Simulating event deposition: effects of storms on the shallow marine stratigraphic record

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Summary

A 2-D process-response model (BARSIM) is presented that combines short-term event bed formation with long-term coastal evolution. It generates storm and fair-weather beds based on wave-base variation due to storm variability. Deposition patterns during both storm and fair-weather conditions show clear differences. These differences can be related to the stratigraphic record as functions of bed-thickness and grain-size variability.

Introduction

Both modern and ancient shelf strata show distinct rhythmic sequences that can be attributed to event deposition. Grain size and thickness of individual beds in a vertical sequence varies considerably. Small-scale stratal variability can be attributed to event magnitude while large-scale variability (e.g. coarsening upward cycles) can be linked to long-scale coastal evolution due to eustatic sea-level changes. Research on bed and event deposition indicates that sedimentation rate and completeness of the stratigraphic record in general is highly variable in time and space (e.g. Gretener, 1967; Kumar and Sanders, 1976; Sadler, 1981; Dott, 1983; Crowley, 1984; Schwarzacher, 2000). Sedimentation is not continuous and beds represent only small fractions of the total time it took to form a stratigraphic column. For shallow marine systems, the variables controlling event bed formation are time sequence of events and the time-average value of fluid power expended by waves and bottom currents, grain size of the available sediment and sedimentation rate (Niedoroda et al. 1989). Preservation of individual event beds will vary along the shoreface as a function of wave erosion and biogenous mixing rate (Wheatcroft, 1990).

Event strata may hold information that can lead to a better understanding of sedimentary systems during deposition. The processes that form individual beds at short time intervals are also responsible for the ability of the sedimentary system to respond to external forces such as sea-level change and sediment supply over geologic time intervals. Bed variability reflects storm frequency and magnitude but may also tell us more about the position at the shelf during the time of deposition. Many workers have successfully modelled bed formation on the marine shelf (Niedoroda et al., 1989; Zhang et al., 1997; Zhang et al., 1999; Wheatcroft, 1990), but none of these models was extrapolated for longer times scales in order to simulate complete cycles of deposition driven by eustacy. A two-dimensional process-response model (BARSIM; Storms et al. in press) has been adapted to simulate storm deposition over geologic times scales. The revised model presented here is semi-deterministic, a stochastic component is added to BARSIM to describe storm climate. The new model discriminates between storm and fair-weather conditions for both hydrodynamic conditions and duration. It provides the opportunity to evaluate event strata by means of grain-size variability, deposition patterns for both fair-weather and storm conditions, reworking and preservation potential of beds, and facies associations based on bed configurations.

Storm deposition

Figure 1. Photograph of shoreface event strata in the Kenilworth Member, Blackhawk Formation exposed in the Book Cliffs, Utah, USA. The section shows a coarsening upward cycle (see arrow). Individual beds can be thicken upward. The vertical section near the arrow is about 15 m high.

Local hydraulic regimes drive processes that transport sediment in different directions along the shallow marine environments. These regimes can be described on many temporal scales ranging from the passage of a single wave to a changing storm climate. At short time intervals, sediment dispersal due to wave-generated oscillatory currents results in typical sedimentary structures that are related to water depth (Madsen, 1991; Myrow and Southard, 1996). A series of waves approaching the coast during high-energy conditions will generate in addition to oscillatory currents, both coast perpendicular downwelling currents (e.g. Field and Roy, 1984; Cacchione et al., 1984) and coast parallel geostrophic currents (Snedden et al., 1988). The combined currents generate a high rate of sediment dispersal and different types of depositional patterns (Kumar and Sanders, 1976; Lavelle et al., 1978; Lee et al., 1998; Swift et al, 1991, Drake, 1999; Niedoroda et al., 1984). The offshore-directed currents are responsible for the formation of continuous event beds. Currents at the upper shoreface during storm conditions are destructive (Hobday and Reading, 1972; Reineck and Singh, 1972; Kreisa, 1981). As a result, the upper shoreface becomes the source environment of a dispersal system from which sediment is transported offshore (Swift et al., 1991).

Event beds are sharp based and have a burrowed or diffuse upper contact (Kreisa, 1981). The base consists of a coarse-grained lag deposit that formed during the storm climax. As the storm passes, current velocity decreases and successively finer grains are deposited which results in a fining upward succession. The upper parts of storm beds are usually bioturbated or eroded during later events. Storm beds may be interbedded with finer-grained beds that formed under less energetic fair-weather conditions (Aigner, 1985). Lithologic variability induced by alternating storm and fair-weather conditions is typical for shallow marine strata (Aigner, 1985; Kreisa, 1981; Bhattacharyya et al., 1980). Event strata is highly irregular, but often reveals a general coarsening, fining, thickening or thinning upward trend (Figure 1). Bed forming mechanisms active at the shoreface are responsible for both long-term responses to external forcings as sea-level change and sediment supply, as well as for the formation of individual depositional beds and their (partial) reworking.

Model approach

Storm beds are essentially the building blocks of the shallow marine stratigraphic record, and yet no attempts have been made to include storm deposition in basin fill models. Since nature is far too complex to include all its intricacies in numerical models, the priority of basin fill modelers has been focused on processes that are important over timescales of centuries to millennia. As a result, a wide range of sedimentary models were developed using

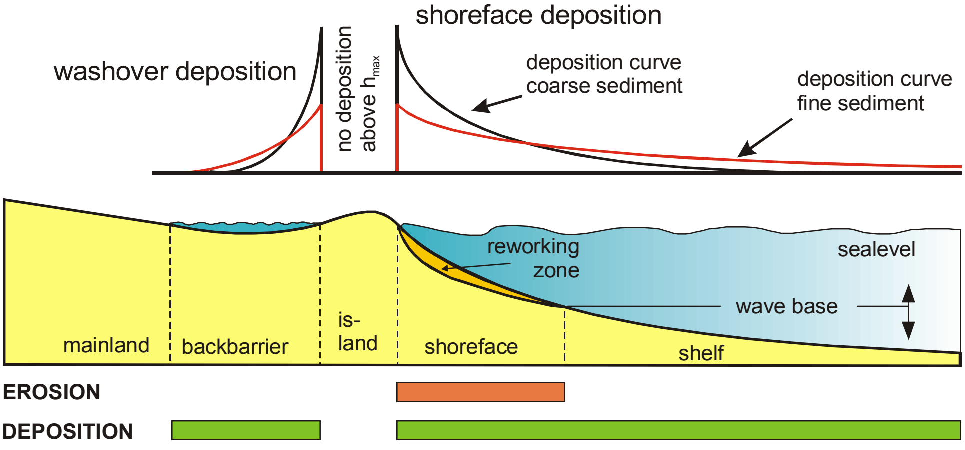


Figure 2. Schematic cross section of a wave-dominated coastal system used in B*ARSIM. See text for explanation.*

a variety of approaches (e.g. Cowell et al., 1999; Niedoroda et al., 1995; Steckler, 1999; Carey et al., 1999; Syvitski and Hutton, 2001). Many of these models tackle comparable problems using different methods, on a variable spatial and temporal scale. Despite their diversity, all of these models assume continuity in simulated processes.

BARSIM is a two-dimensional process-response model that simulates coastal response to external forcings on a geological timescale. It produces a stratigraphic record that reveals both erosional and non-depositional surfaces and detailed information on grain-size distribution (Storms et al., in press). Figure 2 shows a schematic cross section that explains the model's basic approach. Erosion is defined to occur between the wave base and the coastline and varies with both water depth and erodibility of the substrate sediment. Deposition of eroded sediment, including possible extra sediment added to the system by littoral drift, can occur both in the backbarrier and at the shoreface/shelf. Deposition in the backbarrier only occurs if accomodation is available. Deposition rate for individual grain-size classes depends on defined sediment characteristic deposition curves (see upper part of figure 2). For a more detailed description of the original BARSIM model I refer to Storms et al. (in press).

BARSIM has been adapted to simulate individual events using a variable wave-base position and timestep. Algorithms for sediment dispersal remain unchanged. A relation between effective wave height and wave-base depth is established using an approach similar to Hallermeier (1981). Large storms occur less often than small storms but their impact on the

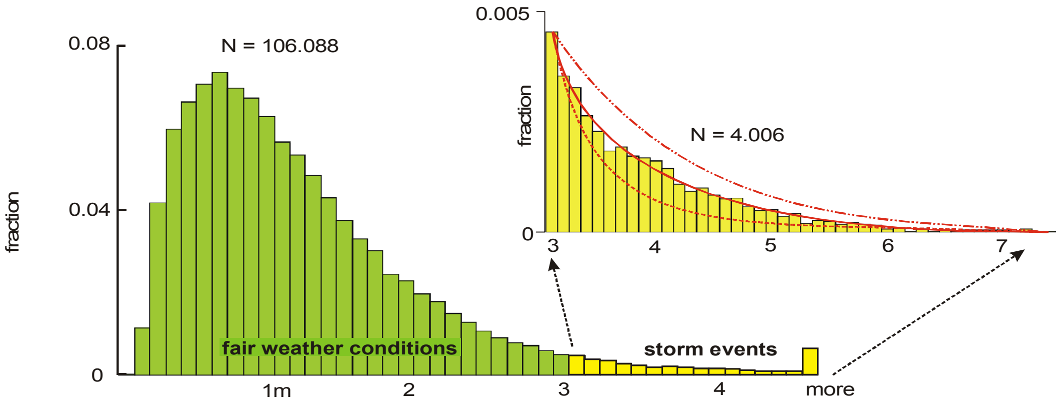


Figure 3. Wave height distribution near Schiermonnikoog, the Netherlands, between 1979 and 1999. In this case, waves higher than 3 m are considered storm waves (yellow) and are described using an exponential function.

coastal depositional environment is larger. Storm conditions typically last a few days while intermediary fair-weather periods can last for months or years. Figure 3 shows the wave-height distribution at a buoy near Schiermonnikoog, the Netherlands, over a twenty-year period. It shows the complete spectrum of waves so both fair-weather and storm waves are included in this distribution. The distinction between fair-weather and storm waves is arbitrary and cannot be determined from figure 3. The right-hand side of the Schiermonnikoog distribution can be described by an exponential function. The shape and intersection (between fair-weather and storms conditions) of this exponential function can be varied to fit different coastal settings (figure 3). Similarly, the duration of fair-weather periods in the model is also described by an exponential curve, where long periods of fair weather are more rare than short periods. The minimum duration for fair weather is arbitrary. To avoid excessive calculation times, the fair-weather period is chosen to be in the order of years to decades. A long fair-weather period will contain more small events (minor and seasonal storms) than a short fair-weather period. These minor and seasonal storms generate waves that are too small to be considered as rare events in the model. A simulated fair-weather bed in reality will contain remnants of minor storm events. The effective wave height chosen to represent fair-weather waves will be higher for a distribution with long fair-weather periods. By combining both exponential distributions, a time series of effective wave height and fair-weather duration can be sampled that is used as input data for BARSIM (figure 4). Time-serie characteristics can be changed by varying the exponential functions for both distributions prior to or during a simulation.

During a storm, sediment is transported to deep water resulting from wave generated currents. The offshore directed components of both downwelling and geostrophic currents increase the capacity to disperse sediment further offshore than during fair-weather conditions. Consequently, the sediment travel distances for all sediment grain-size classes should be increased accordingly.

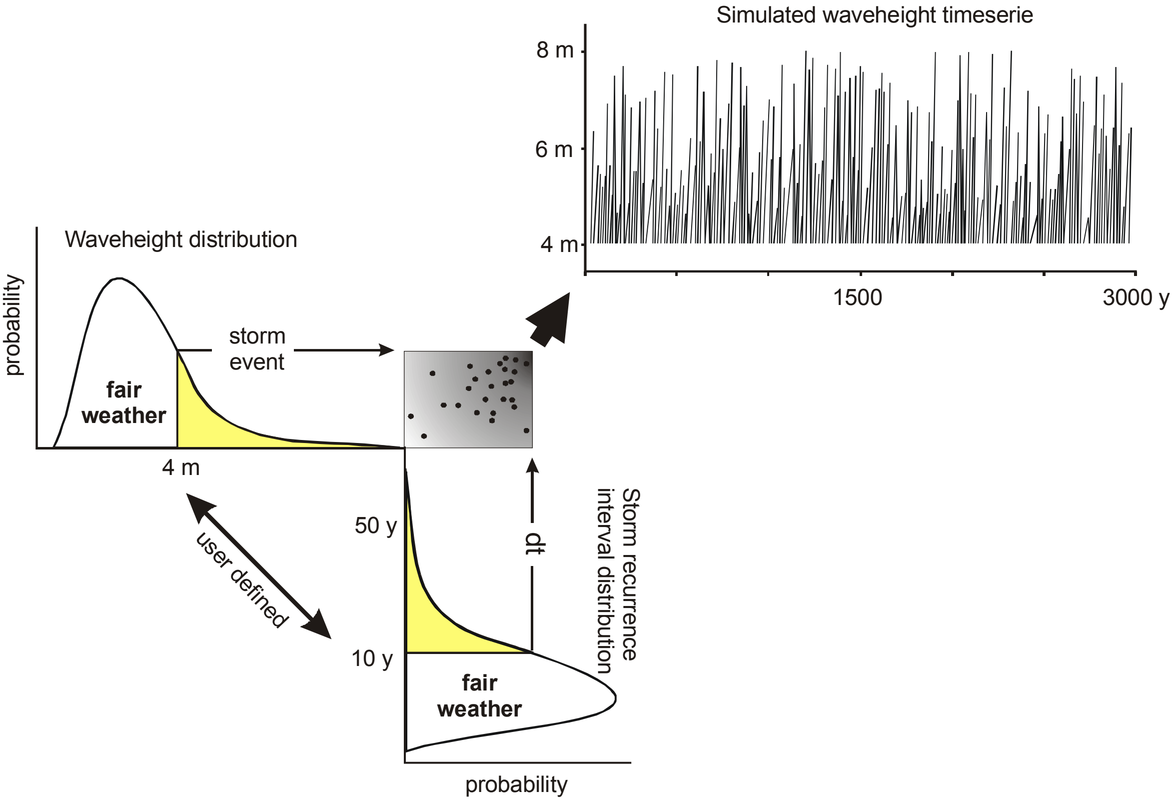


Figure 4. Storm wave height and return period are drawn from two exponential functions. A time series (upper right) is created that serves as input for BARSIM.

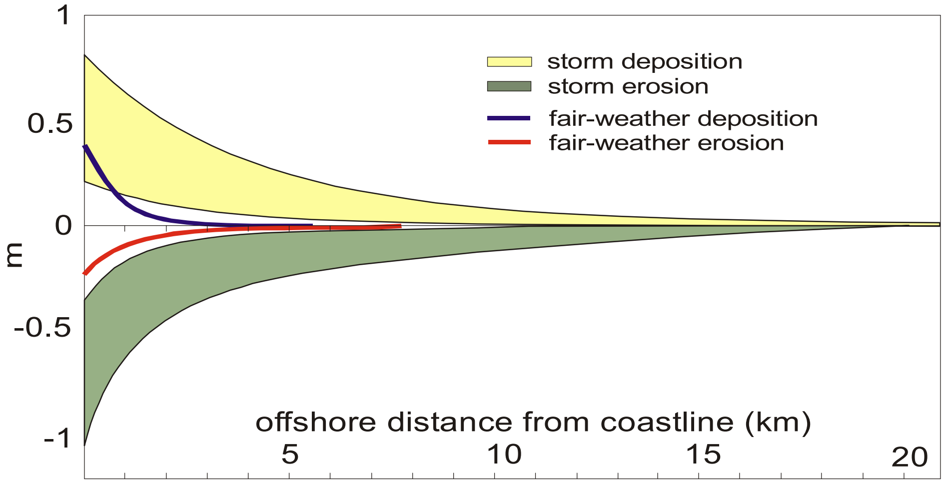


Figure 5. Erosion and deposition rates storm and fair-weather conditions (duration >10 y). Rates are calculated for a 5000 y simulation with a steady sea level and no additional sediment supply. Storm erosion (green) and deposition (yellow) shows a considerable variability as event magnitude is drawn from a predefined distribution.

Storm and fair-weather depositional patterns

Storm deposition results in depositional patterns that are distinctly different from fair-weather deposition. Net onshore transport during fair-weather alternates with net offshore transport of sediment during storm conditions. After a storm, the upper shoreface and beach are flattened and sediment is lost to deeper water (Hobday and Reading, 1972; Reineck en Singh, 1971;Kreisa, 1981). During fair-weather conditions a steady onshore feed of sediment enables the shoreface-beach system to recover and steepen (Lee et al., 1998).

Figure 5 shows simulated erosion and deposition rates after both storm and fair weather conditions for a steady sea level and zero sediment supply. Fair-weather wave height was set to 4 meter and minimum fair-weather duration is 10 year. The storm erosion and deposition curves show a wide range due to the variability in event magnitude. The maximum storm-bed thickness in this case ranges between 0.3 and 0.8 m near the shoreline and it gradually thins in an offshore direction. Storm erosion ranges between 0.35 and 1 m near the coastline. Fair-weather erosion and deposition values are much smaller and more stable, as fair-weather 'storm' magnitude is fixed in the model. Any variability in these curves is due to the dynamic shoreface morphology. The absolute erosion and deposition curves can be used to calculate net deposition curves that illustrate the net topographic change after either an event or a period of fair weather, or both (Figure 6). As expected, events are cause erosion near the coast while sediment is transported offshore (Hobday and Reading, 1972; Reineck and Singh, 1972; Kreisa, 1981). The bulk of the sediment remains fairly close to the coast (between 1and 5 km offshore). Fair-weather conditions are constructive

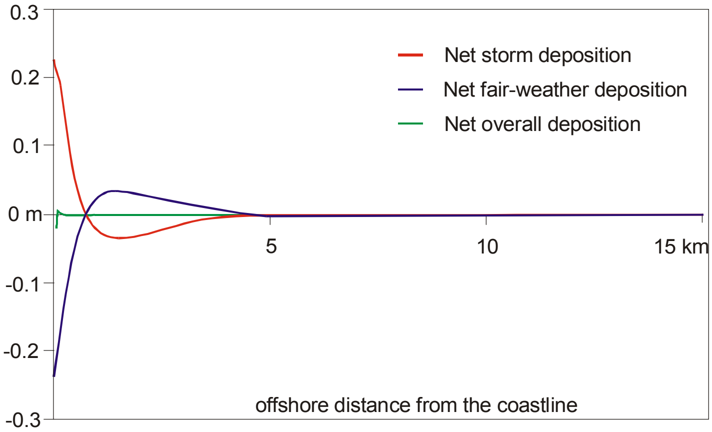


Figure 6. Average shoreface deposition for a simulation with steady sea level and no sediment supply after a storm (red line) and fair-weather period (purple line). The overall average deposition after a storm-fair weather cycle is plotted in green.

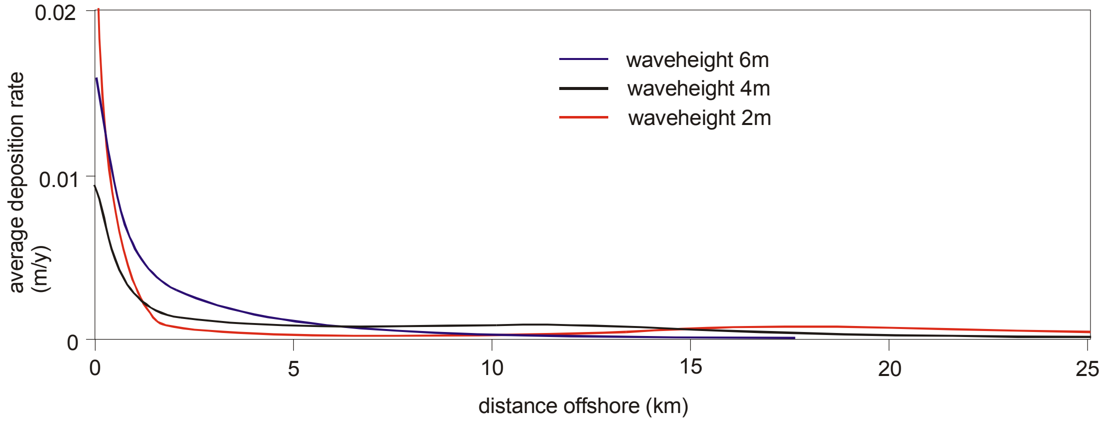


Figure 7. Average offshore deposition rate for three simulations with steady sea level and sediment supply of 25 m^2/y. Deposition rate offshore increases with increasing wave height.

near the coastline. Sediment is returned to the coast by relative gentle waves. The overall effect after a storm – fair weather cycle is negligible as sediment supply is zero.

The overall net deposition curve in figure 6 will change if extra sediment is added as a proxy for littoral drift. Since events last only a day or two, no sediment is added during storm conditions and only reworking takes place. The duration of a fair-weather period combined with the rate of sediment supply, determines the amount of sediment available in addition to reworked sediment during fair-weather conditions. Figure 7 shows net deposition curves for a supply rate of 25 m^2/y and using different fair-weather wave heights. Minimum fair-weather duration remains 10 years al all three cases. A scenario with a steady sea level and a fairly high sediment supply rate will lead to coastal progradation (Figure 8). Deposition rate near the coast is high in all three cases (figure 7). Very little sediment travels beyond 15 km offshore if wave height is low (2 m). More sediment is transported offshore if wave height is increased. A typical maximum in deposition rate occurs near 10 km (wave height is 4 m) and 17 km (wave height is 6 m). This maximum coincides with the average location of the storm wave base. Offshore from this location deposition is dominant which explains the maximum in deposition rate. Sediment starvation results in a further offshore decrease of deposition rate.

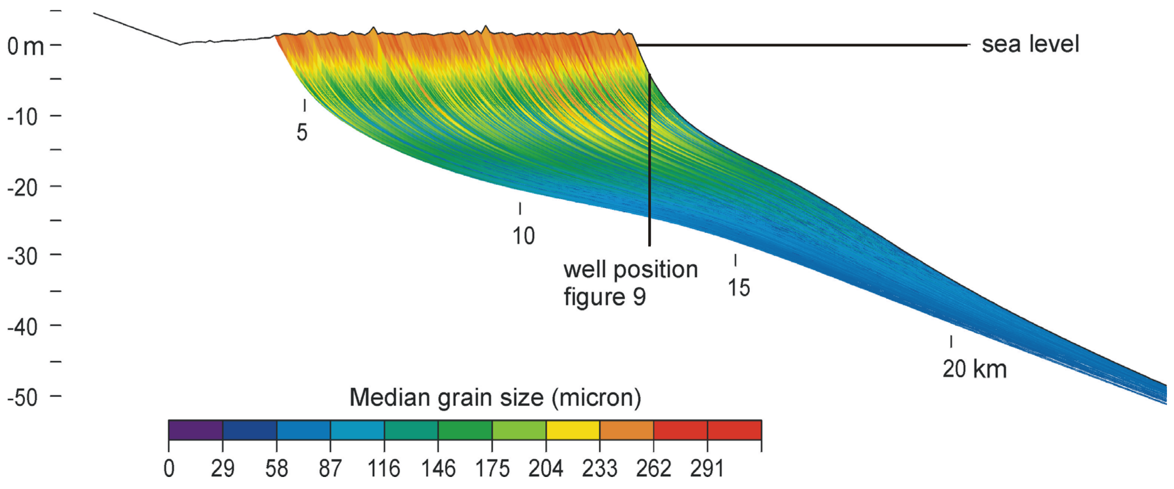


Figure 8. Simulated cross profile for a prograding system (stable sea level, sediment supply is 25m^2/y). The coarse-grained event beds grade into offshore silts and clays.

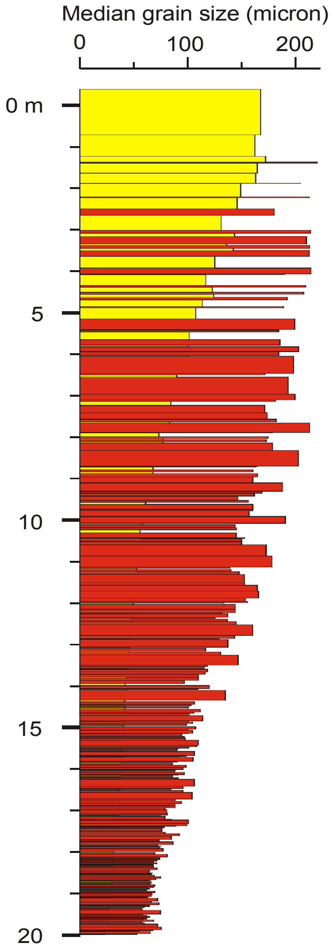
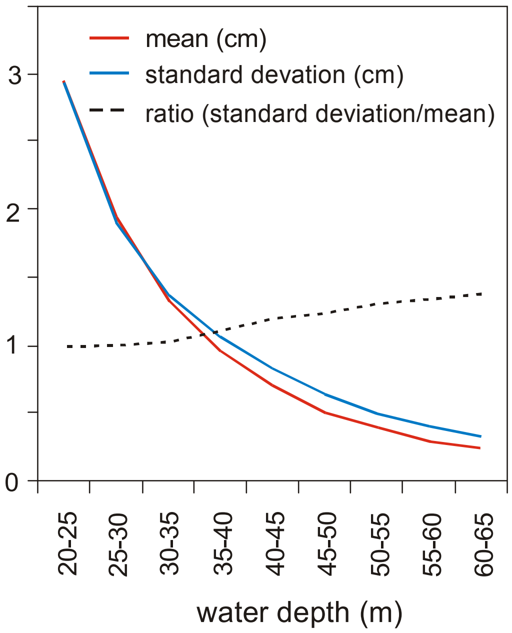


Figure 9 (left). Simulated well showing event beds (red) and fair-weather beds (yellow). Beds coarsen and thicken upwards. For location see figure 8.

Figure 10 (below). Event bed characteristics for a simulated progradational sequence (see figure 8) based on both fair-weather and storm beds. Both mean and standard deviation of bed thickness decreases with water depth.



Simulated storm beds

The net deposition rates described above are very much a theoretical issue and cannot be reconstructed from outcrops or wells. Fair-weather and storm beds as seen in the stratigraphic record are incomplete remnants of initial beds that have undergone subsequent reworking. Initial bed thickness as well as erosion rates can only be guessed and little or no information exists on depositional pattern. However, characteristics of the simulated depositional patterns combined with both simulated and observed stratal bed characteristics might enhance our understanding of event beds and related facies interpretation. Figure 9 shows a simulated well positioned at kilometer 13 in figure 8. Event beds are shown in red while fair-weather beds are shown in yellow. The well shows a typical coarsening upward cycle. Individual beds thicken in upward direction. Fair-weather beds are predominantly preserved in the upper section, which represent upper-shoreface deposits. A high deposition rate at the upper shoreface (figure 7) results in thick initial fair-weather beds, which could not be completely reworked by subsequent storm waves.

Although bed thickness varies considerably, a clear trend can be seen with water depth. Thirty-seven wells were placed at the shoreface at 500m intervals and data of bed thickness were combined with information on water depth during deposition (figure 10). Both mean bed thickness as standard deviation decrease with increasing water depth as previously described by Niedoroda et al. (1989). Relations between water depth and bed characteristics such as these may help to better understand stratal characteristics that can be measured in the field.

Concluding remarks

Much can still be learned about event stratification. Models like BARSIM, that combine short-term bed formation and long-term coastal evolution, may help to do so. Generating event beds based on wave-base lowering as described above appears to work well. Resulting deposition patterns as well as bed characteristics seem plausible. Generated wells show similarity with real logs.

Future work will focus on characteristic bed successions for different types of coastal evolution (forced, normal regression and transgression) which can be simulated using numerous scenarios while varying sea level, sediment supply, substrate gradient, wave characteristics and sediment grain size.

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