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Why the amplitude of sea level excursions cannot be measured but eustatic curves can be used for stratigraphic prediction (2)

A challenge : is it possible to determine eustasy and does it matter?, Kendall,C. G.St.C., Moore, P., Whittle, G., and Cannon R., 1992; in Dott, R. H., Jr., ed., Eustasy: The Historical Ups and Downs of a Major Geological Concept: Geological Society of America Memoir 180 p93-107.

This paper explains how the amplitude of eustatic sea level excursions cannot be determined so that, at the best, the sea level curves published in the literature are dependent on assumed models for the size of these excursions or the tectonic behavior of the crust. Thus when using these curves in the SEDPAK simulation, as is done in the examples described in this manual, it is important to realize that the SEDPAK output is non-unique and model dependent, no matter how well the output appears to match the stratigraphy being simulated.

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Chapter 9

A challenge: Is it possible to determine eustasy and does it matter?

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ABSTRACT

An interest in eustasy, after a long dormancy, has been revived by the development of seismic stratigraphy. Eustatic events signal their occurrence through the synchronous creation or loss of worldwide accommodation of the space available for sediment fill. Such events can only be recognized if this signal is large enough, and of worldwide extent. The signal is dependent on reliable stratigraphic markers spaced sufficiently closely in time to resolve the sea-level events. The amplitude cannot be determined. Evidence for eustatic events are widely separated synchronous sedimentary sequences and the unconformities which bound these features.

To unequivocally interpret the stratigraphic record, one must be able to disentangle the effects of changing tectonics, eustasy, and sediment supply. In practice it is impossible to accomplish a complete calibration of seismic sequences, therefore it will always be a matter of interpretation. However, a wide range of geological characteristics place limits on tectonism and eustasy. This allows the application of a family of reasonable tectonic and eustatic models to explain basin history. In most instances, models within the family are similar enough to reproduce the stratigraphic record at the level of resolution produced by seismic sections. In many cases this is due to the fact that tectonics, eustasy, and sediment supply are linked, rather than being independent of each other. Hence, although absolute values of bathymetry and tectonics may never be determined with precision, models can generate complex basinal sequences with high fidelity using plausible inputs. Thus assumptions heaped on assumptions work.

Examples used to demonstrate the above paradigm are from the Mesozoic and Tertiary of the Bahamas, the Gulf Coast of the United States, and the South Carolina Coast; and the Permian of the Midland basin of Texas.

INTRODUCTION

In this volume, most of the chapters provide a historical perspective to current studies on eustasy, and it is our contention that eustasy has played an important role in punctuating the character of the sedimentary section throughout the Earth's history. Geologists have long recognized that it is difficult, if not impossible, to prove a truly eustatic change of sea level from ancient strata because the magnitudes of the simultaneous influences of tectonics, sediment supply, and sea-level change could not be determined with certainty. What we have long known is that only evidence of a *relative change* of sea level is recorded in the rocks. Until the advent in the petroleum industry of high-resolution seismic cross sections in the 1960s, there has been a dormant period of at least three decades with regard to the study of eustasy. However, the rapid proliferation during the late sixties and seventies of seismic data from several continental margins has seen a mushrooming of interest in, and claims for, detailed documentation of ancient eustatic changes. These studies are so common that many believe we are in the midst of a revolution in geology similar to and as important as that which produced with the advent of plate tectonics. But is such a bold claim justified? In the present chapter, we look to the future and the use of graphical simulations to unravel the sedimentary section. We use

Kendall, C. G. St. C., Moore, P., Whittle, G., and Cannon, R., 1992, A challenge: Is it possible to determine eustasy and does it matter?, *in* Dott, R. H., Jr., ed., Eustasy: The Historical Ups and Downs of a Major Geological Concept: Boulder, Colorado, Geological Society of America Memoir 180.

the fact that sediment accommodation is the product of eustasy and tectonics, so that if one assumes the sea-level behavior, then the residual is tectonic behavior. This assumption of sea-level behavior has far-reaching implications in that it explains why one can use graphical simulations to predict facies and their geometry with great accuracy away from points with good geologic control. This assumption also explains why different sea-level curves and tectonic models can be equally successful in predicting geometries and facies.

This chapter is divided into three parts. We begin by showing that the size of the eustatic excursions cannot be measured. We then demonstrate that geometric simulations can be made that accurately predict the geometry and facies found within the geological record. These simulations use prescribed sea-level curves and prescribed tectonic behavior for the region being simulated. We conclude by demonstrating that prescribed tectonic behavior alone can be used to simulate geometries in the geologic record.

RECOGNITION OF EUSTATIC SIGNALS

Eustatic events signal their occurrence through the synchronous creation or loss of worldwide accommodation, that is, the space available for sediment fill (Jervey, 1988; Posamentier and others, 1988). The evidence for eustatic events consists of synchronous sedimentary sequences and the unconformities that bound them (Vail, 1988). An eustatic signal is recognized only if it is large enough and is of worldwide extent. The correlation of the signal to the stratigraphic record is dependent on reliable time markers spaced sufficiently close in time to resolve the sea-level events. Clearly, eustatic events do occur because we do see evidence of the synchronous creation of worldwide accommodation filled by sediment (Haq and others, 1987). Not all accommodation filled by sediment is synchronously created by eustasy but the Haq and others (1987) curve suggests that many of these sediment packages are synchronous (Figs. 1 and 2).

The problem with eustasy is that, though sea-level events can be recognized, the amplitude of their excursion cannot be determined. Thus, though there are several ways to measure sea level indirectly, there is no way to directly measure the magnitude of the change. This is so because the datum available from which we measure the sea-level variation varies itself. Relative sea level can be measured, but is dependent on the movement of the Earth's crust and eustatic position. Neither of these can be measured with respect to the other without assuming a model of the latter's behavior (Burton and others, 1987). There is simply no place to stand to make the measurement.

There are a number of methods, however, that purport to measure sea-level position indirectly (Vella, 1961; Burton and others, 1987). There is the use of tide gauges (Gutenburg, 1941), but these assume a tectonic behavior to determine the eustasy. For instance, if we compare the tidal gauges of Norway to those of the Bahamas, it is very clear that something is happening differently in either environment. We assume a tectonic behavior to explain the uplift of Norway with respect to a rather stable crustal behavior in the Bahamas. It should be realized, however, that these tectonic models are assumptions, reasonable as they might be (Burton and others, 1987).

We can use strandline position (Cogley, 1981; Harrison and others, 1981; Burton and others, 1987), but in order to use this to measure eustatic movement through geological time, we have to assume either continental relief as a function of time or tectonic behavior for the area, or both (Burton and others, 1987).

We also can use paleobathymetry to measure eustatic sea level (Barrell, 1917; Wanless and Shepherd, 1936; Wells, 1960; Harris and others, 1984); in this particular case we have to assume a tectonic behavior before we can actually extract the residual sea level (Burton and others, 1987).

The same criticism can be applied to the use of seismic sequence onlap. In this case, we assume we can see the relative position of individual sedimentary bodies or seismic sequences as they onlap continental masses to determine eustatic behavior (Vail and others, 1977, 1984; Hardenbol and others, 1981; Vail, 1988). To determine the size of these excursions, however, we have to assume a tectonic model (Hardenbol and others, 1981). The Haq and others (1987) curves require that one assumes a thermotectonic subsidence on extensional margins, and then extract sea level as the residual. However, as we show (Guidish and others, 1984) when we stack a series of crustal subsidence curves, these curves not only contain low-frequency signal but they also have a high-frequency signal. These curves bear little resemblance to the signals of the Vail and others (1977) and Haq and others (1987) curves, so they tend to be conveniently ignored. While a general low-order background thermal subsidence is demonstrably reasonable (Watts and Steckler, 1979), the cause of the erratic high-frequency signal is probably because the Earth's crust is brittle and thus has a jerky high-frequency response to the low-order effects of thermal subsidence. Cloetingh and others (1989) explain how the sea-level events of Vail and others (1977) and Haq and others (1987) may be a response to intermittent phases of accumulated tensional stresses "associated with rift episodes and subsequent rapid relaxation of these stresses." As we see it, these superimposed high-frequency variations in crustal behavior bear little relationship to the weight of the sea water on the crust

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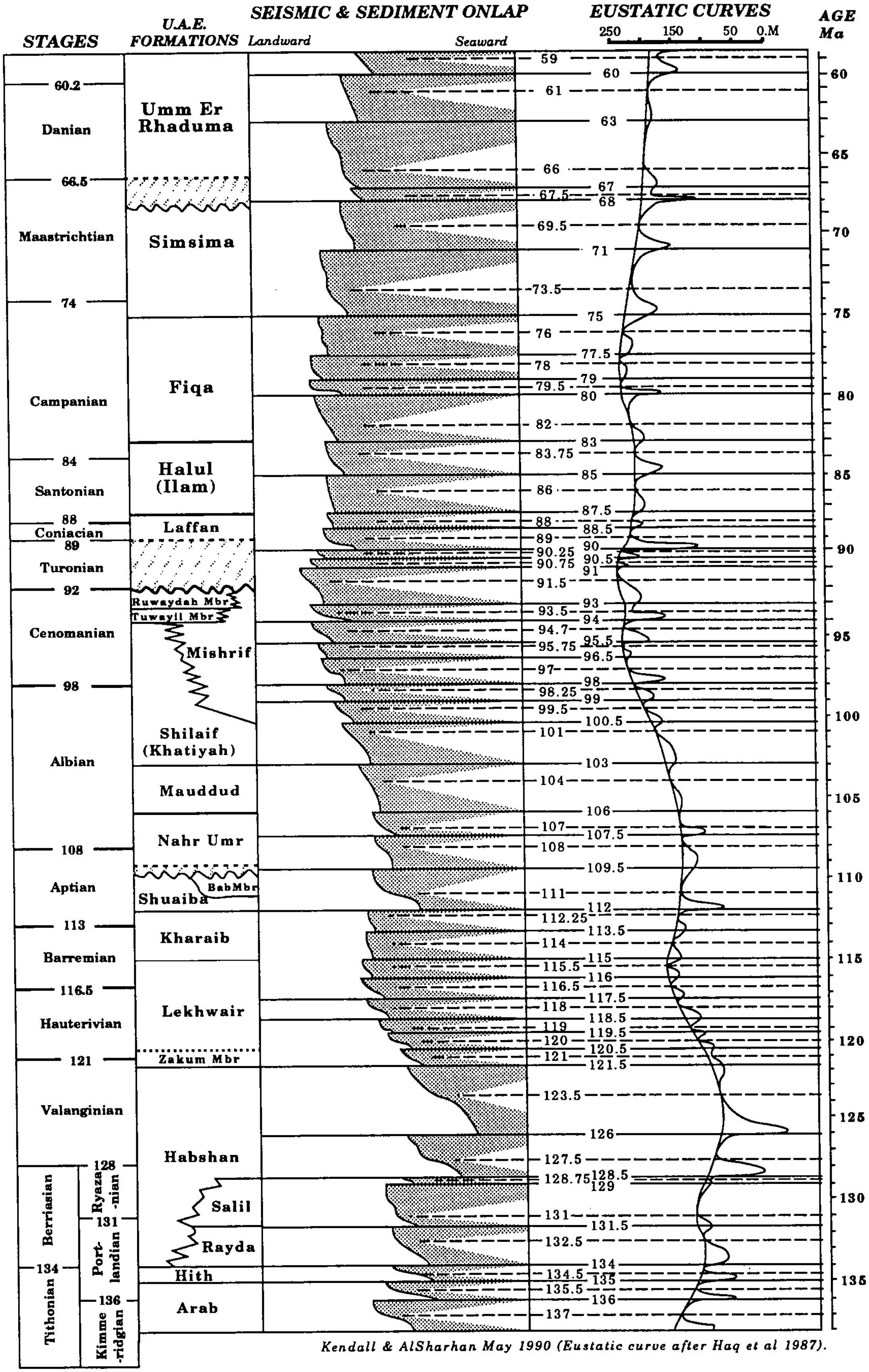
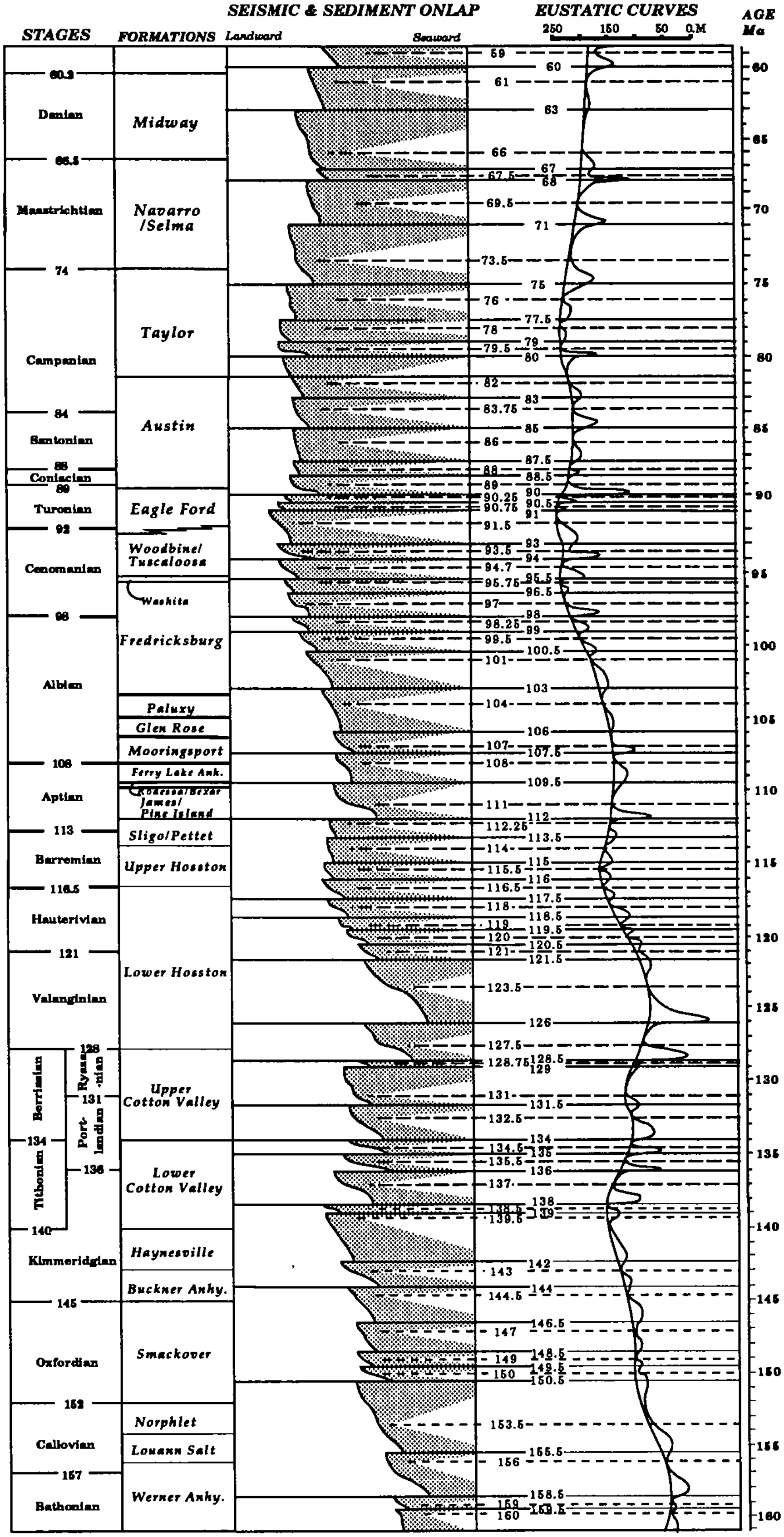
Figure 1. The Haq and others (1987) eustatic curves and their relationship to the stratigraphic column of the United Arab Emirates. For these correlations of sea level to basin stratigraphy it was assumed by Kendall and others (1991) that most of the Haq and others (1987) excursions took place at the times they specify. Where Kendall and others (1991) had access to paleontological age data they have based their correlations on these but where age data are absent, they have extrapolated between events of known ages using the philosophy of Van Hinte (1976a, b). The dashed horizontal lines are intended to coincide with rapid sea level rises, and the gray fill the general occurrence of onlapping seismic facies.



Kendall & AlSharhan May 1990 (Eustatic curve after Haq et al 1987).



Kendall, Cheong, and Bowen 1989 (Eustatic curve after Haq et al 1987).

(Guidish and others, 1984), but may indeed be related to rapid crust and plate movement (Fig. 3).

Finally, we can use sedimentary simulations to match sea level and sequence geometry, but again, though we can do this with remarkable accuracy, we have to assume a sea-level curve to derive tectonic behavior or vice versa (Burton and others, 1987). The simulations derived from these assumptions are accurate and verifiable away from the areas of interest and measurement. The reason we can do this is that the geometry of the sediment is dependent on the rate of sedimentation and the sum of tectonic movement and sea-level position, in other words, the accommodation. Furthermore, if a tectonic model is assumed, then a sea-level model automatically is determined, or vice versa.

One can use an assumed sea-level curve to create accurate graphical simulations of the sedimentary fill of basins. The technology of graphical simulations is becoming more widely accepted and used within the geological community, particularly within university geological departments and oil companies. In the simulation we have designed (SEDPAK), we can track the evolving sedimentary geometry of carbonates and clastics as they fill a basin (Strobel and others, 1989; and Kendall and others, 1990 describe much of what follows; the readers are referred to these papers for more details). To do this, we assume an initial basin geometry, prescribe a sea-level curve, and plot tectonic behavior as a function of time and position. Then for clastic deposition, we determine the volume of clastic sediment as an area of sediment that enters the basin as a function of time, and the distance that it penetrates the basin as a function of time. This sediment deposition obeys simple laws, including the precept that clastic sediment may not be deposited if the sediment depositional surface is above a certain angle, or having been deposited, if compaction and tectonics now cause the sediment to rest at too high an angle, then the sediment is eroded and deposited downslope. The clastic sediments are deposited as either sand or shale (or both), within the marine setting, or upslope as alluvial sediments. The marine setting includes a coastal-plain shelf or the sediment may penetrate the basin below wave base as turbidites or collect as some form of pelagic deposits. Secondary variables handled within the simulation include regional subsidence, hinged subsidence, the isostatic response to sediment loading, the compaction of sediment, the subaerial and submarine erosion, submarine slumping, faulting, and two-sided fill of the basin.

For carbonate accumulation, we assume that its rate is dependent upon water depth, and so rates of accumulation are faster in shallow water and become slower in deeper water. The user must prescribe the rates of accumulation at certain depth positions, and the program interpolates these rates between the user-defined rates. Within the carbonate algorithm, we assume that the rate of carbonate accumulation for a particular run is constant, while we vary the rate of pelagic carbonate input as a function of time. We also can prescribe the amount of sediment that forms on the shelf margin and may be distributed downslope as an apron or as a turbidite or may actually be carried from the break-in slope back onto the shelf to infill the lagoon. We assume that carbonate production for the slope is largely coming from the basin margin, and using this assumption, we have been very successful with our simulations. Not only do we accumulate carbonates, but we can damp their accumulation in response to the input of clastics or as a function of location. In other words, we can have faster or slower rates of accumulation in lagoons, and we can damp them as a function of wave energy. In the latter case, we can prescribe a fall in the rate of accumulation as a function of depth when waves start touching the sea floor. This wave-damping function is subtracted directly from the depth-dependent rate of accumulation.

Figure 2. The Haq and others (1987) eustatic curves and their relationship to the stratigraphic column of the northern Gulf of Mexico. (See also discussion and symbol definitions on Figure 1 caption.)

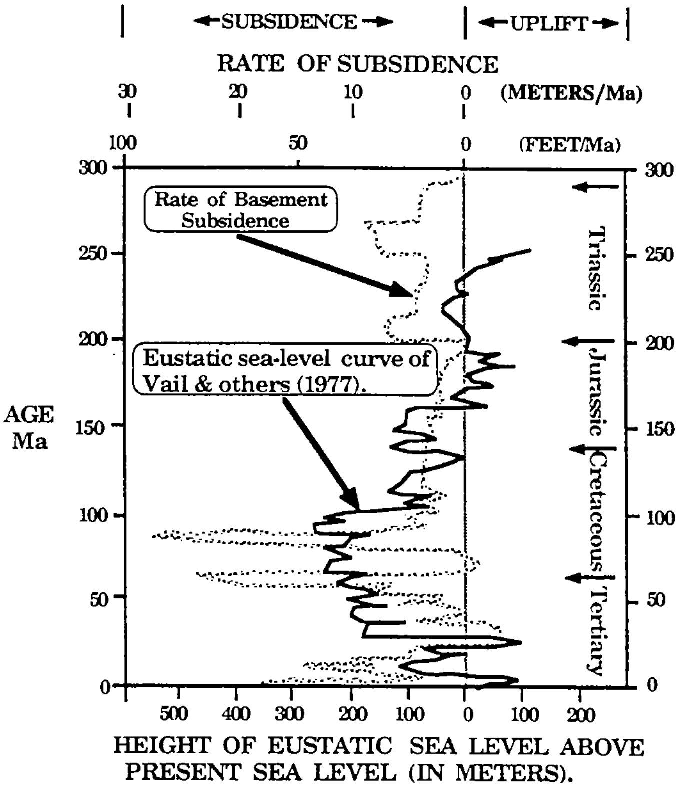


Figure 3. Comparison of global average rate of basement subsidence and eustatic curve of Vail and others (1977); after Guidish and others (1984).

SIMULATION RESULTS

Bahama Banks

Having described the simulation, we will now show how graphical simulations that assume a specific sea-level behavior can be used to model either carbonate geometries or clastics, or mixes of both with incredible accuracy. The first model is for the Bahamas. Here, Western Geophysical acquired a series of seismic lines on the northwestern side of the Great Bahama Banks. These were interpreted by Eberli and Ginsburg (1989), who demonstrated that, from the Late Cretaceous on, a series of carbonate platforms grew upward toward sea level (Fig. 4). Their rates of accumulation were faster over these banks, but the areas between banks accumulated carbonates rapidly enough to fill them to sea level. Here the carbonates aggraded and then prograded as the areas between the banks filled. Eberli and Ginsburg (1989, Fig. 11), recognizing the existence of unconformities, mapped a series of seismic sequences, which they lettered A to Q, and were able to correlate from the western margin of the Bahamas to a region they called the Straits of Andros, in the center of the Bahama Bank. They then related these sequences to the Haq and others (1987) curve, using a well at Great Isaac to determine the position of two major breaks in the sedimentary section. One such unconformity was in the mid-Miocene, another at the Oligocene-Miocene boundary; the rest of the compilation was assumed to be directly correlatable to the events seen in the Haq and others (1987) curve.

Using the Haq and others' (1987) curves then as input to our simulation, varying tectonic subsidence across the section and assuming a particular rate of carbonate accumulation as a function of water depth, and varying pelagic accumulation as a function of time, we were able to match the geometries of the western Bahamas with some accuracy (Figs. 4 and 5; Eberli and others, 1990). Of particular significance was the fact that we were able to cause this sequence to aggrade and not to prograde during the major sea-level fall of the upper Oligocene, by making the fault

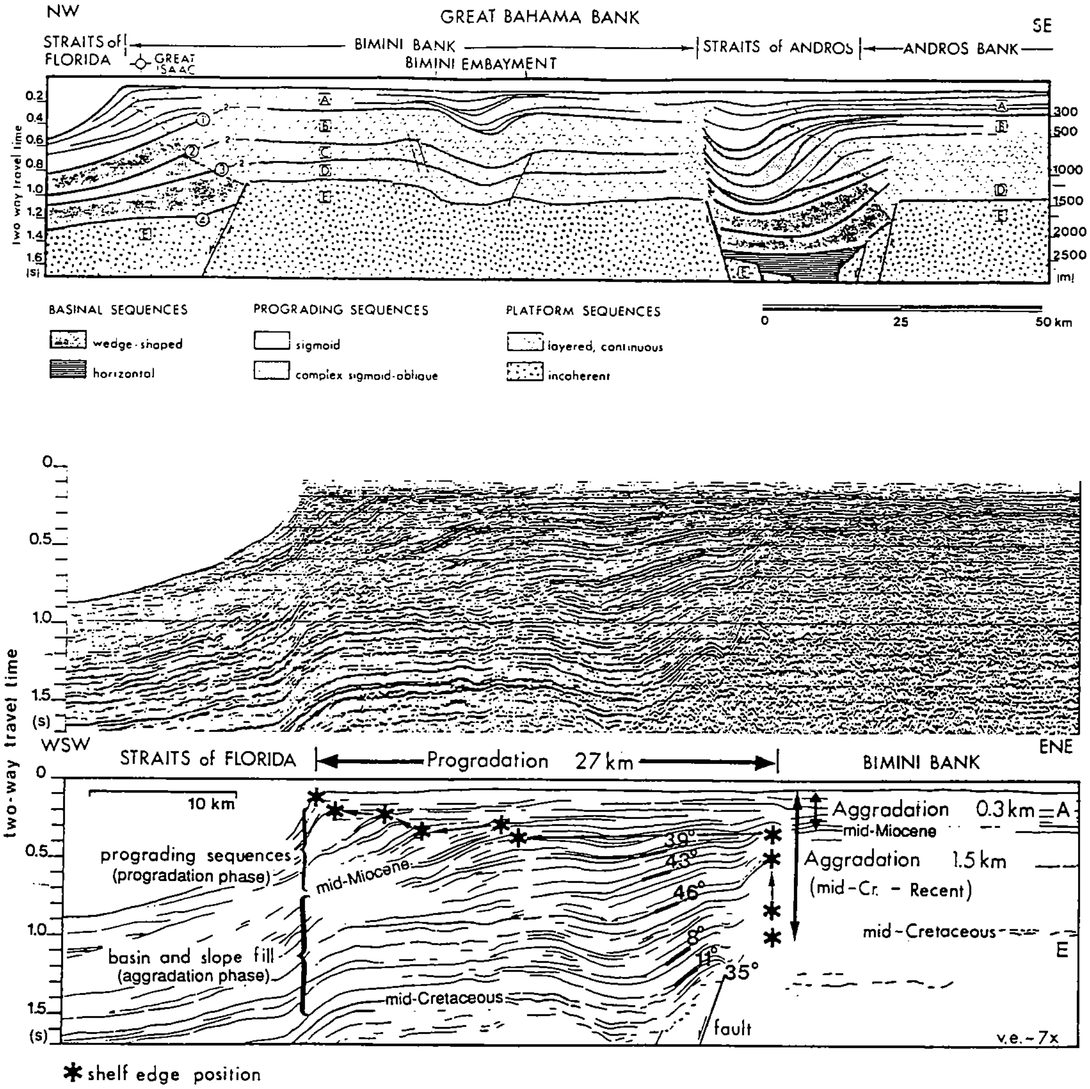


Figure 4. Schematic cross section of the northwest Great Bahama Bank after Eberli and Ginsburg (1987), and an interpreted seismic section of the western edge to the Great Bahama Bank after Eberli and Ginsburg (1987).

against the early western Bahama margin active during deposition as probably initiated by the collision of Cuba with the Bahamas. This prevented the rapid progradation of the sequence during the Oligocene sea-level low; however, during the mid-Miocene sea-level low, rapid progradation was initiated. The match between the seismic section and the simulation is remarkable. Individual unconformities can be matched, as can the timing of events. Low-stand onlapping and the high-stand progradation events are clear. Both the simulation and the seismic sections match beautifully. The interesting thing is that to acquire this match in geometries between the simulation and the actual seismic data, we varied only subsidence behavior and tried different accumulation curves. Eventually we were able to obtain a match between the seismic simulation of the western Bahamas (Fig. 5) and the seismic simulation of the Straits of Andros (Fig. 6) by using the same sea-level curve, similar carbonate accumulations, and tectonic models. Thus we were able to predict the geometries that we see in the Straits of Andros using data from the western margin. In this test of the input parameters, we made very little variation in the sediment accumulation rates, but did change subsidence rates to be different from those we used for the western side of the Bahamas.

In conclusion, by using the Haq and others' (1987) sea-level curve, we are able to recreate the regional stratigraphic geometries from very simple assumptions that we have programmed in our simulation and get remarkable matches in the geometries from the seismic data. This has far-reaching implications with respect to the development of predictive production and exploration models for petroleum.

Gulf of Mexico

We can demonstrate a similar match that can be achieved when the clastic algorithm is used. Here, we used a seismic line from the Gulf of Mexico, provided by the TGS company (Fig. 7;

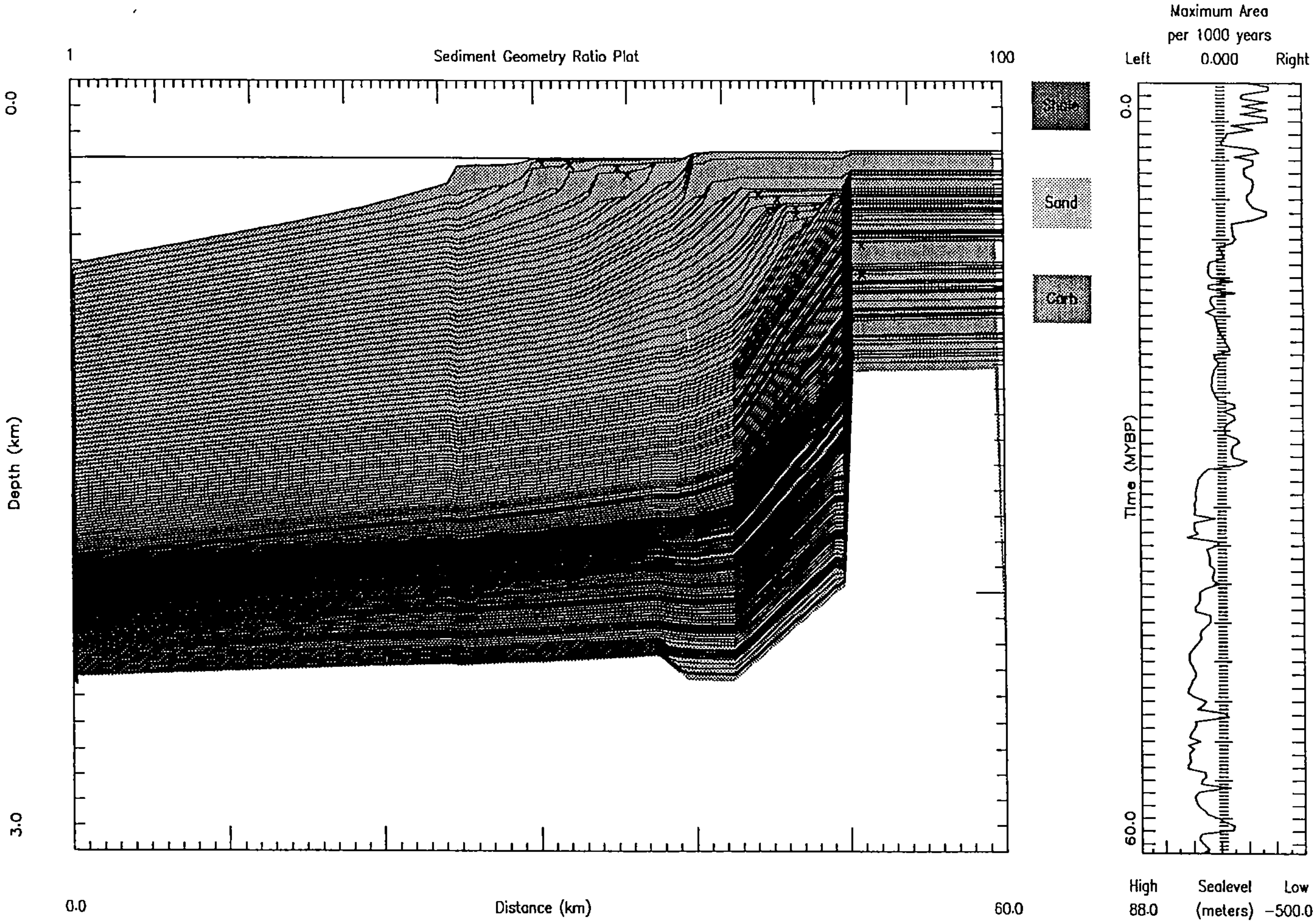


Figure 5. Output for the western Bahamas simulation data set. Note how the system aggrades through the lower Tertiary to the mid-Miocene and then progrades. At the same time, pelagic deposition rates varied. The subdivisions on the upper horizontal axis of the left diagram indicate the columns on which sediment deposition was simulated. The lower horizontal axis shows distances across cross section. The vertical axis is depth in meters. The xs mark the intersection of the coastal plain and sea level (the most seaward edge of the coast). The diagram to the right shows the sea-level curve.

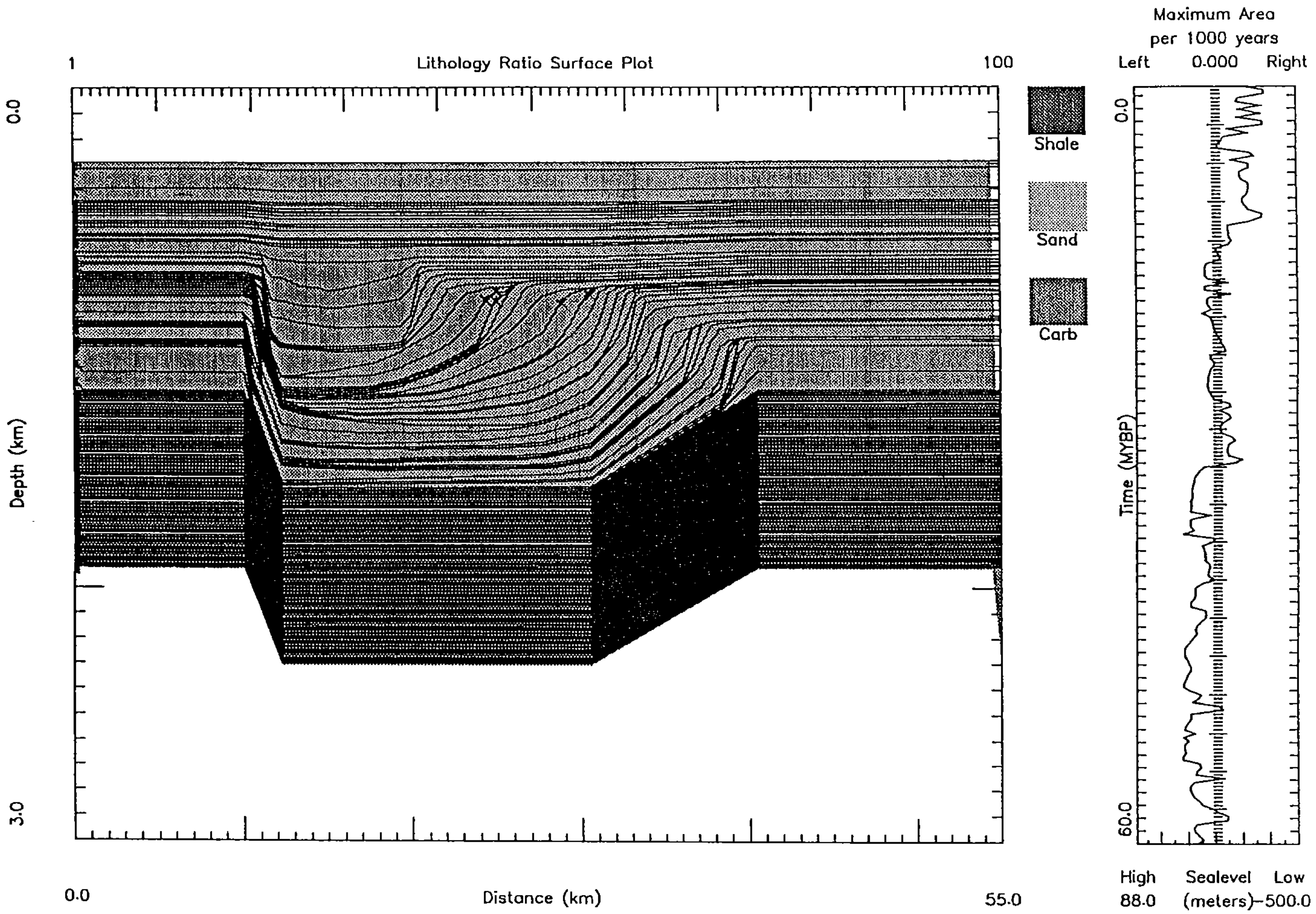


Figure 6. Output for the Andros Channel in the Bahamas simulation data set. Note how the system progrades through the lower Tertiary into the Miocene and then aggrades. At the same time, pelagic deposition rates varied. See Figure 5 caption for explanation.

Kendall and Lowrie, 1990). This line shows a series of small salt domes, which were active during the deposition of deltaic sequences in the late Pleistocene and early Holocene. By varying the amount of clastic input as a function of time expressed as shales and sands, we were able to recreate the general geometries that occur in this area using a sea level that we derived from the seismic line. The match between the seismic data and the clastic fill was not perfect, but suggested that this simulation, which was tied to the seismic section (Figs. 7 and 8), can be used to high-grade the sedimentary potential of the area.

Using the simulation, we should be able to model below the resolution of the seismic data in both the Bahamas and the Gulf of Mexico and produce stratigraphic models, which match with some accuracy.

TECTONICS AS THE SOLE CAUSE OF ACCOMMODATION

Despite the fact that we can reproduce a stratigraphic section through simulation, we are still faced with the problem of separating fact from fantasy. Which sea-level curve do we use, or do we even need to use a sea-level curve? Below, we demonstrate how one can reproduce the geometries of stratigraphic sections, using either a sea-level curve tied to a tectonic signal, or reproduce the geometries using tectonics alone, and ignore the sea-level curve.

Permian Clear Fork Formation

In this particular case, we used seismic data and well logs in an interpretation put together by Sarg (1988) and others from Exxon, and modeled the Permian Clear Fork Formation at the margin of the Midland Basin. Here, a series of prograding clinoform carbonate bodies interfinger down-dip with clastic wedges (Fig. 9). We interpret this sequence to be a product of variations in sea level, and we derive our own sea-level curve for the region using the Ross and Ross (1988) sea-level curve and our own interpretations. We can show that initially there was a prograding, high-stand carbonate body filling the basin, but as sea

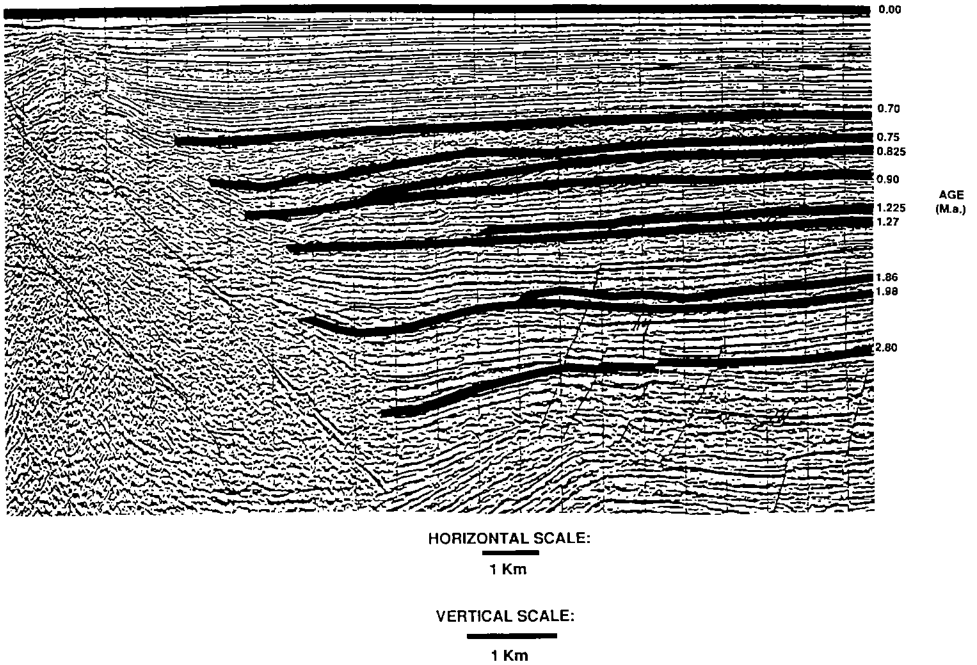


Figure 7. Seismic cross section from the Pleistocene of the Gulf of Mexico. Heavy lines mark sequence boundaries (courtesy TGS Geophysical Company).

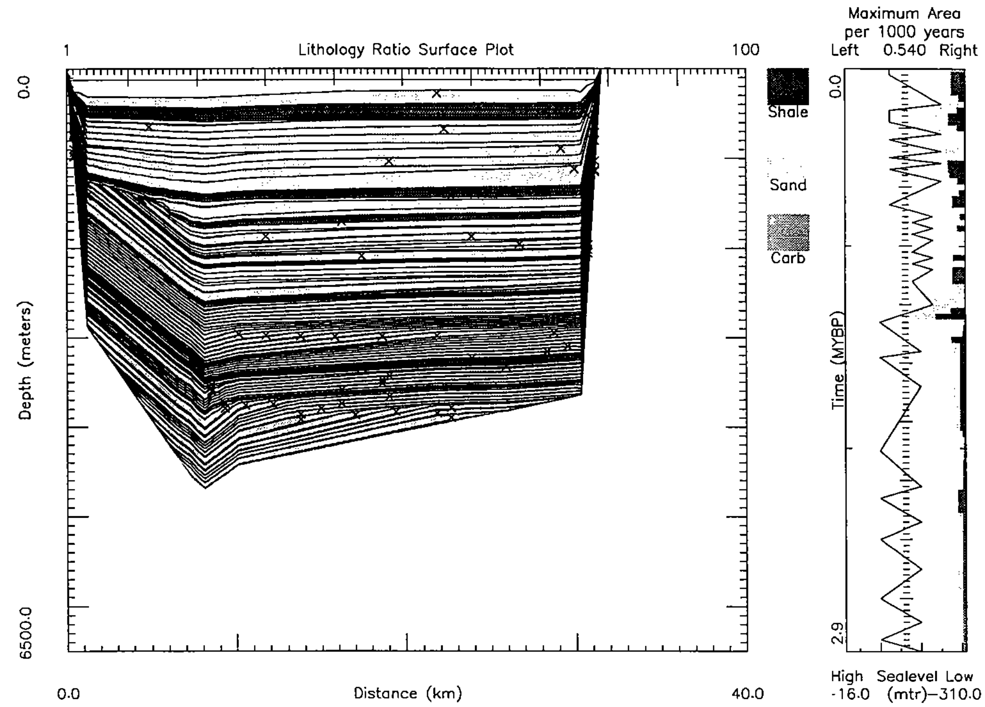


Figure 8. Simulation of the above seismic cross section from the Pleistocene of the Gulf of Mexico, shown in Figure 2. The diagram to the right shows the sea-level curve and the area of clastics (in $km^2/1{,}000$ years) deposited per time step. See Figure 5 for explanation.

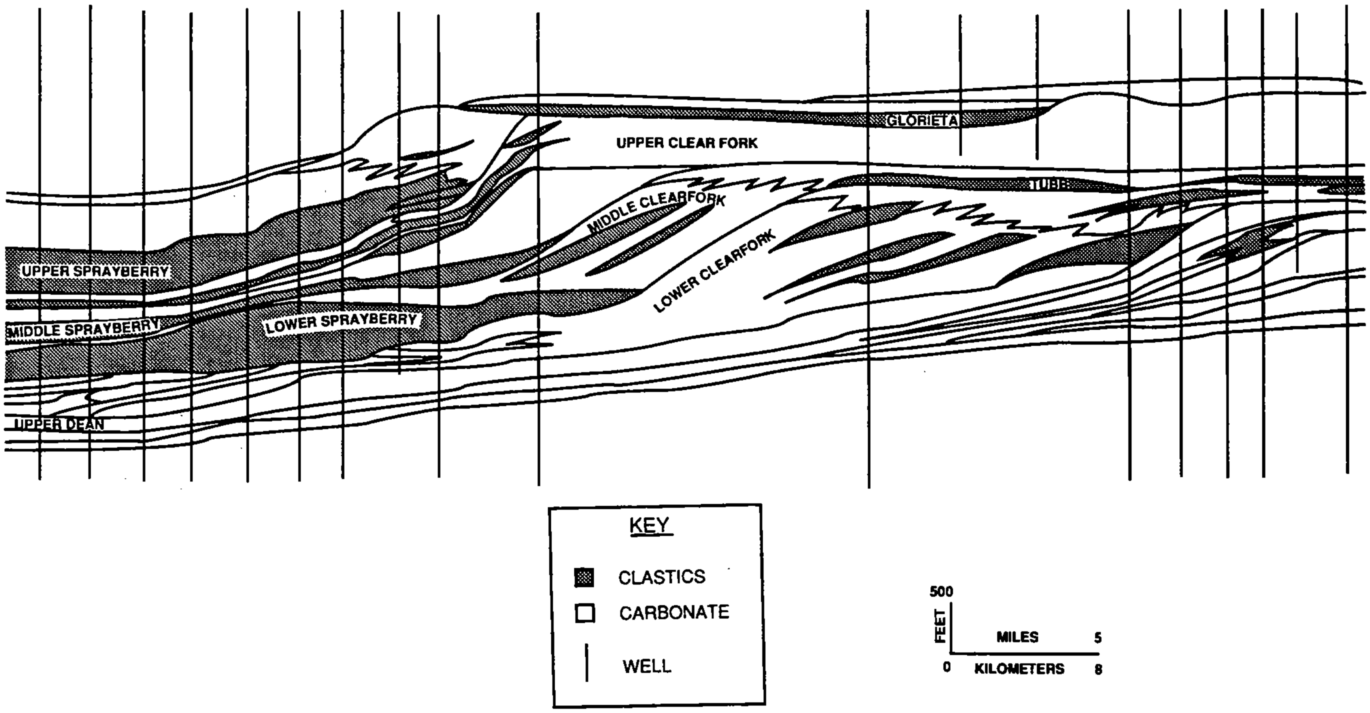


Figure 9. Well cross section from the Permian basin of west Texas of the Clearfork Basin after Sarg (1986).

level fell, clastics were introduced into the basin as a low-stand systems tract. Then, as sea level began to rise again, carbonate production turned on while clastics turned off, thus producing a prograding and aggrading high-stand carbonate depositional systems tract. Sea level rose and fell twice and rose again to produce the geometries preserved (Fig. 10). The input for this simulation first included the sea-level curve seen in Figure 10. To test the tectonic model, we then turned off this variation in sea level, but used its sea-level–derived subsidence behavior for this margin as a function of time (Fig. 11). The subsidence is derived by converting sea-level positions to rates, then scaling the resulting rates according to position across the basin. The result shows a good match between the carbonate margin and low-stand clastics of the simulation and the stratigraphic and seismic sections, suggesting that these geometries might have been produced without varying eustasy at all. The major differences between the two simulation runs are that we did not include a general first-order crustal subsidence, which would have made the two geometries identical.

South Carolina

In two other simulation runs, we tested to see if tectonic behavior would recreate the geometries instead of sea level for the Danian of the South Carolina coastline (Muthig and others, 1990), where carbonates and clastics interfinger with one another (Fig. 12). In one simulation run we used the Haq and others (1987) sea-level curve (Fig. 13), and in the next run (Fig. 14), we took this same sea-level curve and used its sea-level–derived subsidence behavior as input for tectonic behavior (Fig. 15). We used two different crustal subsidence behaviors across the line of section. One had greater amplitude, but the same frequency of events, in a more seaward position where we thought the crust subsided rapidly; and the second one was in a more landward (i.e., inland) position with slower crustal subsidence and less frequency. The timing of the events was determined from the Haq and others' (1987) curve. And the resulting two simulation runs are remarkably similar to one another, suggesting that the geometries we see in this mixed carbonate/clastic terrain could be a product of tectonics alone, or a mix of sea-level and tectonics. Our conclusion is that this sedimentary sequence is not the product of tectonics alone, because it is highly unlikely that the tectonic movement was such that the Earth's crust was moving up and down with such rapidity that it produced this type of sedimentary accommodation (Fig. 15). Instead, we feel that there was a eustatic signal coupled with tectonics that was driving the stratigraphy that we see in the Danian of South Carolina. Nevertheless, the amplitude of the sea-level events cannot be determined, but the frequency of their occurrence can.

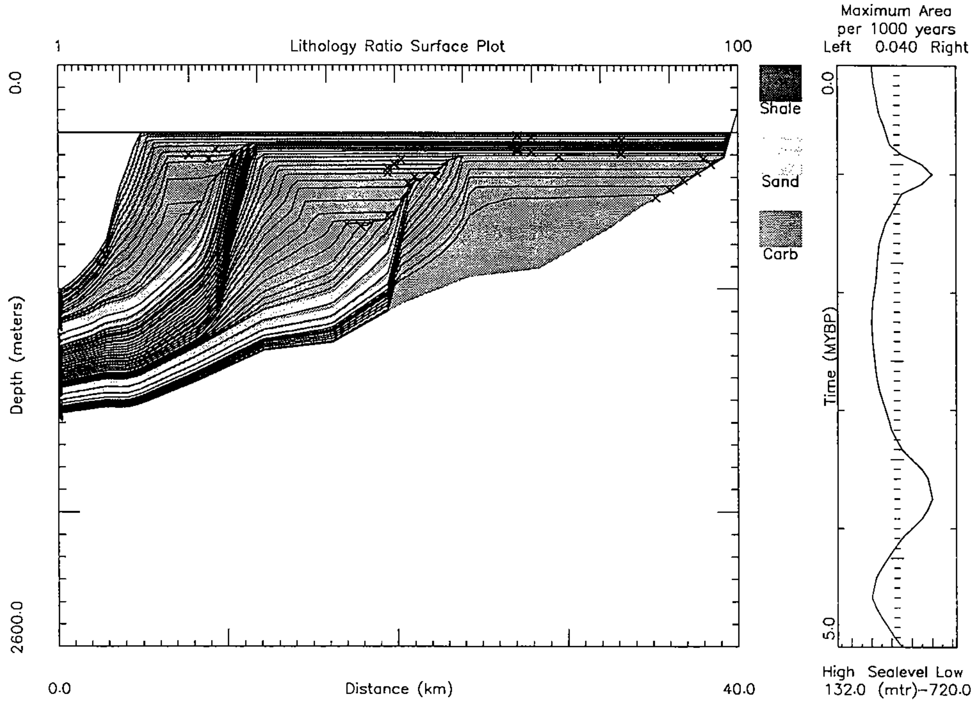


Figure 10. Simulation of the well cross section shown in Figure 9 from the Permian basin of west Texas of the Clearfork basin after Sarg (1986) using our own sea-level curve. In the sediment geometry rates plot, the darkened fill is of percent of carbonate and the lighter fill is percent of sand deposited for each time step. The diagram to the right shows the sea-level curve and the area of sands (in km^2/1,000 years) deposited per time step. See Figure 5 for explanation.

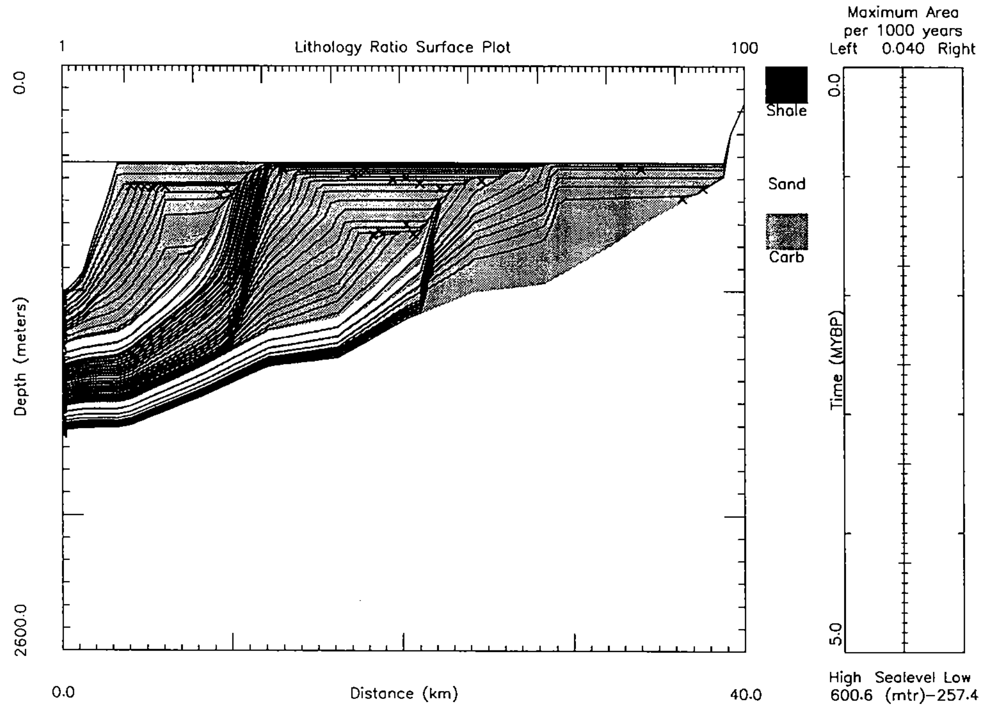


Figure 11. Simulation of the well cross section shown in Figure 9 from the Permian basin of west Texas of the Clearfork basin after Sarg (1986) using a subsidence history derived from the sea-level curve. In the sediment geometry rates plot, the darkened fill is of percent of carbonate and the lighter fill is percent of sand deposited for each time step. The diagram to the right shows the sea level curve does not vary and the area of sands (in km^2/1,000 years) deposited per time step. See Figure 5 for explanation.

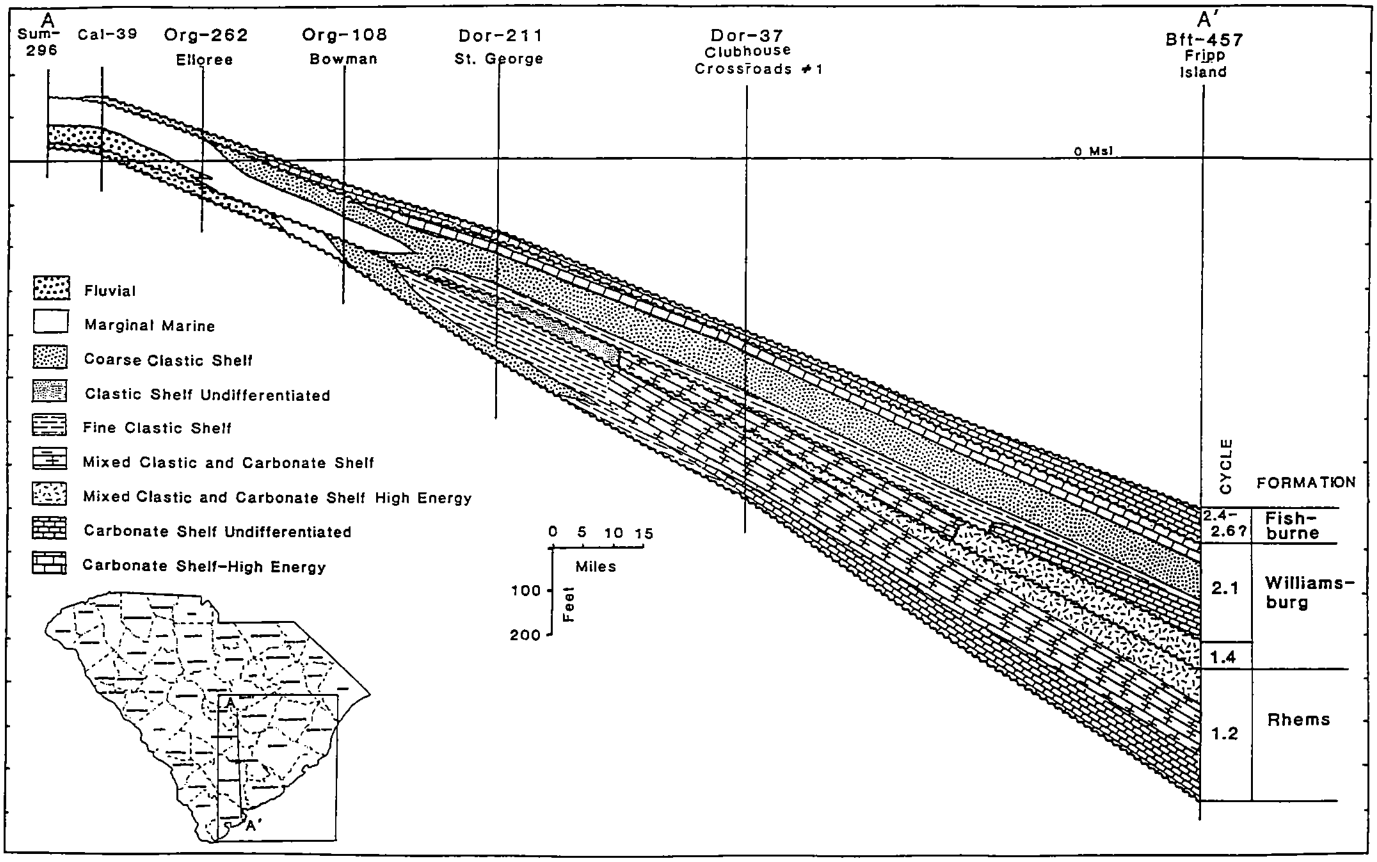


Figure 12. Well cross section of the Danian section from the coast of South Carolina after Muthig and others (1990).

CONCLUSIONS

We can show that eustatic signals can be recognized as worldwide events. The amplitude of the events cannot be determined, but if we assume a eustatic sea-level behavior, then tectonic behavior can be predicted or vice versa. The last two simulation results highlight the importance of taking care in selecting the sea-level model to be used in the simulation. At the same time, it is critical that, once a sea-level model has been selected, no matter what that model, it must be used consistently from basin to basin. Such models can be used to make extremely accurate predictions of sedimentary geometry. This is because sea level is only part of the accommodation for sedimentary fill, which also depends upon the residual of tectonics. The results of such simulations are reviewed in this chapter; they are remarkable in their accuracy. The amplitudes exhibited by sea-level events of Haq and others (1987) are undoubtedly model-dependent, and they may be very wrong or only partly wrong. We feel that with the advent of microcomputers, we are on the edge of a new age in stratigraphic modeling, which will enable us to make great advances in our understanding of the sedimentary section.

ACKNOWLEDGMENTS

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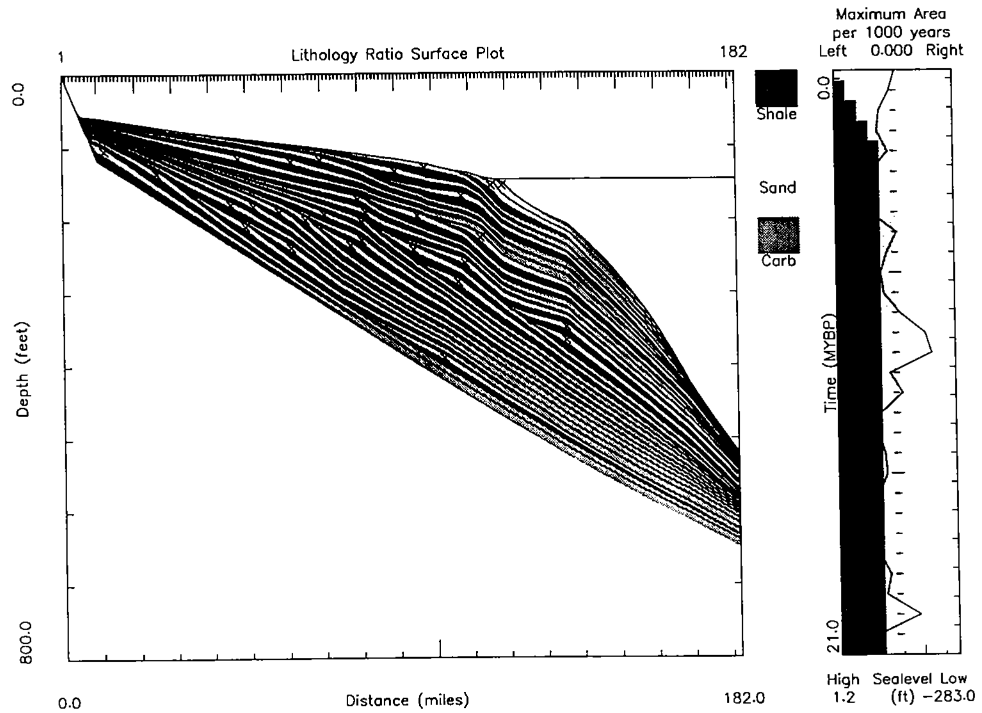

Figure 13. Simulation of the well cross section shown in Figure 12 of the Danian section from the coast of South Carolina after Muthig and others (1990) using the Haq and others (1987) eustatic curves. In the sediment geometry rates plot, the darkened fill is of percent of carbonate and the lighter fill is percent of sand deposited for each time step. The diagram to the right shows the sea-level curve and the area of sands (in km^2/1,000 years) deposited per time step. See Figure 5 for explanation.

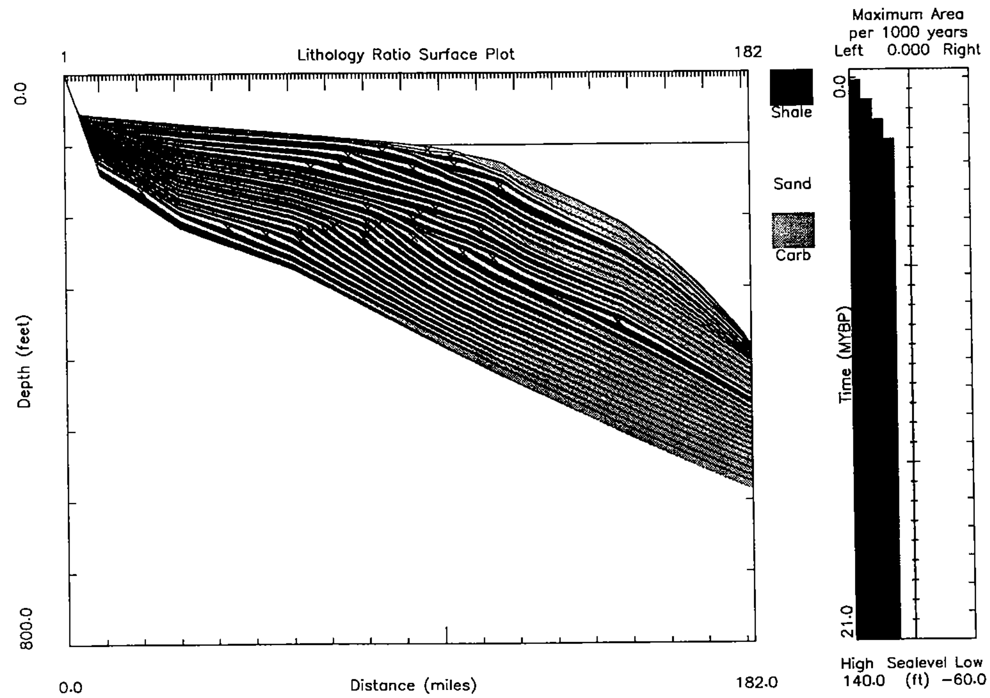

Figure 14. Simulation of the well cross section shown in Figure 12 of the Danian section from the coast of South Carolina after Muthig and others (1990) using a subsidence history derived from the Haq and others (1987) eustatic curves. In the sediment geometry rates plot, the darkened fill is of percent of carbonate and the lighter fill is percent of sand deposited for each time step. The diagram to the right shows the sea-level curve does not vary and the area of sands (in km^2/1,000 years) deposited per time step. See Figure 5 for explanation.

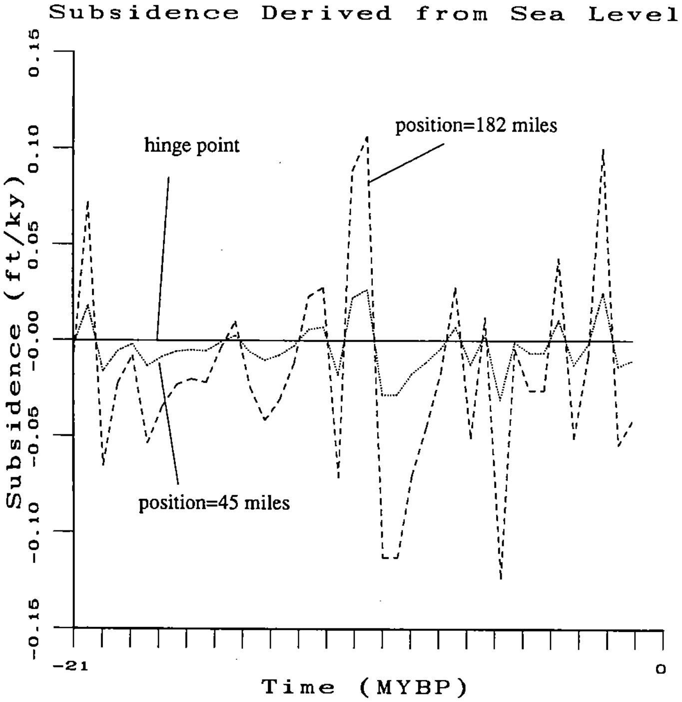

Figure 15. Subsidence history derived from the Haq and others (1987) eustatic curves used in the South Carolina simulation. The horizontal solid line represents the hinge point at the left (landward) side of the simulation. The dotted curve represents the rate of subsidence at a position 72 km (45 mi) basinward of the left side, while the dashed curve represents the rate of subsidence at a position 293 km (182 mi) basinward (i.e., the extreme right side) of the left side.

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