991, Mio-Pliocene sea level fluctuations recorded in core boring from the western margin of Great Bahama Bank (abs.): Geological Society of America Abstracts with Programs, v. 23, p. A182.

Lawrence, D. T., M. Doyle, and T. Aigner, 1990, Stratigraphic simulation of sedimentary basins: concepts and calibration: AAPG Bulletin, v. 74, p. 273-295.

Ludwig, K. R., R. B. Halley, K. R. Simmons, and Z. E. Peterman, 1988, Strontium-isotope stratigraphy of Enewetak Atoll: Geology, v. 16, p. 173-177.

McNeill, D. F., 1989, Magnetostratigraphic dating and magnetization of Cenozoic platform carbonates from the Bahamas: Ph.D. dissertation, University of Miami, Coral Gables, Florida, 210 p.

Mullins, H. T., and A. C. Hine, 1989, Scalloped bank margins: beginning of the end for carbonate platforms: Geology, v. 17, p. 30-33.

Mullins, H. T., A. C. Neumann, R. J. Wilber, C. A. Hine, and S. J. Chinburg, 1980, Carbonate sediment drifts in northern Straits of Florida: AAPG Bulletin, v. 64, p. 1701-1717.

Nelsen, J. E., and R. N. Ginsburg, 1986, Calcium carbonate production by epibionts on Thalassia in Florida Bay: Journal of Sedimentary Petrology, v. 56, p. 622-628.

Neumann, A. C., and L. S. Land, 1975, Lime mud deposition and calcareous algae in the Bight of Abaco, Bahamas: a budget: Journal of Sedimentary Petrology, v. 45, p. 763-786.

Pitman, W., and X. Golovchenko, 1983, The effect of sea level change on the shelf-edge and slope of passive margins, *in* D. J. Stanley and G. T. Moore, eds., The shelfbreak: critical interface on continental margins: SEPM Special Publication 33, p. 41-58.

Pomar, L., 1991, Reef geometries, erosion surfaces and high-frequency sea-level changes, upper Miocene reef complex, Mallorca, Spain: Sedimentology, v. 38, p. 243-270.

Sarg, J. F., 1988, Carbonate sequence stratigraphy, *in* C. K. Wilgus, B. S. Hastings, C. G. St. C. Kendall, H. W. Posamentier, C. A. Ross, and J. C. Van Wagoner, eds., Sea-level changes - an integrated approach: SEPM Special Publication 42, p. 155-181.

Scaturo, D. M., J. S. Strobel, C. G. St. C. Kendall, J. C. Wendte, G. Biswas, J. Bezdek, and R. Cannon, 1989, Judy Creek: a case study for a two-dimensional sediment depositional simulation: *in* P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Reed, eds., Controls on carbonate platform and basin development: SEPM Special Publication 44, p. 63-76.

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

Schlager, W., 1991, Depositional bias and environmental change—important factors in sequence stratigraphy: Sedimentary Geology, v. 70, p. 109-130.

Schlager, W., and R. N. Ginsburg, 1981, Bahama carbonate platform—the deep and the past: Marine Geology, v. 44, p. 1-24.

Schlager, W., F. Bourgeois, G. MacKenzie, and J. Smit, 1988, Boreholes at Great Isaac and Site 626 and the history of the Florida Straits: *in* J. A. Austin, Jr. et al., Proceeding of the Ocean Drilling Program, Scientific results, v. 101, p. 425-437.

Schlager, W., K. T. Biddle, and J. Stafleu, 1991, Pico di Vallandro (Dürrenstein) a platform-basin transition in outcrop and seismic model: Guidebook Excursion D: Dolomieu Conference on Carbonate Platform and Dolomitization, 22 p.

Sheridan, R. E., J. T. Crosby, G. M. Bryan, and P. L. Stoffa, 1981, Stratigraphy and structure of the southern Blake Plateau, northern Florida Straits, and the northern Bahama platform from multichannel seismic reflection data: AAPG Bulletin, v. 65, p. 2571-2593.

Shipboard Party, 1988, Leg 101–an overview, *in* J. A. Austin, Jr., et al., eds., Proceedings of the Ocean Drilling Program, Scientific Results, v. 101, p. 455-472.

Smith, S. V., and D. W. Kinsey, 1976, Calcium carbonate production, coral reef growth and sea level changes: Science, v. 194, p. 937-939.

Stockman, K. W., R. N. Ginsburg, and E. A. Shinn, 1967, The production of lime mud by algae in south Florida: Journal of Sedimentary Petrology, v. 37, p. 633-648.

Strobel, J., R. Cannon, C. G. St. C. Kendall, G. Biswas, and J. Bezdek, 1989a, Interactive (Sedpak) simulation of clastic and carbonate sediments in shelf to basin settings: Computers & Geosciences, v. 15, p. 1279-1290.

Strobel, J., F. Soewito, C. G. St. C. Kendall, G. Biswas, and J. Bezdek, and R. Cannon, 1989b, Interactive simulation (SEDpak) of clastic and carbonate sediments in shelf to basin settings: *in* T. A. Cross, ed., Quantitative dynamic stratigraphy: Englewood Cliffs, New Jersey, Prentice Hall, p. 433-444.

Tator, B. A., and L. E. Hatfield, 1975, Bahamas present complex geology: Oil & Gas Journal, v. 73 (November 10), p. 172-176.

Vail, P. R., F. Audemard, S. A. Bowman, P. N. Eisner, and C. Perez-Cruz, 1991, The stratigraphic signatures of tectonics, eustasy and sedimentology–an overview: *in* G. Einsele, W. Ricken, and A. Seilacher, eds., Cycles and events in stratigraphy: Berlin, Springer-Verlag, p. 615-659.

Watts, A. B., and J. Thorne, 1984, Tectonics, global changes in sea level and their relationship to stratigraphical sequences at the U. S. Atlantic continental margin: Marine Petroleum Geology, v. 1, p. 319-339.

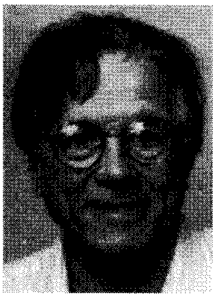
Wilber, R. J., J. D. Milliman, and R. B. Halley, 1990, Accumulation of Holocene banktop sediment on the western margin of Great Bahama Bank: modern progradation of a carbonate megabank: Geology, v. 18, p. 970-975.

ABOUT THE AUTHORS

Gregor P. Eberli

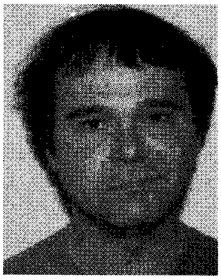
Gregor P. Eberli, received his Ph.D. in 1985 from the Swiss Federal Institute of Technology (ETH) in Zürich. For his dissertation, he studied carbonate turbidite sequences in Jurassic rift basins of the Tethys. During his postdoctoral tenure at the University of Miami, he began to work on carbonate platform development and sequence stratigraphy. His current research interests include the response of carbonate and mixed carbonate-siliciclastic systems to sea level fluctuations, and petrophysics of carbonates. He is an associate professor at the University of Miami.

Christopher Kendall



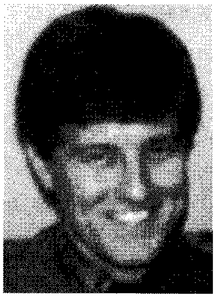
Christopher Kendall has published numerous papers on carbonate depositional systems, basin modeling, and sedimentary simulations working in both academia and industry. He is currently a professor at the University of South Carolina, where he heads the research group that developed the sedimentary simulation reported in this paper. Currently, the 10-member team is extending the algorithms to include fluid and heat flow, and structural deformation on the vertical plane.

Philip D. Moore



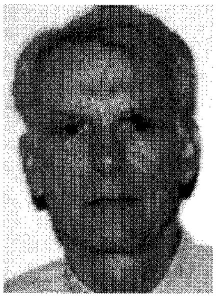
Philip D. Moore received B.S. and M.S. degrees in computer science at the University of South Carolina, and is a Ph.D. candidate in the Geological Science Department at U.S.C. His research involves applying new software design techniques for the computer simulation of geological processes. His dissertation topic focuses on the design of an extendible system framework for computer modeling of sedimentation and tectonics.

Gregory Whittle



Gregory Whittle worked for his M.Sc. degree on Holocene carbonate deposition and cementation of the Bahamas at Lee Stocking Island. For his Ph.D., he simulated carbonate and clastic depositional fill of sedimentary basins using seismic and well data from oil companies. Currently on a postdoctoral fellowship, he is studying the subsurface of the United Arab Emirates at the University of Al Ail and is to be a leader of the AAPG field trip to the Holocene coastal sabkhas of the United Arab Emirates in April 1994.

Robert L. Cannon



Robert L. Cannon received a Ph.D. in computer science from the University of North Carolina at Chapel Hill in 1973. Since then, he has been a member of the faculty of the Department of Computer Science at the University of South Carolina. He began working on geological applications of computing in 1987. He is interested in scientific visualization and the issues which arise when designing computer systems for a wide variety of users.