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Multivariate sequence stratigraphy: Tackling complexity and uncertainty with stratigraphic forward modeling, multiple scenarios, and conditional frequency maps

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ABSTRACT

Sequence-stratigraphic conceptual models typically focus on accommodation as a dominant control. Although useful in many ways, this approach may not address the full range of possible controls on stratal patterns, nor is it likely to fully address uncertainty in the identification and quantification of controlling processes. Consequently, predictions from sequence-stratigraphic conceptual models may be more limited than generally stated. Progress in addressing this problem can be achieved by applying the latest generation three-dimensional stratigraphic forward modeling to (1) investigate and include more of the parameters that may control stratal architectures and (2) consider multiple scenarios to help determine the impact of uncertainty in operating processes and their parameter values. Results from a three-dimensional diffusional stratigraphic forward model illustrate this approach, suggesting that relative sea level change, shelf width, and sediment-transport efficiency are important large-scale controls on the spatial and temporal distribution of deep-marine stratal volumes. If this result is sufficiently independent of model assumptions and can be replicated in other models, it suggests that all three controlling factors should be included in interpretations and predictions of outcrop and subsurface deep-marine strata. Modeling results also suggest that combining multiple forward-model scenarios to form conditional frequency

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maps may be a useful, practical method to present and analyze multiple scenarios. The use of multiple forward-modeling scenarios to consider multiple controls on stratal architecture could begin to account more fully for uncertainty in controlling processes and parameter values, in sequence stratigraphy generally, and evaluation of subsurface uncertainty specifically.

INTRODUCTION

Sequence-stratigraphic conceptual models (e.g., Vail et al., 1977; Posamentier et al., 1988; Van Wagoner et al., 1990; Posamentier and Morris, 2000) have been widely applied, particularly in the hydrocarbon industry where they have been used to predict reservoir distributions and geometries. Early versions of these models had several weaknesses. One particular area of weakness was the conceptual, somewhat speculative nature of the model and the logic commonly used in an attempt to test it; i.e., if it is possible to interpret strata in terms of the model, the model must be valid, although this commonly constitutes circular logic. These problems were, in part, addressed by some of the first-generation numerical stratigraphic forward models. These models represented eustasy, subsidence, and sediment supply quantitatively and helped support the interpretation that certain aspects of the postulated sequence architectures could indeed develop as predicted (Jervey, 1988), although rarely exactly as predicted (e.g., Lawrence et al., 1990; Jordan and Flemings, 1991; Karner and Driscoll, 1997) and sometimes by different mechanisms entirely (Burgess and Hovius, 1998; Burgess, 2001).

Despite this work, many aspects of sequence-stratigraphic conceptual models still do not capture the complexity of real-world processes and parameters. To illustrate this problem more directly, consider a hypothetical example of a vertical section of deep-marine strata that shows a change from a mud-dominated to a sand-dominated facies. An explanatory interpretation of these strata should seek to understand why this change occurred and what implications the causal mechanism has for predictions of stratal geometries elsewhere in the basin, but numerous possible explanations exist. The observed facies change may have occurred because of a change in the accommodation on the shelf; a change in sediment input, either in total volume or in the grain-size proportion or both; a change in dominant sediment-transport process or transport energy and efficiency; or a change in basin physiography. Note that in this case, total sediment volume input, type of sediment-transport process operating, and the sediment-transport efficiency are considered as potentially separate and variable controlling parameters. These numerous possibilities are rarely given equal consideration in the interpretation of ancient strata. Instead, most workers choose to simplify the interpretation and focus on accommodation as the main control, despite the fact that this may ignore many equally plausible explanations. Sediment supply is assumed to be constant or varying only in a manner driven directly by sea level oscillations or only causing subordinate modification of geometries controlled primarily by accommodation. For example, Coe and Church, (2003) provide a useful, comprehensive summary of the sequence-stratigraphic conceptual model. They describe how parasequence stacking patterns develop under relative sea level control, and they state that a decrease or increase in sediment supply can generate retrogradation or progradation, respectively, but there is no discussion of the consequences of temporal variations in supply. Similarly, tectonic subsidence is still most commonly considered to be a simple monotonic function of time (e.g., Posamentier et al., 1988). Clearly, these are simplifications that do not capture the real range of possibilities. Schlager (1993) suggested that sediment supply variations are important in determining sequence architecture, and Leeder et al. (1998) and Carroll et al. (2006) have provided examples of how sediment supply variation through time impacts on stratal architectures. Posamentier and Allen (1993) pointed out that basin physiography is also a key parameter, but still, it is rarely systematically considered as a significant modifier to basic predictions of sequence architecture, except perhaps on submarine slope systems. Swift and Thorne (1991) and Thorne and Swift (1991) proposed a regime model applicable to shallow-marine shelf systems that is significantly more complex than the basic sequence-stratigraphic model, but this regime model is rarely applied to the interpretation of outcrop and subsurface examples. Other authors have also proposed models that account for more possibilities (e.g., Gawthorpe et al. 1994; Reading and Richards, 1994), and there are examples where various controlling mechanisms are considered (e.g., De Wet, 1998; Modica and Brush, 2004; Rasmussen and Dybkjær, 2005), but most of the attempts to interpret and explain ancient strata in outcrop and the subsurface still tend to assume that accommodation is the single most important mechanism (e.g., Schroeder and Greenlee, 1993; Ewing, 2002; Posamentier and Kolla, 2003; Armentrout, 2004; Atchley et al., 2004).

This simplifying approach may well be adopted for good practical reasons, recognizing that considering a broader range of possibilities is significantly more difficult and time consuming, but as Schumm (1991, p. 11) points out, ''when only one hypothesis is generated and an attempt is made to demonstrate its correctness, it becomes a 'ruling hypothesis,' which dominates the thinking of an investigator and may lead to serious error.'' Sequence-stratigraphic predictions made with an overemphasis on accommodation as the controlling factor may lead to underestimates of the actual complexity involved in the generation of strata, with potential for significant errors in determining what lithologies and architectures may actually be present away from outcrop or well penetration data points.

Uncertainty in parameter values is also a major contribution to this issue; even if sequence-stratigraphic models include a realistic number of controlling processes, how can these be reliably and uniquely quantified for ancient systems? Such uncertainty is ubiquitous in sequence stratigraphy, but rarely seriously considered. Attempts to bring attention to this problem are commonly ignored. For example, Miall (1997) demonstrated that purported global sea level curves are fundamentally flawed, at least for oscillations with duration of less than a few million years, and Burton et al. (1987) demonstrated that eustasy cannot be uniquely determined without making assumptions regarding subsidence and sediment supply. A consequence of this work would seem to be that eustatic history is an uncertain, poorly constrained parameter. These criticisms of global sea level curves and associated methods have never been countered, yet eustasy is still commonly treated as a known parameter in models and interpretations of ancient strata (e.g., Schroeder and Greenlee, 1993; Pinous et al., 2001; Armentrout, 2004; Atchley et al., 2004).

To begin to address these weaknesses and provide a practically applicable tool to deal with complex multicontrol sedimentary systems, both in outcrop and in the subsurface, we propose a multiple-control treatment of variation in accommodation, sediment supply, basin physiography, and sediment-transport efficiency, based on application of numerical stratigraphic forward modeling using an experimental and multiple-scenario approach. The aim is to consider more of the multiple parameters that control stratal architectures, as well as the uncertainty in determining the values of these parameters. This would represent a more robust and perhaps a more realistic treatment of controls on sedimentary systems, hopefully leading to better understanding and prediction of their products.

THE STRATIGRAPHIC FORWARD-MODEL FORMULATION

Dionisos is a three-dimensional numerical stratigraphic forward model developed by the Institut Français du Pétrole. It is based on a generalized, modified diffusion formulation of sediment transport, where transport rate is split into a long-term component dependent on topographic slope, diffusion coefficient, and water discharge volume and a short-term component also dependent on water velocity and inertia (Granjeon and Joseph, 1999; Granjeon et al., 2002). Long-term low-energy gravity-driven sediment flux is calculated per model cell from

$$Q_s = \kappa S$$

where Q_s is the sediment flux in square meters per year, κ is the diffusion coefficient in square meters per year, and S is the gradient of the topographic surface at a point in the model grid. Similarly, long-term, low-energy water-driven sediment flux is calculated per model cell from

$$Q_s = \kappa Q_w S$$

where Q_w is a dimensionless number representing relative water discharge that is routed across the model grid using a simple steepest descent algorithm (Granjeon and Joseph, 1999). Short-term high-energy sediment transport is modeled using

$$Q_s = \kappa Q_w m(u) S$$

where $m(u)$ is a dimensionless velocity multiplier term derived from the Meyer-Peter and Müller equation for short-term water flow (Granjeon et al., 2002). Other important processes, such as tectonic subsidence, flexural isostatic loading, mechanical sediment compaction, eustasy, and slope failure, are also represented in the process, alongside the diffusional transport (Granjeon and Joseph, 1999; Allen and Allen, 2005), allowing the construction of reasonably complex three-dimensional models.

One significant advantage of this kind of numerical stratigraphic forward model, as compared to conceptual models, is the ability to adopt an experimental approach and to deal systematically with more parameters than are considered in most sequence-stratigraphic analyses. Some of these variables are only implicit in most conceptual models, hidden behind numerous assumptions. Of course, assumptions are also required by stratigraphic forward models (e.g., Perlmutter et al., 1999; Paola, 2000). In the case of Dionisos, the most significant assumptions in most applications are in the use of diffusion to represent sediment transport, but because the diffusion relationship is derived from first principles (Granjeon and Joseph, 1999), the assumptions tend to be low level, reducing the possibility of circular reasoning in the application of the model results. However, it is still important to state that the appropriateness of the diffusion process to represent sediment transport remains an issue of debate and is definitely limited to the representation of large-scale depositional systems over geological time scales. As with all models, results should not be overinterpreted beyond these basic limits, and interpretations that are made should be checked back against the original assumptions inherent in the model to avoid circular reasoning.

THE REFERENCE MODEL RUN

To illustrate how stratigraphic forward modeling may contribute to a sequence-stratigraphic analysis, we have created a hypothetical model with an initial bathymetry consisting of a continental shelf, slope, and basin floor plus a submarine canyon (Figure 1A). Some initial relief on the basin floor is also present. Mud-grade and sand-grade sediments are introduced to the model at the central point of the western margin and distributed according to the diffusional processes described above, using the parameter values listed in Table 1. The sediment input volume in the standard reference model is 40,000 km^3 m.y.^{-1} (9596 mi^3 m.y.^{-1}). This value represents a midpoint in the range of 24 river-mouth suspended-sediment-load values given in Burgess and Hovius (1998) and, hence, is considered a reasonable, representative sediment supply value to use in an experimental modeling study. Eustatic oscillations are modeled using a 1.0-m.y.-period, 25-m (82-ft) amplitude sinusoid. Consequently, the range between eustatic lowstand and eustatic highstand is 50 m (164 ft). Flexural isostasy with an elastic thickness of 25 km (15 mi) also contributes to the relative sea level signal in the model, and mechanical compaction of buried sediment adds additional accommodation in the main depocenters.

Modeled strata have been classified according to a simple facies scheme based on sand proportion, water depth of deposition, and volume of water discharge involved in sediment transport (Table 2). Note that in this facies scheme, the distinction between deep-marine sand-prone fan and channel is based on the water-discharge volume. The use of the term ''channel'' is not intended to indicate that this stratigraphic forward model represents actual channelization processes. However, the model does distinguish between areas of

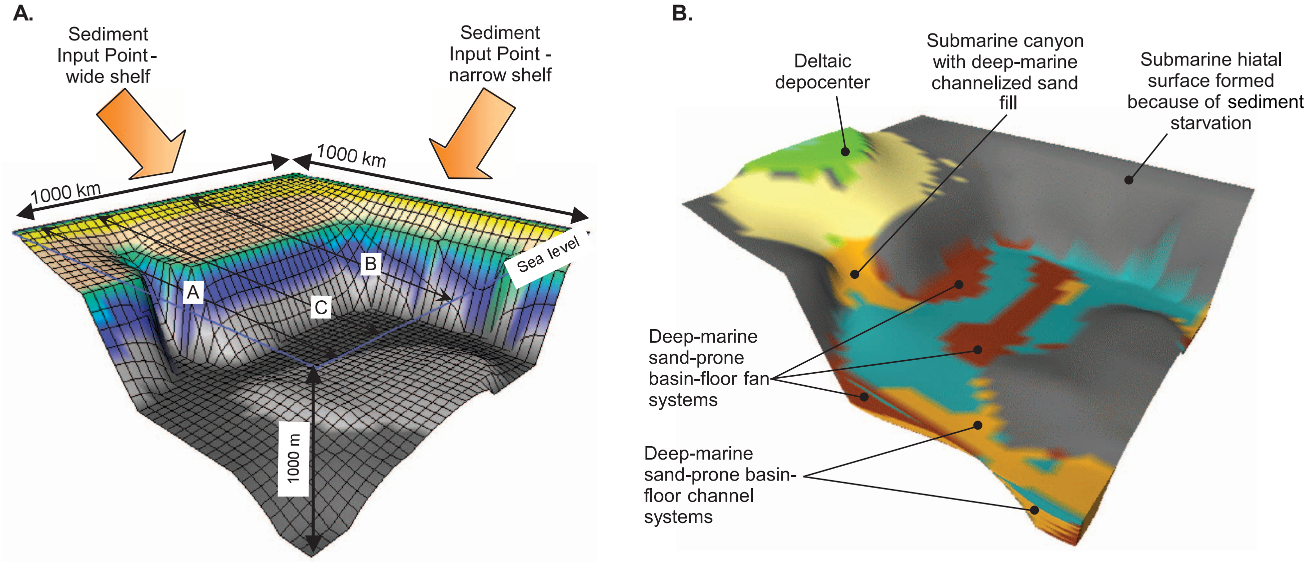


Figure 1. (A) Initial model bathymetry showing coastal plains, shelves, and slopes on two margins and a basin floor at 600–1000 m (1968–3300 ft) water depth, with some local highs and lows. Also present on the western margin is a submarine canyon cutting into the shelf. (B) Final stratal architecture produced by the standard reference model. The features to note are the delta system that has prograded across the western shelf, the submarine canyon on the western margin that is largely filled with sediment, and the complex basin-floor topography that has had an obvious impact on the distribution of deep-marine sandstones.

high-discharge transport, where channel systems might be expected to develop, and areas of lower discharge, more analogous to a dispersive deep-marine fan setting.

The initial basin bathymetry and the various tectonic and sedimentary processes represented in the model combine in the standard reference model run to generate a reasonably complex facies architecture on the shelf and in the deep-marine realm (Figure 1B). Nevertheless, because we know the entire history of the processes operating in the model, we can subdivide

Table 1. Parameters and Parameter Values Used in the Model Scenarios

Process	Parameter	Reference Value	Range
Tectonic subsidence	Uniform subsidence rate	50 m m.y.$^{-1}$	25–75 m m.y.$^{-1}$
	Tilting event	No tilting	Up to the west; up to the north
Eustasy	Period	1.0 m.y.	0.5–2.0 m.y.
	Amplitude	25 m	5–50 m
Sediment supply	Input volume	4.0×10^4 km^3 m.y.$^{-1}$	2.0–8.0 $\times 10^4$ km^3 m.y.$^{-1}$
	Sand proportion	25%	90–60% mud
	Point source	$x = 0$, $y = 400$	$x = 0$, $y = 400$ and $x = 400$, $y = 1000$
	Q_W water discharge	100%	50–200%
Sediment transport	κ, terrestrial, gravity only, sand	250 m^2 s^{-1}	125–500 m^2 s^{-1}
	κ, terrestrial, gravity only, shale	750 m^2 s^{-1}	375–1500 m^2 s^{-1}
	κ, marine, gravity only, shale	10 m^2 s^{-1}	5–20 m^2 s^{-1}
	κ, terrestrial, water and gravity, sand	250 m^2 s^{-1}	125–500 m^2 s^{-1}
	κ, terrestrial, water and gravity, shale	750 m^2 s^{-1}	375–1500 m^2 s^{-1}
	κ, marine, water and gravity, sand	1 m^2 s^{-1}	0.5–2.0 m^2 s^{-1}
	κ, marine, water and gravity, shale	10 m^2 s^{-1}	5–20 m^2 s^{-1}
	κ, continental, high-energy, sand	250 m^2 s^{-1}	125–500 m^2 s^{-1}
	κ, marine, high-energy, sand	5 m^2 s^{-1}	2.5–10 m^2 s^{-1}

Table 2. Properties Used to Define Facies in the Model

Facies Name	Water Depth (m)	Sand (%)	Water flow (% of Reference Discharge)	Thickness per Time Step (m)
Delta top	<0			
Shoreface sand	0–20	25–100		
Shelf shale	0–400	0–40		
Shelf sand	20–400	40–100		
Deep-marine fan sand	>400	25–100		
Deep-marine channel sand	>400	25–100	280–1000	
Marine hiatus	>0			0–0.01
Subaerial hiatus	<0			0–0.01

the strata into depositional sequences without the assumptions and interpretation that maybe required when dealing with ancient strata in outcrop or the subsurface. In this modeled case, unconformity surfaces, generated by subaerial exposure of deltaic and shelfal strata, can be used to subdivide the strata into depositional sequences (Figure 2). The sequence-bounding unconformities are best developed in the area of the main sediment input, where a delta system has developed (Figures 1B, 2B), although they are also present in the area of the submarine canyon (Figure 2C). They are not developed in the far south of the model, where there is no deposition on the shelf (Figure 2A).

Associated with development of the sequence-bounding unconformity surfaces are regressive-transgressive cycles of deposition, marked by basinward and landward shifts in the deltaic and shallow-marine facies belts (Figure 2). Submarine hiatuses associated with transgression and maximum flooding are also present within the area of deltaic deposition. In the line of section along the main axis of sediment transport (Figure 2B), hiatuses form on the distal shelf during transgression because of trapping of all available sediment in newly created accommodation on the proximal part of the shelf. To the south, however, in the section along the line of the submarine canyon, the situation is more complex. There, the hiatuses generated during flooding occur on the middle of the shelf, with continuous shallow-marine or deltaic deposition in both more proximal and more distal shelf positions. This more complex sediment distribution occurs because of the presence of the submarine canyon. The canyon is a topographic low and acts as a sediment sink, attracting sediment transported by gravity-driven and water-driven diffusion. Thus, in this case, transport processes and the influence of the initial topography tend to overprint the standard, simple motif of transgression and regression related to relative sea level oscillations.

Considering the deep-marine part of the modeled area, as depicted in the chronostratigraphic sections in Figure 2, what is striking is that converse to some sequence-stratigraphic models (e.g., Posamentier et al., 1988), there is no clear link between eustatic lowstands and the development of sand-prone, deep-marine facies. In the south of the model, sand-prone, deep-marine facies are deposited throughout all three eustatic cycles, although the spatial distribution does vary. For example, there is a progressive shift toward more distal deposition because of previous proximal deposition, the development of a proximal diffusional equilibrium surface (cf. Prather, 2003; Smith, 2004), and consequent sediment bypass into the more distal part of the basin. A similar temporal distribution of sand-prone, deep-marine strata throughout the eustatic cycles occurs in the section through the submarine canyon. In this location, however, there is also progressive trapping of sand in the upper parts of the canyon during later stages of the model run (after ~1.8 m.y. elapsed model time) caused simply by the reduction in topographic gradient as the canyon is filled.

Although it appears from the chronostratigraphic diagrams in Figure 2 that the distribution of deep-marine sand is not simply controlled by eustatic sea level falls, note that this may be somewhat misleading because the eustatic falls are not big enough to cause relative sea level falls in this case and also because the described stratal architectures do not give a direct indication of sand volume partitioning between shallow- and deep-marine environments. So although the chronostratigraphic diagrams indicate that deep-marine sand deposition was more or less continuous through some of the modeled relative sea level cycles, they do not

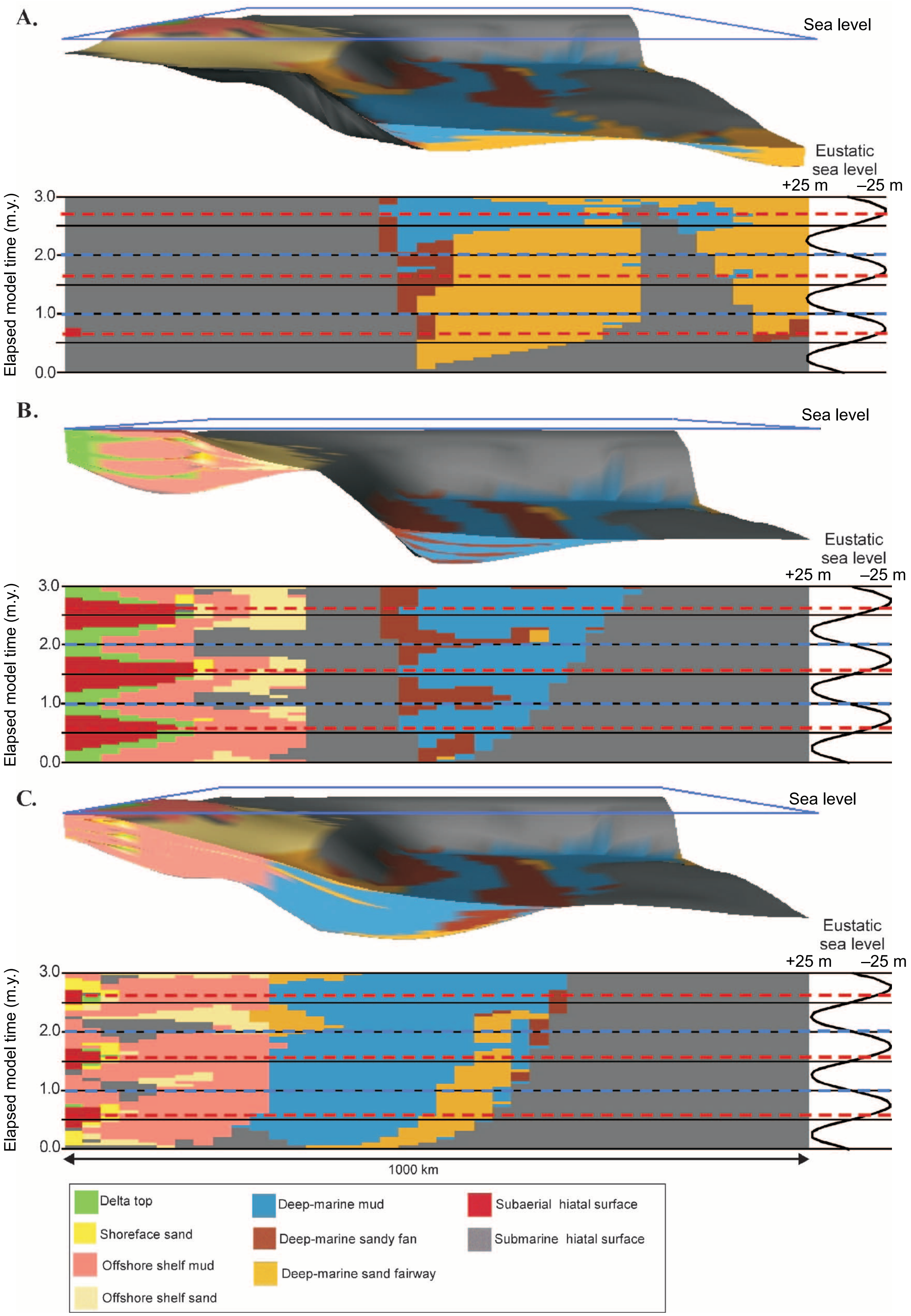


Figure 2. Cross sections and chronostratigraphic diagrams from the standard reference model. Sections are taken at (A) the southern margin of the model grid, (B) through the center of the deltaic depocenter at the point of maximum sediment input, and (C) along the length of the submarine canyon (Figure 1A). Sequence-bounding surfaces are marked on the chronostratigraphic diagrams as dashed red lines, and maximum flooding surfaces are marked as dashed blue lines.

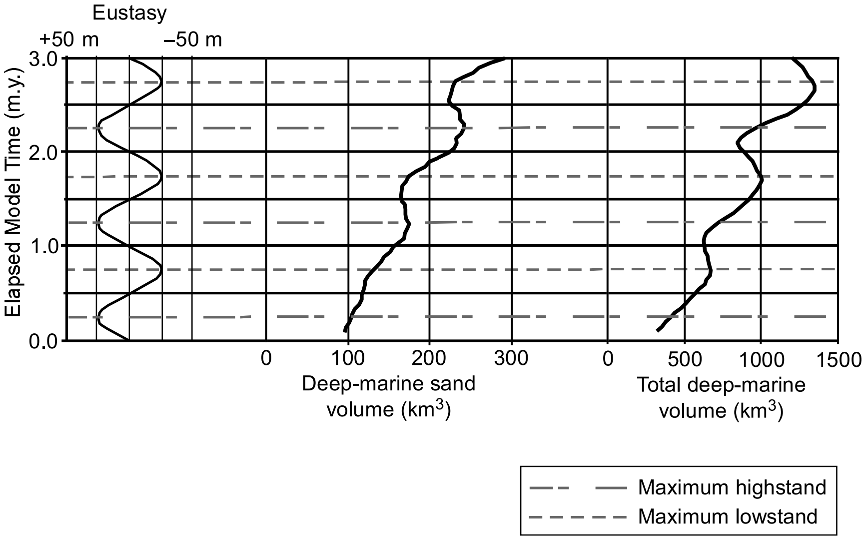


Figure 3. Deep-marine sand volume and total deep-marine sediment volume from the standard reference model, plotted against elapsed model time and alongside the eustatic curve. See text for discussion.

show directly how the volumes of sand deposition changed through time.

Variations through time in the volume of all deep-marine strata, and deep-marine sand, in the standard model run are shown in Figure 3. These plots show that total deep-marine sediment volume per model time step increases through time from about 300 to 1200 km^3 (71 to 287 mi^3). This is caused by the filling of the initial bathymetry and progressive development of a diffusional equilibrium profile that tends to increase the efficiency of sediment transfer from the shelf to the deep-marine basin over time. Superimposed on this increase are higher frequency fluctuations in volume, controlled by eustatic oscillations. Total deep-marine sediment volume per time step peaks at lowstand time and then decreases to a minimum just prior to highstand and then rises again steadily until the next lowstand. Deep-marine sand volume peaks just prior to highstand time and then decreases to a minimum just prior to lowstand, controlled by a complex interaction of shelfal accommodation, transport dynamics, and storage of sand on the shelf. Importantly, these interactions, together with the lack of actual relative sea level fall, lead to a more complex response in deep-marine sand volume than is predicted by some sequence-stratigraphic conceptual models.

In summary, the stratal architectures and volume partitioning exhibited in this standard reference model are influenced by relative sea level oscillations, but are more complex than predicted in the basic sequence-stratigraphic templates because of interactions between relative sea level and other processes such as sediment transport. This relative complexity occurs although the stratigraphic forward model, like all current similar models, represents a marked simplification of real sedimentary systems. Given this complex response to relative sea level oscillations, we can proceed to use the stratigraphic forward model to conduct a simple sensitivity analysis to determine in more detail how the modeled system responds to different amplitudes and periods of eustatic oscillation and to other controls such as sediment-transport efficiency and shelf width.

SENSITIVITY TO EUSTATIC PARAMETERS

Taking the same parameters as used in the reference model described above, but varying the amplitude and period of eustatic oscillation, allows the investigation of the possible impact of eustasy on deep-marine sand volumes. Results are compiled from forward-model runs with the parameters from the reference model described above, but with eustatic periods of 0.5 or 1.0 m.y. and amplitudes ranging from 5 to 50 m (16 to 164 ft). Figure 4 shows the proportional volume of total sand contained in deep-marine facies for these model runs, plotted against eustatic amplitude. For a 0.5-m.y. period, the proportion of sand content in the deep-marine facies changes in an approximately linear manner from 0.471 for no eustatic oscillations to 0.511 for 50-m (164-ft) amplitude oscillations. The no- and low-amplitude examples show that in this model, it is not necessary to have relative sea level falls to deposit significant volumes of deep-marine sand. In these cases, shelf bypass of sand occurs because of unforced regression; because of delta progradation, as originally

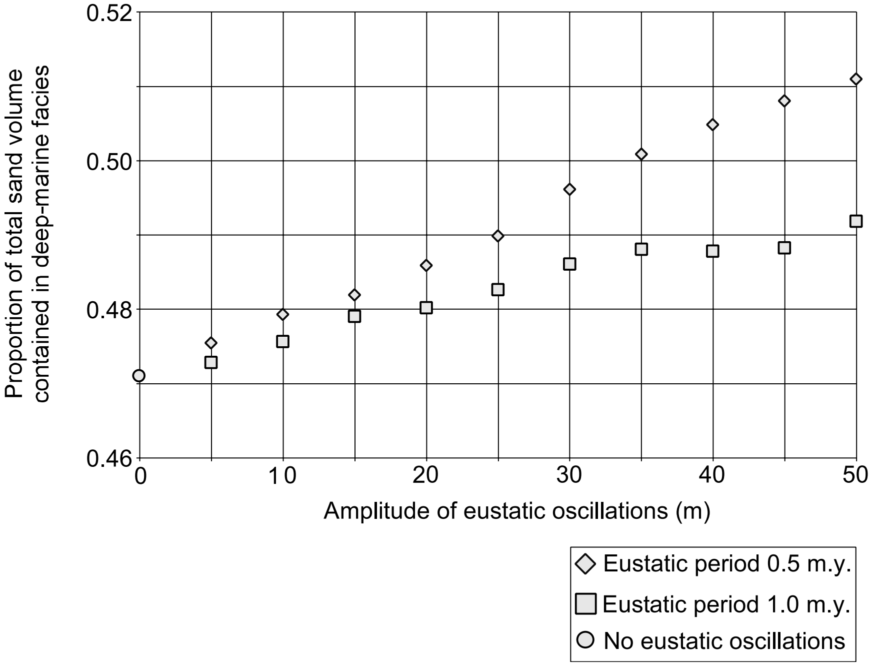


Figure 4. The proportional volume of total sand input into the model that is deposited in the deep-marine (>400-m [>1312-ft] water depth) part of the model grid, plotted against the amplitude of eustatic oscillation. Results are taken from 21 separate model runs. In all cases, sediment input is onto the wide shelf on the western margin of the model (Figure 1A). See text for discussion.

suggested by Burgess and Hovius (1998); and because of the development of equilibrium profiles that lead to the bypass of sediment through the submarine canyon into the deep-marine environment. However, the volume of deep-marine sand clearly increases with increasing amplitude, simply because of the impact of eustatic and relative sea level oscillations on the development of shelf accommodation. Note, however, that the volume increase is still less than 5% of total sediment input volume for the amplitudes tested, which is perhaps less than would be expected based on published sequence-stratigraphic models (e.g., Posamentier et al., 1988).

Results from the standard reference model described above show that modeled deep-marine sand volume changes through time, but is not controlled simply by eustatic sea level falls. This is partly caused by the fact that the eustatic falls in the standard reference model are of insufficient amplitude to cause a relative sea level fall. So what happens if we increase the amplitude of eustatic oscillation so that relative sea level falls do occur?

Figure 5 shows the total deep-marine sediment volume and deep-marine sand volume through time for two model runs with 50-m (164-ft) amplitude and 1.0- and 0.5-m.y.-period eustatic oscillations. In both cases, the model shows the same behavior as already described from the standard reference model. Total deep-marine sediment volume per model time step increases with time because of the filling of the initial bathymetry and progressive development of a diffusional equilibrium profile. Superimposed on this increase are higher frequency fluctuations in volume controlled by eustatic oscillations. Total deep-marine sediment volume per time step peaks at lowstand time and then decreases to a minimum just prior to highstand and then rises again steadily until the next lowstand. Deep-marine sand volume peaks just prior to highstand time and then decreases to a minimum just prior to lowstand. This shows that even with higher eustatic amplitude and high amplitude and frequency leading to relative sea level falls of about 30 and 55 m (98 and 180 ft), respectively, deep-marine sand volume does not respond in the manner predicted by the sequence-stratigraphic model. Clearly, shelf storage and sediment-transport dynamics are still exerting an important control in this model and tending to reduce the impact of the relative sea level falls.

SENSITIVITY TO SHELF WIDTH

What happens to modeled deep-marine sand volumes if the potential for shelf storage of sand is reduced because of a reduced shelf width? Figure 6 shows the proportion of total sand volume contained in deep-marine facies plotted against the amplitude of eustatic oscillation for model runs with sediment input only onto the narrow shelf (width ~100 km [~62 mi]) on the northern margin of the model (Figure 1A). For all

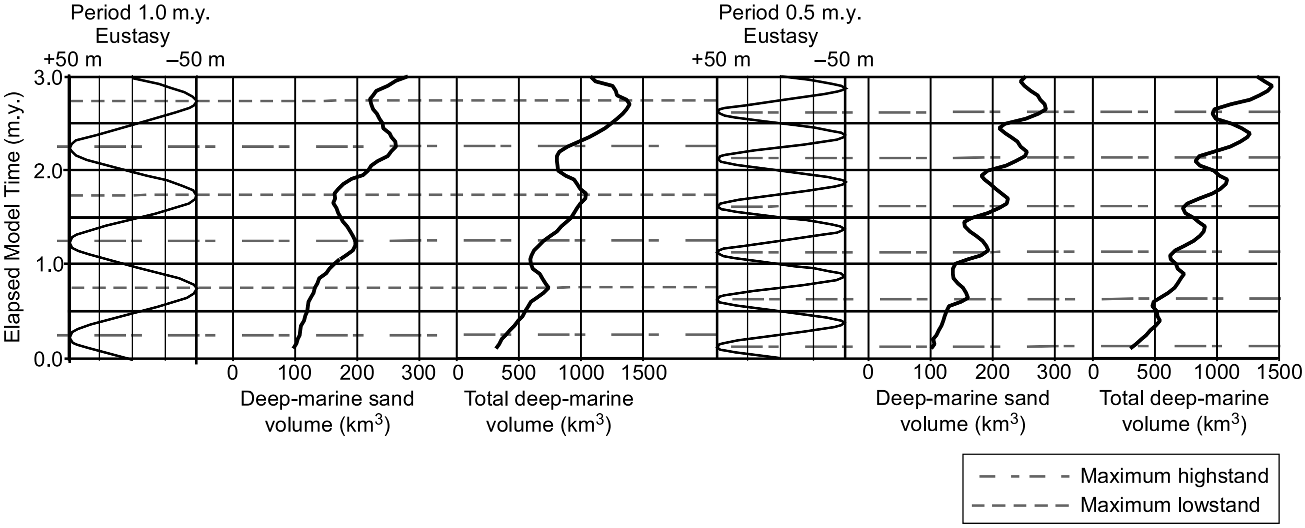
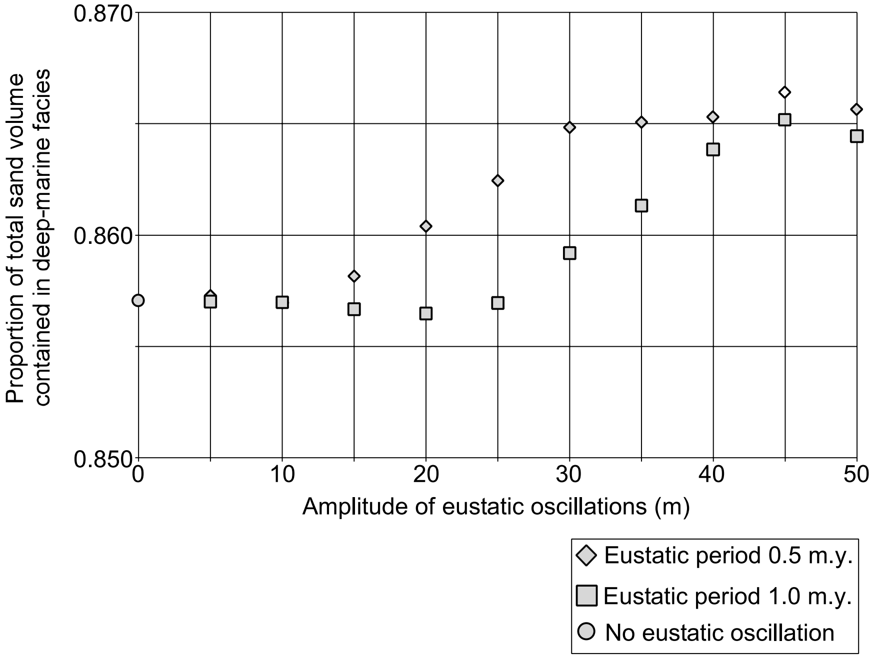


Figure 5. Deep-marine sand volume and total deep-marine sediment volume from two model runs, one with a eustatic oscillation period of 1 m.y., and the other with a eustatic oscillation period of 0.5 m.y., both with sediment input onto the wide shelf (Figure 1A). See text for discussion.

eustatic amplitudes, the deep-marine sand volume is higher than in the wide-shelf examples (~0.86 of the total sand volume, as opposed to 0.47–0.51 of the total in the case of the wide shelf). In addition, the volume increases by less than 1% as amplitude of eustatic oscillation increases from 0 to 50 m (0 to 164 ft), as opposed to an increase of 4% for the wide-shelf case. These results indicate that the modeled total deep-marine sand volume is sensitive to shelf width.

Shelf width also has an impact on the variation of deep-marine sediment and sand volume through time in the model runs. Deep-marine volumes through time for a eustatic amplitude of 50 m (164 ft) and periods of 1.0 and 0.5 m.y. are shown in Figure 7. The variation in volume through relative sea level cycles is less than for the wide-shelf case, but most notable is the synchronicity between peaks in the total deep-marine sediment volume, peaks in the deep-marine sand volume, and

Figure 6. The proportional volume of total sand input into the model that is deposited in the deep-marine (>400-m [>1312-ft] water depth) part of the model grid, plotted against the amplitude of eustatic oscillation. Results are taken from 21 separate model runs. In all cases, and in contrast with the plot in Figure 4, sediment input is onto the narrow shelf on the northern margin of the model (Figure 1A). See text for discussion.



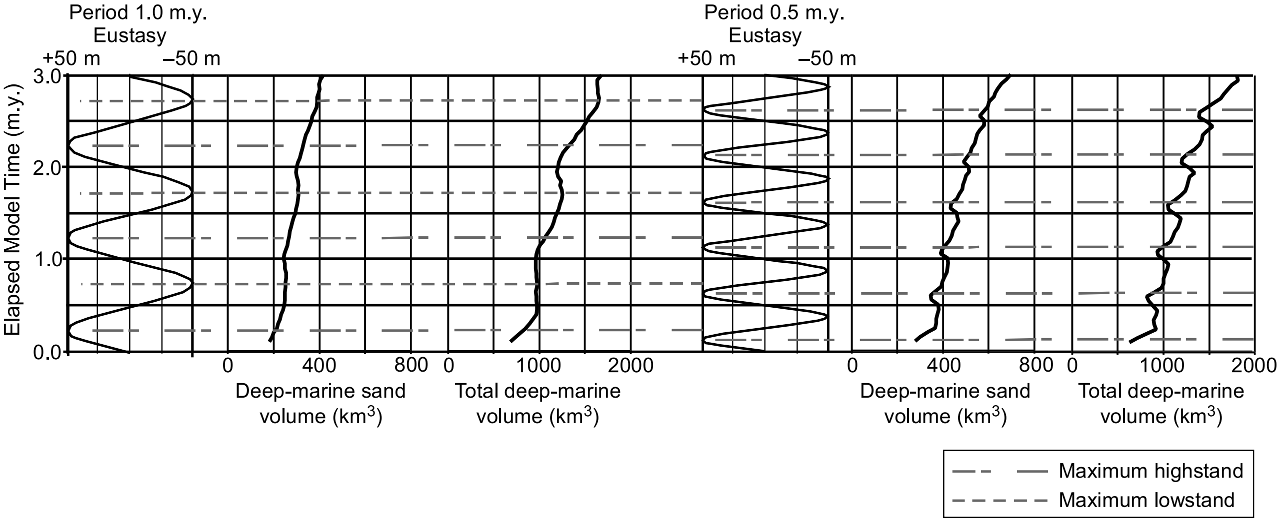


Figure 7. Deep-marine sand volume and total deep-marine sediment volume from two model runs, one with a eustatic oscillation period of 1 m.y., and the other with a eustatic oscillation period of 0.5 m.y., both with sediment input onto the narrow shelf (Figure 1A). See text for discussion.

eustatic lowstands. This result suggests that narrow shelves, with less potential for sediment storage, will show a more direct link between deep-marine sand volume and relative sea level oscillations, although the amplitude of relative sea level oscillations has less influence on the proportion of total sand supply deposited in the deep-marine environment.

SENSITIVITY TO SEDIMENT-TRANSPORT EFFICIENCY

Although Thorne and Swift (1991) included sediment-transport rate in their regime model of continental-margin sedimentation, few other sequence-stratigraphic studies explicitly consider sediment-transport rate as a parameter that can control stratal architecture on a large scale. Figure 8 shows the proportion of total sand input deposited in the deep-marine environment for eight model cases with increasing sediment-transport efficiency. The proportion of deep-marine sand increases as sediment-transport efficiency increases, reaching about 80% in the model case with a transport efficiency 10 times that used in the standard reference model. This result clearly shows that transport efficiency has the potential to be a significant control on deep-marine sand volumes. Figure 9 shows deep-marine total sediment volume and sand volume through time for a model case with the same parameters as the standard reference model, but transport coefficients an order of

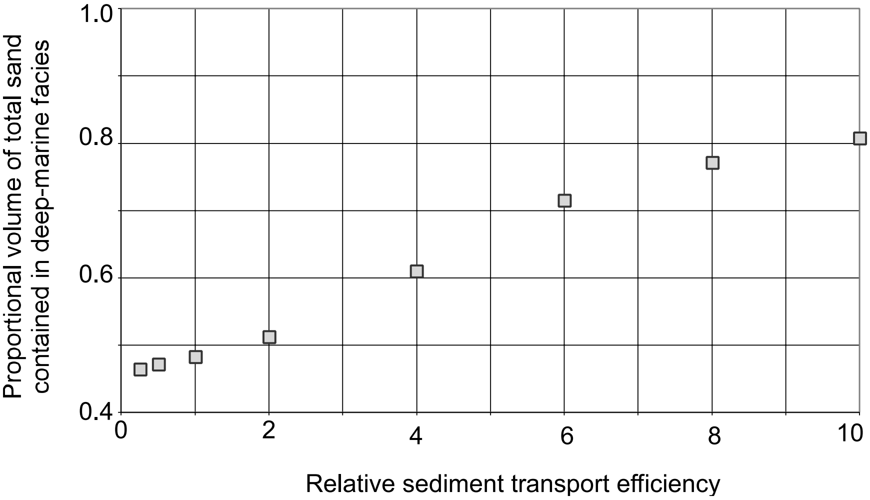


Figure 8. The proportional volume of total sand input into the model that is deposited in the deep-marine (>400-m [>1312-ft] water depth) part of the model grid, plotted against the relative efficiency of sediment transport. Results are taken from eight separate model runs which have, except for modified diffusion coefficient values, the standard model parameters, e.g., sediment input onto the wide shelf on the western margin of the model (Figure 1A). See text for discussion.

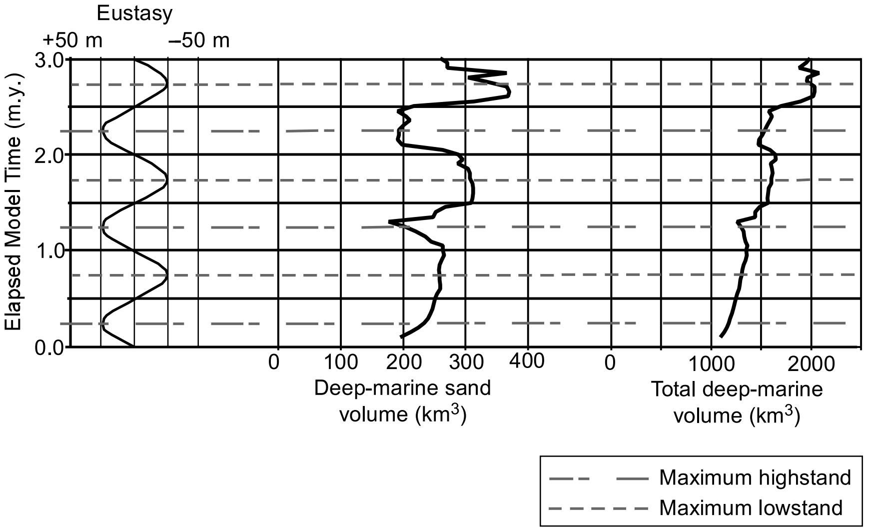


Figure 9. Deep-marine sand volume and total deep-marine sediment volume from a model run with a eustatic oscillation amplitude of 25 m (82 ft) and a period of 1 m.y., with sediment input onto the wide shelf (Figure 1A), and a sediment transport efficiency 10 times that of the standard reference model. See text for discussion.

magnitude greater. In this case, as with the narrow-shelf case, volume peaks coincide with eustatic lowstands, although in this case, the amplitude of eustatic fall was not enough to cause a relative sea level fall. This suggests that systems with high transport efficiency may be highly sensitive to accommodation variations on the shelf, even more so than suggested by current sequence-stratigraphic models.

PARAMETER UNCERTAINTY

The analysis described above applies a stratigraphic forward model to investigate the sensitivity of deep-marine sand supply to eustatic, shelf physiography and sediment-transport parameters. The analysis is unsophisticated relative to other available sensitivity analysis techniques (Saltelli et al., 2000) typically applied to basin modeling (e.g., Bagirov and Lerche, 1999; Wendebourg, 2002), but despite this, it demonstrates how sensitivity to multiple parameters may be important and also begins to illustrate the problems that might occur because of the uncertainty in values of parameters such as eustatic oscillation amplitude, shelf configuration, or sediment-transport processes. Attempts to explicitly define such parameter values are likely, in most cases, to lead to the conclusion that significant uncertainty exists. This uncertainty stems from the fact that many parameters cannot be quantified uniquely for ancient systems; only a range of possible values can be determined (e.g., Burton et al., 1987; Heller et al., 1993). Inverse methods are increasingly used with stratigraphic numerical models to address this problem by determining best-fit parameter values and, hence, reducing these uncertainty ranges. However, even the most sophisticated (e.g., Cross and Lessenger, 1999) do not overcome this basic problem of quantification and uniqueness because the inverse method still only delivers a range of probable results, and the resulting best-fit range of models commonly cannot be demonstrated to be unique because searching the whole parameter space is computationally too expensive. Furthermore, the best-fit range also depends greatly on the chosen objective function and on the type and resolution of observational data used in the process.

Multiple Scenarios

Recognizing the existence of multiple controlling parameters, the difficulty in defining appropriate parameter values, and the resulting uncertainty that arises from both these factors, how else can stratigraphic forward models be applied to deal systematically with multiple uncertain parameters? One possibility is to construct multiple model scenarios and try to capture the range of parameter uncertainty. Note that this scenario approach is by no means a new method because it is widely applied in static and dynamic reservoir modeling (Deutsch, 2002) and hydrocarbon charge modeling (Wendebourg, 2002).

However, despite the application of the technique in other areas of subsurface analysis, multiple scenarios are rarely considered in the application of the sequence-stratigraphic method. The main principle of this multiple-scenario approach is to define a reference parameter set and then to modify all parameters within realistic ranges to create a set of scenarios (sensu Deutsch, 2002), which finally leads to a set of simulations. The analysis of this set allows the estimation of the sensitivity of the reference simulation to each parameter (Wendebourg, 2002). Such an analysis can also lead to the understanding of how uncertainty in the parameter values leads to the uncertainty in the predictions of lithologies and stratal architectures.

As an example to illustrate the method, we have run 20 scenarios, each of which has the standard reference model parameters (Table 1) apart from one parameter that has been set to one of the end-member values also given in Table 1. Parameters that have been varied cover all the main controls: tectonic subsidence and uplift, eustasy, sediment supply, and sediment-transport efficiency. The tectonic subsidence and uplift scenarios include spatially uniform subsidence at various rates as well as an up-to-the-north tilting event. Sediment supply scenarios cover total input volume, proportion of sand in the input volume, position of the input point source, and the volume of the input water volume. For each of the 19 scenarios run, the total volume of deep-marine sand is plotted in Figure 10. The relative impact of the various controls on deep-marine sand volume is evident. This plot also indicates the volumetric uncertainty that may result in a situation where any of these different processes could have operated, with parameter values falling within the given range.

MULTIPLE SCENARIOS AND CONDITIONAL FREQUENCY MAPS

Combining output from multiple scenarios has an obvious benefit over a single model run because it immediately elucidates some of the variability likely to arise from the range of possible processes and parameter values. We have developed a new method to achieve this using conditional frequency maps. The first step in generating a conditional frequency map is to take several modeled scenarios with some common spatial coordinates and define selection criteria that can be applied to the modeled strata. As an example, we have defined a simple reservoir presence criteria, namely, a total stacked (i.e., vertically continuous) thickness greater than 20 m (66 ft) of strata with a net-to-gross value greater than 25%. These criteria are then applied to each point on the model grid for each modeled scenario, and the number of scenarios that meet these criteria is counted. Plotting this count as a color-coded proportion of the total number of scenarios creates a conditional frequency map (Figure 11).

With the particular criteria listed above, the conditional frequency map in Figure 11 can be considered as a reservoir presence probability map because it indicates, within the limiting context of the model formulation

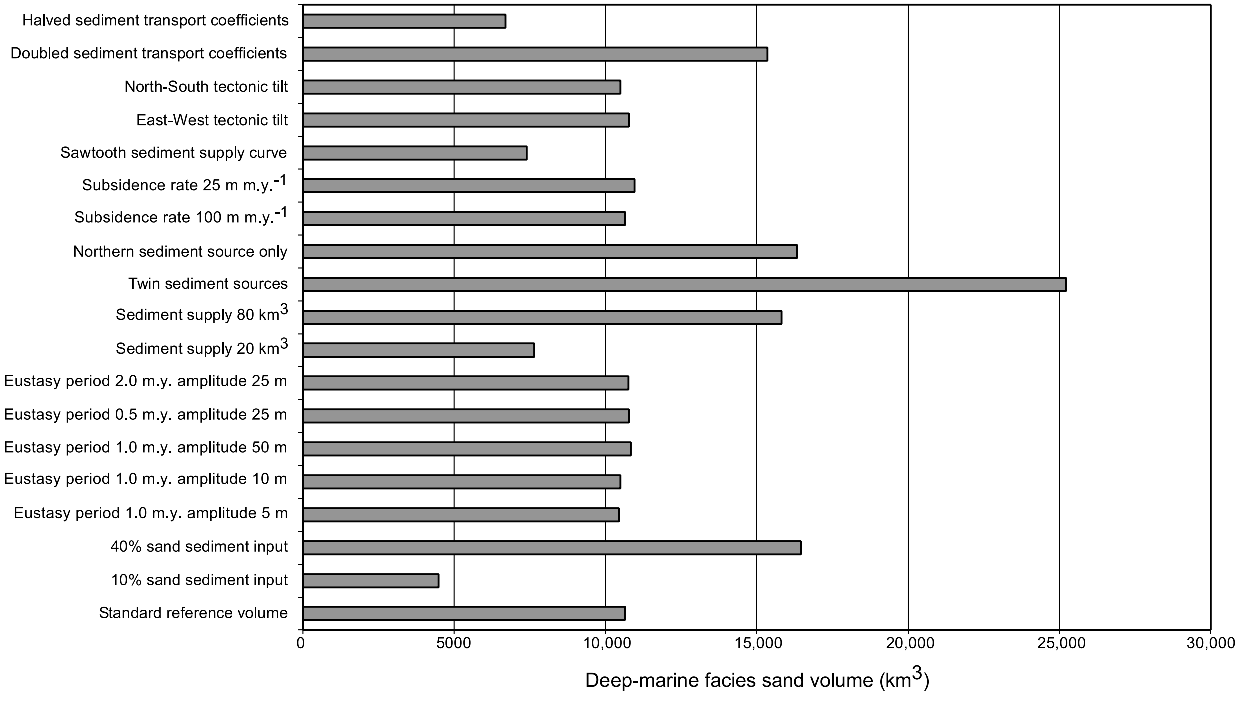


Figure 10. Deep-marine sand volume from 19 model scenarios with model parameters varying as described in Table 1. The plot indicates the degree of variability arising from the various scenarios. See text for discussion.

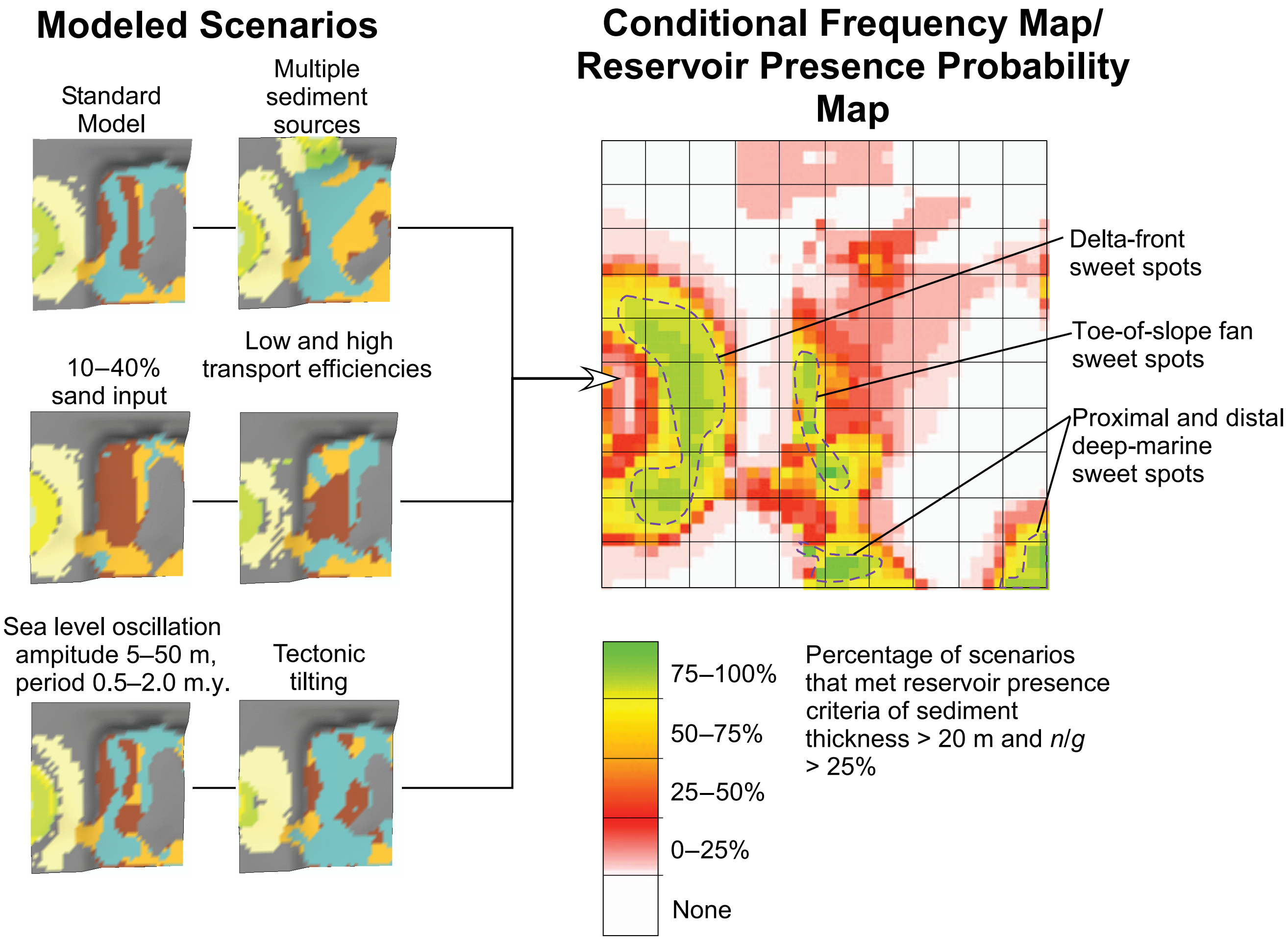


Figure 11. On the left are examples of the multiple model scenarios shown in map view illustrating the variations in distribution of deep-marine sandstones that result from varying the model parameters as in Table 1. The 19 scenarios are then combined to form a conditional frequency map based on a total continuous, vertically connected sediment thickness greater than 20 m (66 ft), with a net-to-gross greater than 25%. With these criteria, the conditional frequency map is effectively a reservoir presence probability map. Areas are delineated on the map where, within the context of the forward model, sand deposition shows low sensitivity to the range of parameter values used in the scenarios, and the reservoir criteria are met. These areas therefore have a high probability of reservoir presence.

and the model scenarios executed, the probability of an appropriate reservoir lithology occurring in each grid square. Looking at the conditional frequency map in Figure 11, four spatially distinct areas with a more than 50% reservoir presence probability occur on the delta front, in a toe-of-slope deep-marine fan, and in more proximal and more distal basin-floor settings (cf. Figure 1). These all represent areas where more than half of the modeled scenarios produced what could be considered good reservoir potential. There are also some places in the delta front and in the proximal and distal deep-marine areas, all color coded in green, where more than 75% of the modeled scenarios produced good reservoir. These areas represent places where the presence of good reservoir is relatively insensitive to the range of modeled scenarios. In cases where real subsurface scenarios had been modeled, these may represent reservoir sweet-spot areas where explorers could be reasonably confident of reservoir presence, despite uncertainty in the values of subsidence, eustatic, sediment supply, and sediment-transport parameters, although obviously limited by the assumptions and formulation of the stratigraphic forward model.

The same conditional frequency map approach can be applied with different reservoir presence criteria. Figure 12 shows two different conditional frequency maps that produced net-to-gross cutoff values of 25 and 40%. In the case of 25% net-to-gross, several areas on the map show a high probability of reservoir presence, but in the 40% net-to-gross case, reservoir presence

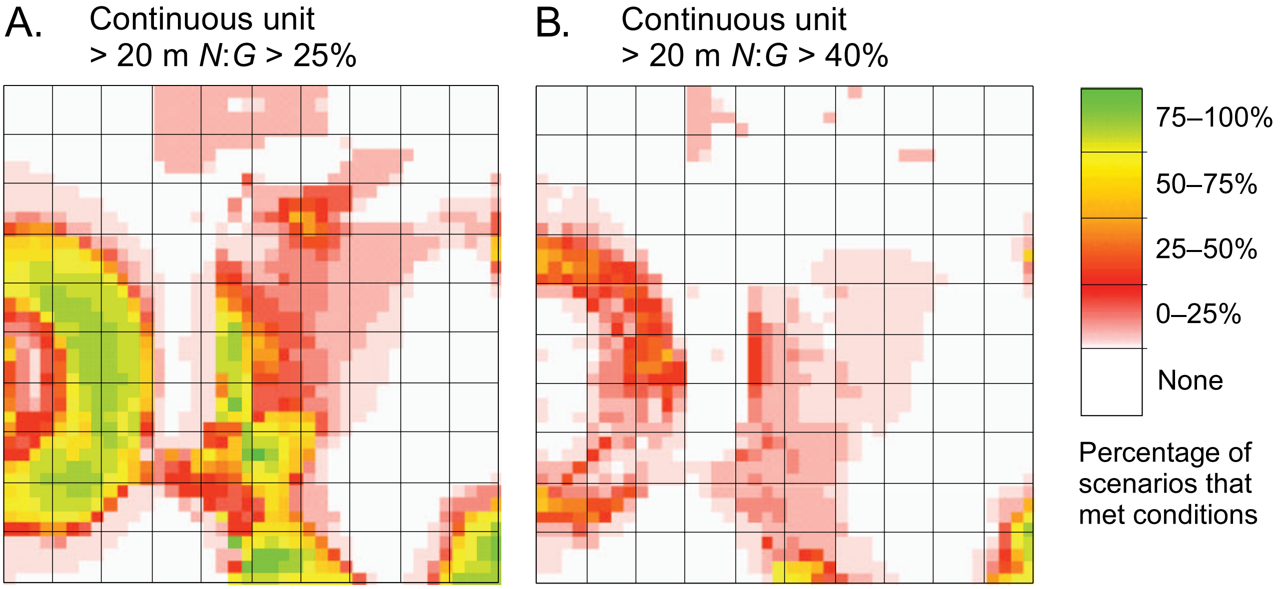


Figure 12. Conditional frequency maps generated for continuous 20-m (66-ft)-thick strata with 25 and 40% net-to-gross, respectively. The two maps illustrate the importance of the criteria selected to calculate conditional frequency. See text for discussion.

criteria were met in only two small areas on the southern margin and southeast corner of the grid. This is only a hypothetical example, but it illustrates how the approach could be used to determine the reservoir presence probability in a data-sparse area where significant uncertainty existed regarding the processes likely to have operated. Reservoir presence probability maps of this type can be usefully incorporated into play summary maps of the type described by White (1988). Such an approach is limited by the realism and applicability of the forward model, but may still represent a significant advance over the application of more traditional sequence-stratigraphic methods.

A similar conditional frequency map approach can be used to determine the sensitivity of the spatial distribution of strata to some of the eustatic and basin physiography factors discussed above. Figure 13 shows conditional frequency maps calculated using the criteria of greater than 20-m (66-ft) continuous 25% net-to-gross strata applied to both wide-shelf and narrow-shelf cases for the standard reference model, with eustatic amplitudes of 5–50 m (16–164 ft) and 0.5- and 1.0-m.y. eustatic periods. Three maps are shown for each shelf configuration, applying the counting criteria to strata deposited throughout the sea level cycles, lowstand strata only, and highstand strata only. Comparing the wide- and narrow-shelf allstand examples, it is clear that a greater number of grid points meet the applied criteria in the narrow-shelf model, showing that the spatial distribution of the deep-marine sand in the model is sensitive to shelf width. Considering the eustatic lowstand strata examples, a similar number of grid points meet the applied criteria for both wide- and narrow-shelf examples, suggesting less sensitivity to shelf width. For the highstand example, there are no points in the deep-marine part of the wide-shelf model grid that meet the criteria. Conversely, in the highstand narrow-shelf example, almost as many points meet the criteria as in the lowstand case, which tends to confirm the results described above showing that a narrow shelf reduces the sediment partitioning impact of relative sea level changes. However, note that the criteria of 20 m (66 ft) continuous 25% net-to-gross strata are a limiting factor; if sedimentation rate is reduced during highstand but sand proportion is high, deep-marine grid points may fail to meet the criteria simply because sediment thickness is too low, generating a misleading impression of overall low sand input.

LIMITATIONS OF THE CONDITIONAL FREQUENCY MAP METHOD

If this method is to help progress beyond the current sequence-stratigraphic methods, it must be applied with caution, bearing in mind several caveats. Most significant of these is the observation that the results

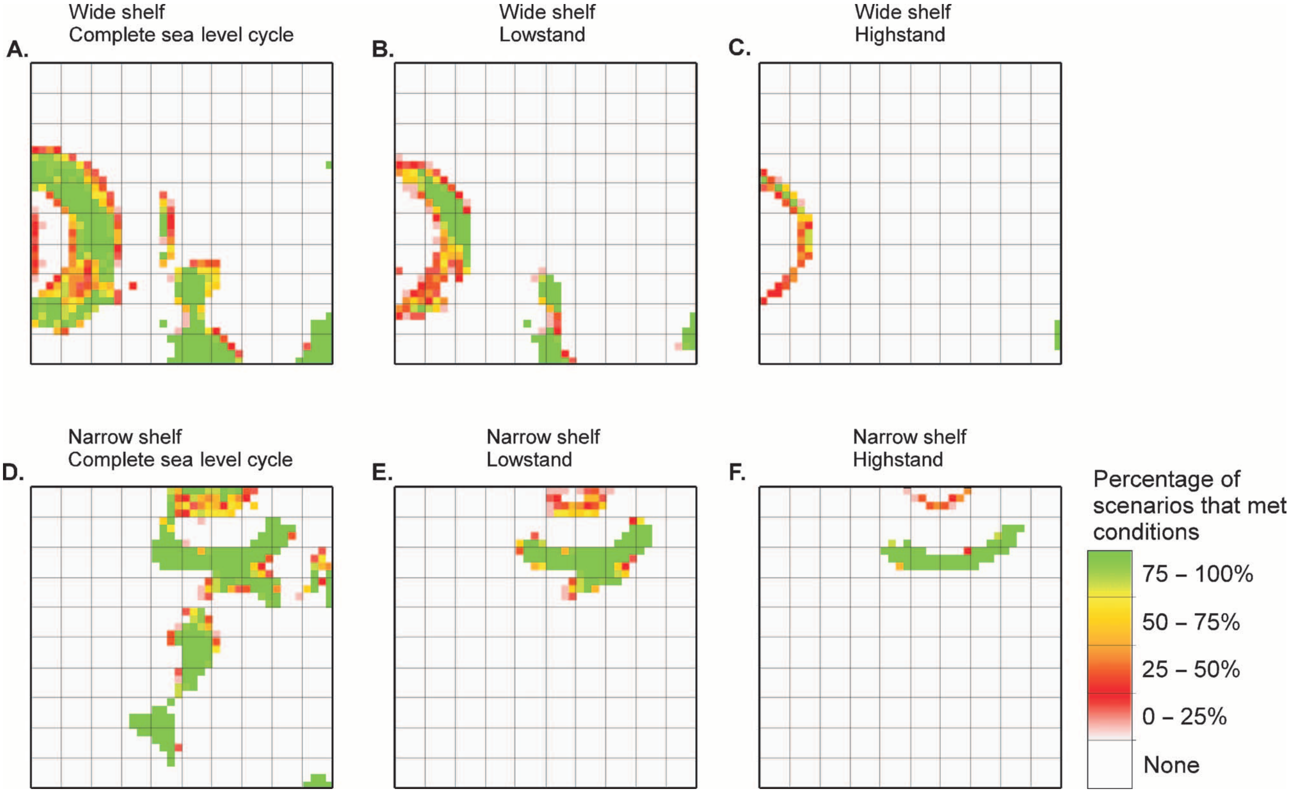


Figure 13. Conditional frequency maps from two sets of model runs, the first (A–C) with sediment input onto the wide, western shelf (Figure 1A), and the second (D–F) with sediment input onto the narrow, northern shelf (Figure 1A). For both sediment input configurations, 21 models were run with a range of eustatic amplitudes from 0 to 50 m (0 to 164 ft) and periods of 1 and 0.5 m.y. The conditional frequency maps from these model runs use criteria of more than 20-m (66-ft) continuous thickness of more than 25% net-to-gross strata, applied to the whole modeled interval (0–3 m.y. elapsed model time) (A, D), to strata deposited during lowstand times only (B, E), and to strata deposited during highstand times only (C, F). See text for discussion.

of individual model runs and, therefore, the conditional frequency maps produced are highly dependent on the realism and appropriateness of the stratigraphic forward model used. In other words, if processes such as sediment transport are not represented with sufficient realism in the forward model, the results will be of little use, whatever form they are presented in. The realism of these representations is a function of the formulation used in the modeling, the reliability of estimates for the physical constants and variables used, and the robustness and accuracy of the numerical schemes used to solve the equations. It is also important to determine if all the relevant parameters have been considered, if the range of possible values for those parameters has been adequately captured, and if the possibility of interdependence between the parameters has been adequately considered. The assumption of equal probability of the scenarios also requires consideration. Clearly, the quality of the conditional frequency map depends on this, but alternative probability models could easily be incorporated; e.g., scenarios considered more probable could be given some additional weighting.

Methods other than end-member sampling of the parameter range might also prove to be preferable, and the use of experimental design methods and consideration of parameter interactions will certainly be critical, but the purpose here is only to illustrate the potential of this method using a simple example. Map quality will also depend on the selection of criteria or conditions. In the example shown, is it really appropriate to think about reservoir presence in terms of the criteria given? This is dependent on the purpose for which the maps will be used; for example, in situations where higher reservoir volumes are required, the thickness cutoff value could be increased. Similarly, the case of highstand deep-marine sand deposition described above may be misleading because the thickness cutoff criteria mean that thinner high net-to-gross strata are not counted. Finally, in most cases where this kind of approach is applied to real systems, some kind of acceptance criteria or conditioning for the various scenarios will be necessary; it would not make sense to include in the conditional frequency map model scenarios in which modeled strata did not match observed strata at available data points.

Many of these issues apply to sequence stratigraphy and stratigraphic forward modeling generally. All of them are significant in applying the technique, but all may be ultimately resolvable. We believe that this conditional frequency map approach represents a significant advance over existing sequence-stratigraphic qualitative, conceptual predictions, combining a more rigorous, systematic treatment of model parameters with an easily applied visual result.

SIGNIFICANCE OF THESE RESULTS TO SEQUENCE STRATIGRAPHY

Based on the results presented above, we suggest that consideration of a wider range of controls on sedimentary systems is important if we are to correctly interpret and predict ancient outcrop and subsurface strata. Outcrop and subsurface studies should consider variations in sediment supply, sediment-transport efficiency, and basin physiography, as well as changes in accommodation. Restricting interpretation to a single dominant control by accommodation may appear more straightforward, but it most likely underestimates the complexity of sedimentary systems and, therefore, seems unlikely to provide sufficient predictive power to significantly reduce uncertainty. Experimental and multiple-scenario applications of stratigraphic forward models offer a practical method to begin to address this issue. Specifically, the examination of model sensitivity to different parameters has the potential to increase the understanding of how sedimentary systems may operate and provide multiple hypotheses testable with data from modern systems and ancient outcrop and subsurface strata. Construction of conditional frequency maps from multiple-scenario forward-model runs has the potential to encompass multiple controlling processes and parameter uncertainty in one simple map form, addressing model sensitivity and outcome uncertainty in a straightforward, practical, and rapidly applicable way.

Some of the results described above directly contradict assumptions and predictions made by conceptual sequence-stratigraphic models because this stratigraphic forward model does not emphasize accommodation as the main control on stratal architectures. However, this model and other similar stratigraphic forward models also contain elements based on poorly constrained assumptions (e.g., diffusional representations of sediment transport). So are the predictions of sedimentary system behavior presented here on the basis of stratigraphic forward-modeling results more reliable than assumptions and predictions made by other conceptual sequence-stratigraphic models? We do not believe it is yet possible to answer this question, given current levels of knowledge of sedimentary systems, modern or ancient. It is possible, however, to treat the results presented here as testable hypotheses, competing with the mostly still-untested hypotheses presented by more conventional sequence-stratigraphic models. The obvious way to proceed is to test both sets of hypotheses via a combination of observations of modern and Pleistocene sedimentary systems, where, unlike in most ancient examples, it is possible to begin to directly identify the influence of extrinsic and intrinsic controls (e.g., Anderson et al., 1996; Blum et al., 2001). Experimental application of other analog models (e.g., Van Heijst and Postma, 2001; Sheets et al., 2002) and numerical stratigraphic forward models (e.g., Martinez and Harbaugh, 1993; Syvitski et al., 1999; Meijer, 2002) based on different founding assumptions must also be an important factor in this testing process. Whatever the outcome, if unequivocal data and knowledge replace questionable interpretations and assumptions (e.g., Thorne, 1992), clearly, it will be an important advance for understanding and predicting sedimentary systems in the subsurface.

CONCLUSIONS

Based on the results presented, the following conclusions can be drawn:

1. Despite the acknowledgement of the problem, and despite some important, more realistic alternative models, many sequence-stratigraphic conceptual models consider too few controlling parameters and do not deal adequately with uncertainty in values of those parameters. A consequence of this is that in many cases, sequence-stratigraphic models may have less predictive power than commonly assumed.
2. Analysis of the sensitivity of modeled deep-marine sand volumes to relative sea level change, shelf width, and sediment-transport efficiency, although limited by the formulation and assumptions inherent in the

forward model, suggests that all three controls are important. All these controlling factors should be included in interpretations and predictions of outcrop and subsurface deep-marine strata; limiting explanatory interpretations to relative sea level control alone is not tenable.

3. Adopting a multiple-scenario approach to sequence stratigraphy using stratigraphic forward models is a practical step toward overcoming some of the limitations of one-variable sequence-stratigraphic models. We propose using numerical stratigraphic forward models to consider more controlling parameters, including their temporal and spatial variations, and making multiple scenarios that can be combined to make conditional frequency maps. This approach has useful applications to the evaluation of subsurface uncertainty and sedimentary system behavior generally.
4. Because of the underlying assumptions in both cases, further explicit testing of these numerical model predictions, and the predictions made by sequence-stratigraphic models generally, is required. This will perhaps be best achieved by a combination of the study of modern and Pleistocene systems and experimental work with analog and numerical forward models of sedimentary systems.

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