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Sediment transport on continental shelves: storm bed formation and preservation in heterogeneous sediments

T. R. KEEN*, R. L. SLINGERLAND†, S. J. BENTLEY‡, Y. FURUKAWA*, W. J. TEAGUE* AND J. D. DYKES*

*Naval Research Laboratory, Stennis Space Center, Mississippi, USA (E-mail: keen@nrlssc.navy.mil)
†Dept. of Geosciences, Pennsylvania State University, University Park, Pennsylvania, USA
‡Dept. of Earth Science, Memorial University of Newfoundland, St. Johns, Newfoundland, Canada

ABSTRACT

Many storm beds are constructed of silt/sand layers interbedded with mud. The coarse sediment fraction originates from reworking of marine sands and/or erosion of the coastal active zone, which extends from fair-weather wave base to the beach berm or coastal dune. Observations and modelling studies show that some sand is removed from the active zone to the inner shelf during extratropical and tropical cyclones. On continental shelves that have large wave events superimposed on offshore near-bottom flow, this coarse material is incrementally transported across the shelf. Storm waves and swell sort this sediment during transport and thus produce storm deposits in water depths of 5–80 m. Observations of storm beds in the Gulf of Mexico indicate initial storm bed thicknesses of millimetres to decimetres. These observations are supported by event-scale numerical models, which also reveal the interaction of oceanographic and geological factors in generating storm beds. Historical records for hurricanes in the Gulf of Mexico suggest recurrence intervals on the order of 10 years for storm-bed deposition. For typical Gulf of Mexico environments, a storm bed must exceed 10 cm in initial thickness in order to survive physical and biological reworking. These results are compared to a storm-dominated sequence from the Cretaceous system of Utah for which the preservation interval for storm beds is estimated to be 266 years. By using the recurrence interval for great storms from the Gulf of Mexico, a preservation rate of less than 20% is estimated for storm beds from the past.

Keywords: Storm beds, preservation, resuspension, sediment transport, stratigraphic model.

INTRODUCTION

The marine storm bed is a type of event bed that was first recognized in the rock record by its systematic vertical arrangement of facies (Fig. 1A) and the occurrence of hummocky cross stratification (HCS). HCS is a bed form that is unique to deposits on the shoreface (the steeply dipping seabed seaward of the low-tide line) and the nearly horizontal seafloor of the continental shelf. Storm beds are 0.1–2 m thick, have erosive bases, and consist of very fine sandstones interbedded with mudstones (Dott & Bourgeois, 1982; Driese *et al.*, 1991). They are thought to be deposited from suspension as storm currents wane but waves remain large (Duke *et al.*, 1991). The presence of mudstones and specific ichnofauna suggest deposition in water too deep for non-storm waves to have a significant impact on the seafloor (i.e. below fair-weather wave base). Storm beds containing HCS have been observed in modern shoreface sediments from North Carolina (Beavers, 1999), South Korea (Passchier & Kleinhans, 2005), and the North Sea (Yang *et al.*, 2006).

Although storm deposits from the Permian to the Cretaceous have been correlated with atmospheric processes (Agustsdottir *et al.*, 1999) it remains problematic to identify ancient storm beds that were created by individual storms because the stratigraphic record represents the cumulative history of erosion and deposition from many storms that can partially erode or amalgamate individual beds. Bioturbation and diagenesis further obscure the original character of these sediments. Thus it is

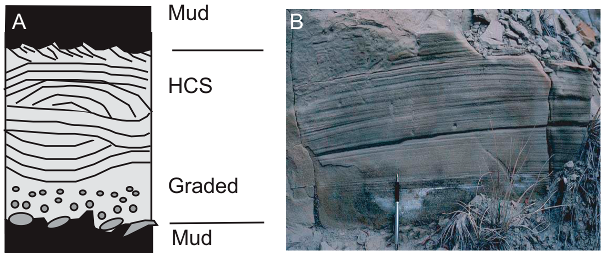

Fig. 1. (A) Schematic cross-section through a fining-upward storm bed. The bottom is eroded into finer sediments and may contain a coarse lag deposit. The top is wave rippled and overlain by fine sediment. (B) Example of hummocky cross stratification (HCS) from the Ferron Sandstone in Utah. The lower part of the bed (behind the pen) contains planar laminae, which indicate a high flow regime during the main depositional event. The upper part contains HCS, which forms as the flow speed decreases but waves remain high. (Photo courtesy of C.L. Summa, Winona State University).

difficult to characterize the initial fabric of storm beds, estimate their frequency of occurrence, or identify the processes that generated them from the rock record alone. In order to better understand the origins of storm beds, it is necessary to look at modern environments in which the oceanographic and geological factors during storms can be measured and the resulting marine sediments observed first hand. It is not straightforward to observe storm bed deposition on modern shelves and apply this knowledge to the rock record because the thick storm sequences observed in the stratigraphic record (e.g. the parasequences of Hampson & Storms, 2003) are uncommon in modern environments. Holocene shelf sediments are typically thin, transgressive successions that overlie a Pleistocene surface eroded during the last glacial maximum. This paper will discuss modern examples that are analogues for the formation and preservation of the ancient storm beds and for which the oceanographic and geological processes during their formation are reasonably well known.

The next section discusses both observational and modelling evidence for the sources of sand and silt during storms and the physical processes that deposit these particles as storm beds. Observations and predictions from numerical models of modern storm beds will then be used to elucidate the processes that created them. The last section uses historical data to discuss the recurrence frequency of modern storm beds and applies the principle of uniformitarianism to estimate the preservation potential of beds within a storm-dominated shelf sequence from the upper Cretaceous of Utah.

SHELF SEDIMENTATION DURING STORMS

Storm bed generation on continental shelves requires a source of silt or sand to construct the characteristic layers, storm waves that can maintain high turbulence levels near the seafloor to entrain silt and sand and keep them in suspension, and steady unidirectional currents to transport sediment. This section will discuss these components and present some of the available evidence for their relative contributions to storm beds.

Sources of silt and sand

Producing storm beds like those in Fig. 1 requires a source of coarse sediment (silt or sand). On allochthonous shelves like those that prevailed during the Cretaceous, these coarser-grained particles originated from rivers or were eroded at the coast and transported to the inner shelf (Swift, 1978). Autochthonous shelves like the Middle Atlantic Bight (MAB), however, are sediment starved and the sand to form storm beds is reworked from the marine sand sheet. The identification of individual storm beds is thus unlikely on the east coast of North America where the transgressive systems tract is only a few metres thick (Nordfjord *et al.*, 2006). The northern Gulf of Mexico shelf near the Mississippi River delta, however, has enough new sediment input by rivers to serve as a model for the allochthonous shelves of the past. This section will demonstrate that both the marine sand sheet and the beach are sources of sand for storm beds on both types of shelves. The preservation potential of these beds will be discussed in a later section.

The coastal active zone

The beach zone is conveniently defined as including the foreshore and backshore. The foreshore is traditionally the zone between the low- and high-tide marks and the backshore extends to the berm or seaward-most dune. The upper shoreface can be defined as being above everyday wave base (Friedman & Sanders, 1978). This depth is dependent on waves but 5–15 m is reasonable for many shelves. It is proposed that the ultimate source for the storm sand pool is the beach and upper shoreface. Following Robertson *et al.* (2007), this area will be referred to as the active zone because the sand and silt within it are mobile during storms.

Finally, the inner shelf is the nearly horizontal seafloor that extends from the lower shoreface (between fair-weather wave base and storm wave base) to an arbitrary depth of 30 m.

The coastal response to storms has been studied extensively at fine scales (<1 km) in several field programs at the US Army Corps of Engineers Field Research Facility (FRF) at Duck, North Carolina (http://www.frf.usace.army.mil). An extra-tropical low pressure system storm (northeaster) passed over the FRF during the SandyDuck experiment in October 1997, and the measured waves, currents, and seafloor elevation were correlated with x-radiographs of cores collected before and after the storm (Beavers, 1999). The data indicate seaward transport and net deposition at a depth of 13 m. A numerical sediment transport model was used to examine the relative roles of across- and along-shore transport during this storm (Keen *et al.*, 2003). The predicted seafloor elevation was in agreement with the observations only if sand was transported offshore and replenished by along-shore transport. In combination with the observations, which indicate no net loss of sediment at 5.5 m and 8 m depths, these results suggest that sand was removed from the upper shoreface and beach and some of it was transported to the inner shelf, as indicated by other studies (Swift *et al.*, 1985; Wright *et al.*, 1986; Kim *et al.*, 1997).

Recent studies suggest that coastal erosion is highly variable at multi-kilometre scales, with sediment mobility varying by more than a factor of three between adjacent coastal sections (List *et al.*, 2006). Remote sensing data and models are useful to study coastal erosion at this scale. A system of numerical models was applied to a northeaster within the MAB and the results suggest that seaward transport extended beyond the 30 m isobath along the Outer Banks of North Carolina (Keen *et al.*, 1994). The net loss of sediment from the active zone that would result from this offshore transport is consistent with airborne laser measurements after Hurricane Ivan in the Gulf of Mexico (Robertson *et al.*, 2007).

Potential erosion

The potential erosion is the maximum volume of sediment mobilized during an event (Lawrence & Davidson-Arnott, 1997). This is an important concept for interpreting the predictions from numerical models when direct measurements of active zone loss are unavailable. A case in point is Tropical Storm Isabel, which made landfall on the Outer Banks in September, 2003, and created a new channel across Hatteras Island. This storm has been simulated using numerical wave and current models and the potential coastal erosion was calculated with a sediment transport model (Keen *et al.*, 2005). The resolution of the numerical models (≈3 km) allowed the oceanographic causes of breaching to be examined at the scale of reversing hot spots (List *et al.*, 2006). The extreme erosion along Hatteras Island probably does not indicate a hot spot. Instead, the island was inundated by a rare storm surge and the potential erosion exceeded the active zone volume, resulting in permanent sand loss. Much of the eroded beach sand was deposited as overwash sheets and fans but the sedimentation model predicted seaward transport by storm surge ebb currents as proposed by Hayes (1967).

These examples of tropical and extratropical cyclones demonstrate extensive erosion of the active zone. The available observations and modelling studies further indicate that some of this material is transported to the continental shelf below fair-weather wave base. The next section will discuss what might happen to this sediment on the continental shelf where only storm waves and long-period swell can interact with the bottom.

Resuspension and transport by combined wave and current action

Sand that is deposited on the inner shelf during storms is subject to remobilization by mean currents, astronomical tides, ocean swell, and subsequent storms. Whenever sediment is mobilized, some sorting occurs because of differences in the critical shear stresses and settling velocities of different sizes and types of grains. A recognizable storm bed results from either deposition or resuspension (Fig. 2A). Both processes can produce graded bedding as in Fig. 1. Larger than normal waves occur throughout a storm and thus some part of the seabed will be suspended even after near-bed currents have weakened. This wave-dominated regime can produce HCS in the upper part of storm beds (Fig. 1B). The final storm bed thickness (Fig. 2B) is thus attributable to both resuspension and deposition after transport but the relative contribution of each process is difficult to discern from observations alone. This section discusses the potential impacts of these processes on storm bed generation.

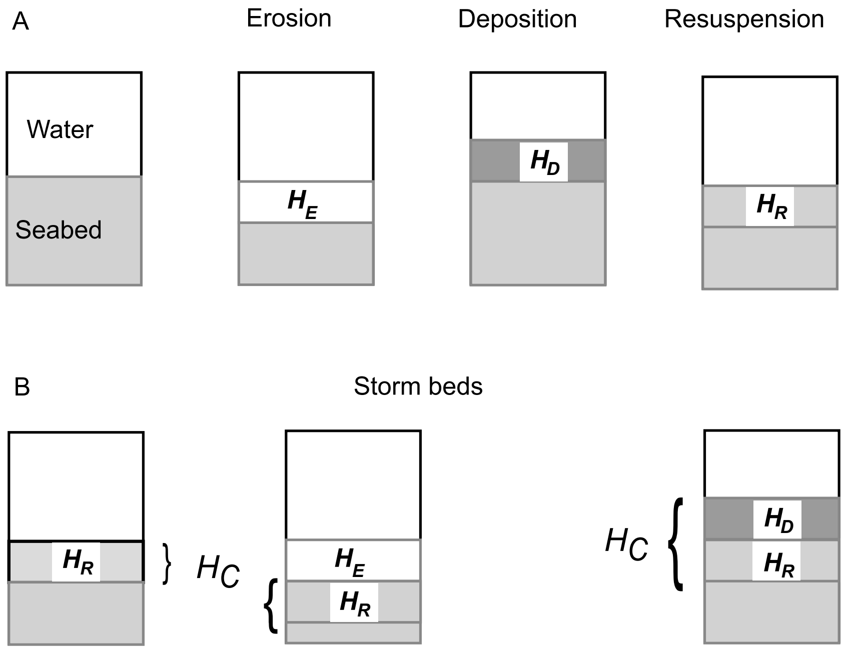

Fig. 2. Schematic drawing of storm bed components. The upper panel (A) shows the effects of erosion, deposition, and resuspension on the seabed. H_E is the thickness of eroded sediment caused by a net loss from the seabed. H_D is the thickness of new material deposited at seabed (shown in darker shade). H_R is the thickness of suspended sediment with no net change in mass at seabed. The storm bed H_C (shown in lower row (B)) is a result of either resuspension or a combination of either net loss (erosion) or net gain (deposition), and resuspension (Keen & Glenn, 1998).

Observations of seaward transport

Observations from the east and west coasts of North America show that offshore motion is common on the continental shelf, although its strength, duration, and frequency are dependent on atmospheric forcing as well as shelf topography. Sixteen sediment transport events associated with storm waves and swell were observed during the winter of 1990 on the northern California shelf where the bottom consists of fine sand and silt (Sherwood *et al.*, 1994). Net offshore transport in depths of 50–130 m was driven by both downwelling flows during storms and mean circulation. Forty-one events were recorded ≈700 km to the north in 1995–1996 (Ogston & Sternberg, 1999). Similar sediment transport events have been observed in the MAB where the bottom consists of 50% medium sand (Butman *et al.*, 1979). The MAB along-shore flow is correlated with the wind and is coherent at scales of 100 km whereas the cross-shelf component is variable. Offshore transport is dominant for water deeper than 60 m but onshore flow prevails for shallower depths. Onshore transport was also noted at a 15 m site with a medium sand bottom by Styles & Glenn (2005). The landward transport is as bed load transported by shoaling swell waves in the absence of strong near-bottom currents. It thus appears unlikely that sediment delivered to the inner shelf of the MAB is transported further seaward as suspended load. However, this is not the case for the west coast where offshore flows accompanied by large waves are apparently common.

Hurricane Ivan passed directly over a bottom-mounted current meter array in water depths of 60–80 m (Teague *et al.*, 2006a; Jarosz *et al.*, 2007). Measured wave heights greater than 10 m (Wang *et al.*, 2005) would have entrained the sandy sediment at this location at a time when bottom currents were also high. Instead of resting in scour pits after the hurricane, the instruments at all locations were found on a level seafloor that was up to 36 cm lower than before the storm (Teague *et al.*, 2006b), suggesting that most of the suspended sediment was transported as far as 30 km to the southwest by bottom currents.

Model-predicted resuspension and transport

The limited number of observations of sediment resuspension and transport events on the shelf can be supplemented by numerical models. For example, Graber *et al.* (1989) demonstrated that resuspension events are common during storms on wave-dominated shelves like the East China Sea. The relative contributions of resuspension and transport to storm bed generation during hurricanes have been examined by Keen & Glenn (1998) for Hurricane Andrew, which made landfall southwest of New Orleans, Louisiana, in August 1992. The Hurricane Andrew simulation suggests a complex transport regime on the shelf. The modelled storm flow was current dominated as the eye approached and the resulting storm bed would have been predominantly due to transport. However, the waves increased during the peak and the near-bottom flow would have been dominantly oscillatory. After landfall, large waves were only present near the coast and thus the simulated storm bed on the shelf was again created mostly by transport. An important result of this study was that resuspension produces a relatively uniform bed whereas transport tends to be irregular because of the sensitivity of bottom currents to bathymetry and the evolving storm flow. The predicted suspended load transport was to the west for a distance of ≈40 km, with 4 cm of erosion east of landfall and a 1 cm storm bed predicted to the west (Keen & Glenn, 2002). This transport path and distance is consistent with the observations from Hurricane Ivan (Teague *et al.*, 2006b).

This section has reviewed observational and modelling evidence for coastal erosion, offshore transport, and resuspension and transport of sediment on the continental shelf during large storms. These data suggest that sand moves incrementally from the beach to the shelf break at time intervals ranging from weeks to years. Thus, sand eroded from the active zone is initially deposited on the shoreface in water depths less than 20 m as a storm bed. If it is not transported back to the beach by fair-weather waves or currents, it may be resuspended during a subsequent storm and transported further offshore to be redeposited as a new storm bed. With each such event, this material undergoes differential transport and sorting and may be deposited as the graded beds shown in Fig. 1. The volume of sand that may be transported to the continental slope is unknown but Teague *et al.* (2006b) estimate transport of as much as 10^8 m^3 of sediment during Hurricane Ivan.

MODERN STORM BED DEPOSITION

Coastal storms create storm beds by the resuspension and transport of heterogeneous seafloor sediments. These processes winnow the finer material and produce the sand-mud layers observed in rocks. Storms that produce significant rainfall over land also produce event beds as a result of river inflow, which introduces large volumes of fine-grained terrestrial sediment onto the inner shelf after high-energy storm conditions have waned (Geyer *et al.,* 2000). These flood deposits, which contribute to the mud drape after a severe storm, have not been clearly identified in the stratigraphic record because of their greater homogeneity and it is thus not possible to compare modern and ancient examples. This discussion will, therefore, focus on storm beds produced by resuspension of mixed sand/silt and mud sediments.

Observations of recent storm beds

The majority of modern storm beds discussed in the literature have been observed in the northern Gulf of Mexico (Fig. 3) where the transgressive systems tract is 20–120 m thick (Simms *et al.*, 2007). Individual storm beds are more easily identified in these sediments because of their textural heterogeneity, which results in intercalated coarse and fine sediment layers. These discrete, high-energy deposits are unique because they are produced by tropical cyclones with a low recurrence interval on an otherwise low-energy shelf. Sediment cores collected from the inner shelf of Texas reveal at least 4 m of sand beds up to 20 cm thick and interbedded with bioturbated sand and mud layers (Morton, 1981). Hayes (1967) identified an event bed with a maximum thickness greater than 9 cm that he proposed was deposited by Hurricane Carla in 1961. The Carla bed, which was found as far as 240 km south of landfall, was mapped by Snedden *et al.* (1988) over an area of 7200 km^2 and into water depths greater than 40 m.

Bentley *et al.* (2002) attributed a sandy layer with unique texture, bedding, and radiochemical signature within Mississippi Sound and the adjoining inner shelf to Hurricane Camille (1969). In addition, an older sandy layer in these same cores is thought to have been deposited by an unnamed hurricane in 1947 (Keen *et al.*, 2004). These beds were finer grained and contained greater variability than was observed on the Texas shelf.

Seabed cores collected in depths of 23 m and 14 m on the Louisiana shelf in January 2006 (Fig. 4A) contained a 5–30 cm storm bed of mud and coarse silt that is attributed to Hurricanes Katrina (August) and Rita (September) in 2005. The beds were deposited after storm waves had eroded into consolidated deltaic clay. A core from the western shelf included a single storm layer ≈12 cm thick (Fig. 4B). A core from further east and nearer the track of Hurricane Katrina contained two event layers (Fig. 4C). The lower bed was probably deposited during Katrina and the

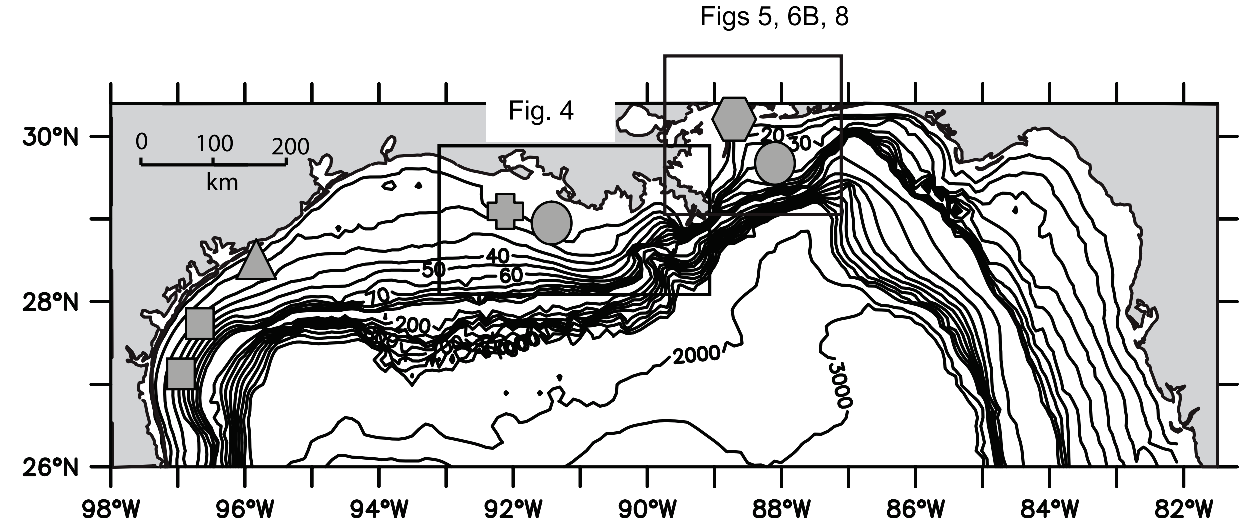

Fig. 3. Bathymetry (m) of the northern Gulf of Mexico with locations of shelf storm bed deposits described in this paper: Hurricane Carla, 1961 (squares); multiple unnamed storms (triangle); Hurricane Camille and an unnamed 1947 storm (hexagon); and Hurricanes Katrina (circles) and Rita (cross), 2005. The rectangular outlines indicate the approximate locations of maps used in later figures.

upper bed would have been created during Rita. The mean bed thickness for 13 cores is 10 ± 4 cm.

Sediment cores were collected east of the Mississippi River delta in water depths of approximately 27 m in December 2005 (Sites 1–4 in Fig. 5A). The increased densities (Fig. 5B) near the surface of these cores indicate a silt and sand layer overlying mud. This storm bed reached a

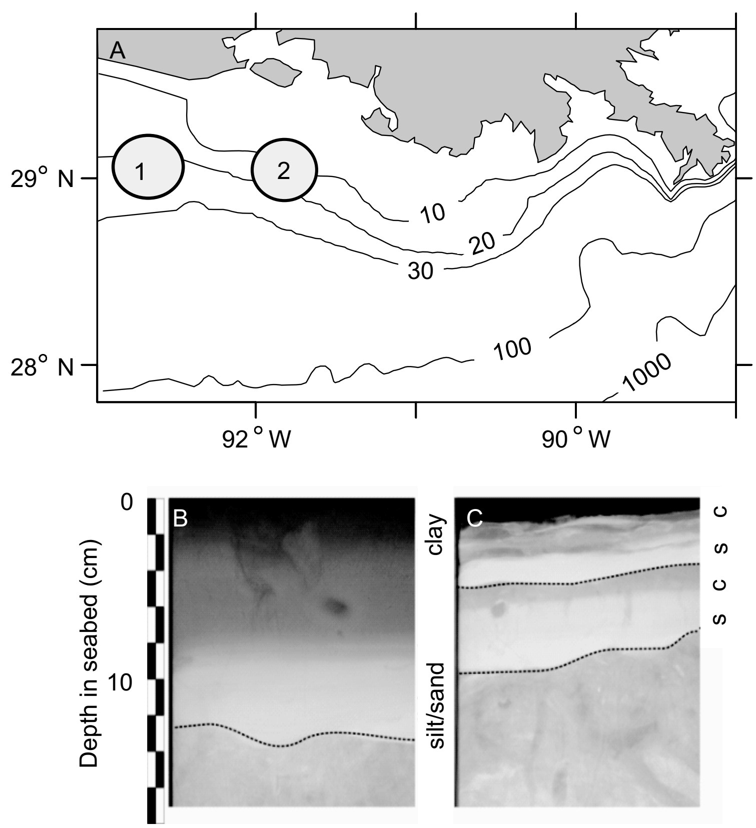

Fig. 4. (A) Location map of cores collected from the Louisiana shelf in 2006. The circled numbers indicate stations referred to in text and in this figure. See Fig. 3 for location. (B) X-radiograph of a core collected on the west Louisiana shelf at site 1. (C) X-radiograph of a core collected at site 2. These negative images show coarse sediment (high density indicated as silt/sand or s) as light shades, and fine sediment (low density, indicated as clay or c) as dark shades. Storm beds are visible with sharp lower boundaries (indicated by dotted lines) overlying more intensely bioturbated sediment, and more bioturbated upper boundaries.

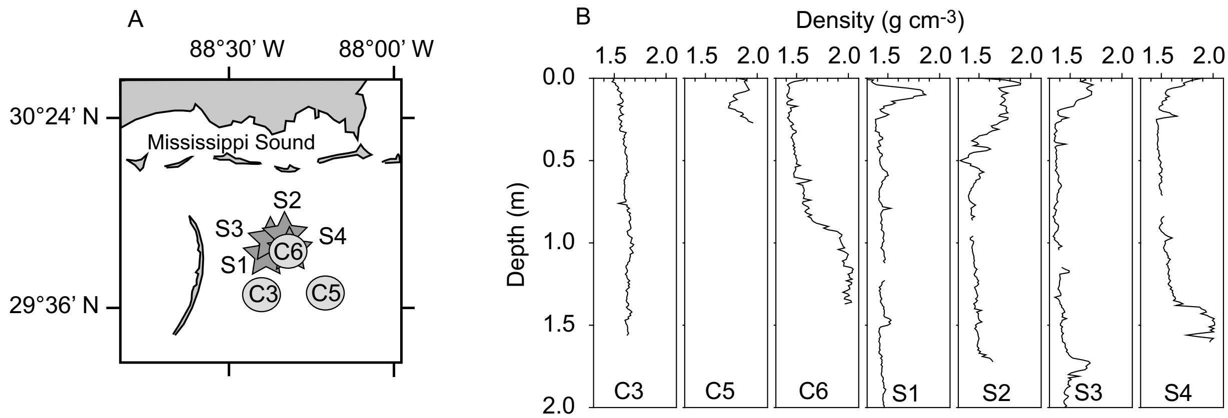

Fig. 5. (A) Locations of bottom samples collected before (circles) and after (stars) Hurricane Katrina. (B) Density profiles of cores. Pre-Katrina cores C3 and C6 have densities of $\sim$1.5 g cm^{-3} at the seafloor, whereas the post-Katrina cores (S1–S4) have values above 1.7 g cm^{-3}. Note that core C5 also has a higher density because it is near the edge of the extensive sand sheet to the east. The deepest evidence of the Katrina bed is in core S2, which shows a spike of sandy (density $\approx$1.7 g cm^{-3}) sediment at 0.58 m. The full dataset is presented in Furukawa *et al.* (2006). The sand that is present in the upper 0.5 m of the post-Katrina cores was probably transported from the sand sheet by southwestward currents as observed for Hurricane Ivan (Teague *et al.*, 2006b).

maximum thickness of 58 cm (Furukawa *et al.*, 2006). This bed contains a fining-upward sequence consisting of colloidal clay, coarse silt, and shell fragments. It is attributed to Katrina because sediment cores from the same locations taken in 1999 (C3 and C6) did not have these characteristics.

Modelling storm bed formation

Storm-dominated stratigraphy is often simulated using process-response models that calculate erosion, deposition, and grain size as a function of storm wave statistics and shelf geometry. These models predict stratigraphy at different spatial and temporal scales (e.g. Niedoroda *et al.*, 1989; Storms, 2003; Driscoll & Karner, 1999) but they do not capture short-term processes that control the deposition of individual event beds. In order to gain insight into these coupled wave-current processes, high-resolution event-scale models have been developed (e.g. Keen & Slingerland, 1993a; Blaas *et al.*, 2007). While undergoing some refinement over the years, the use of a coupled system of numerical models to simulate the winds, waves, currents, and sedimentation during storms has produced consistent and realistic results.

Simulations of sandy storm bed deposition by a northeaster show a maximum bed thickness of 1.6 cm on the inner shelf of the southern MAB (Keen *et al.*, 1994). Simulated muddy flood deposits initially 5–10 cm thick on the northern California shelf are transported to the outer shelf within days (Harris *et al.*, 2005). Storms in smaller basins produce somewhat thinner deposits. Episodic wind events for March 1998 over Lake Michigan produce a simulated monthly net deposition rate $R = \sim 2$ kg m^{-2} on the 50 m isobath (Lee *et al.*, 2007), from which the bed thickness h can be estimated by, $h = (1 - \varphi) \times (R/\rho) = 0.3$ mm; where φ = initial porosity (0.6), and ρ = grain density (2650 kg m^{-3}). Storm deposition during strong wind events in the northern Adriatic Sea appears to produce coarse sediment layers with bed concentrations near 10 kg m^{-2} at the 50 m isobath (Wang *et al.*, 2007), which is approximately 2.2 mm for $\varphi = 0.4$. The extreme waves and strong currents during tropical cyclones have produced simulated storm beds exceeding 20 cm within the western Gulf of Mexico in water depths up to 100 m (Keen & Slingerland, 1993b), storm beds thicker than 3 cm on the Louisiana inner shelf (Keen & Glenn, 2002), and deposits up to 20 cm on the inner shelf and within the enclosed waters of the Mississippi Bight (Bentley *et al.*, 2002). It is encouraging that the predicted storm beds range from millimetres to decimetres given the wide range of conditions encountered in these disparate environments. This multiple order of magnitude result is also predicted for the kind of very-large storm that is thought to have occurred during the Cretaceous period. The simulated storm bed for such an extratropical cyclone that lasts 4 days was deposited as deep as 75 m and had a maximum thickness of 54 cm (Slingerland & Keen, 1999).

It is clear from the observations of coastal erosion during storms as well as the modelling studies discussed above that storm beds will be spatially variable. This is especially true of any sediment that is transported because near-bed currents change in response to the evolving stratification, storm surge and wind field (Keen & Glenn, 1999). This aspect of storm bed deposition can be examined using examples of tropical cyclones on two very different coasts. Hurricane Isabel approached the Outer Banks on a shore-normal track and the impact of the coastal waves and currents was felt throughout the barrier islands (Keen *et al.*, 2005). The predicted storm bed (Fig. 6A) consisted of both transported and resuspended sand. It thinned offshore to less than 1 cm in water depths of 30 m and followed the Outer Banks for ≈700 km. Note the seaward tongues that are associated with openings in the islands and capes. Hurricane Katrina made landfall on a more complex coast and shallower shelf. The predicted storm bed was widespread (Fig. 6B) and exceeded 8 cm on the outer shelf with a maximum thickness of ≈13 cm predicted on the inner shelf at 88.9 °W (Keen *et al.*, 2006). The

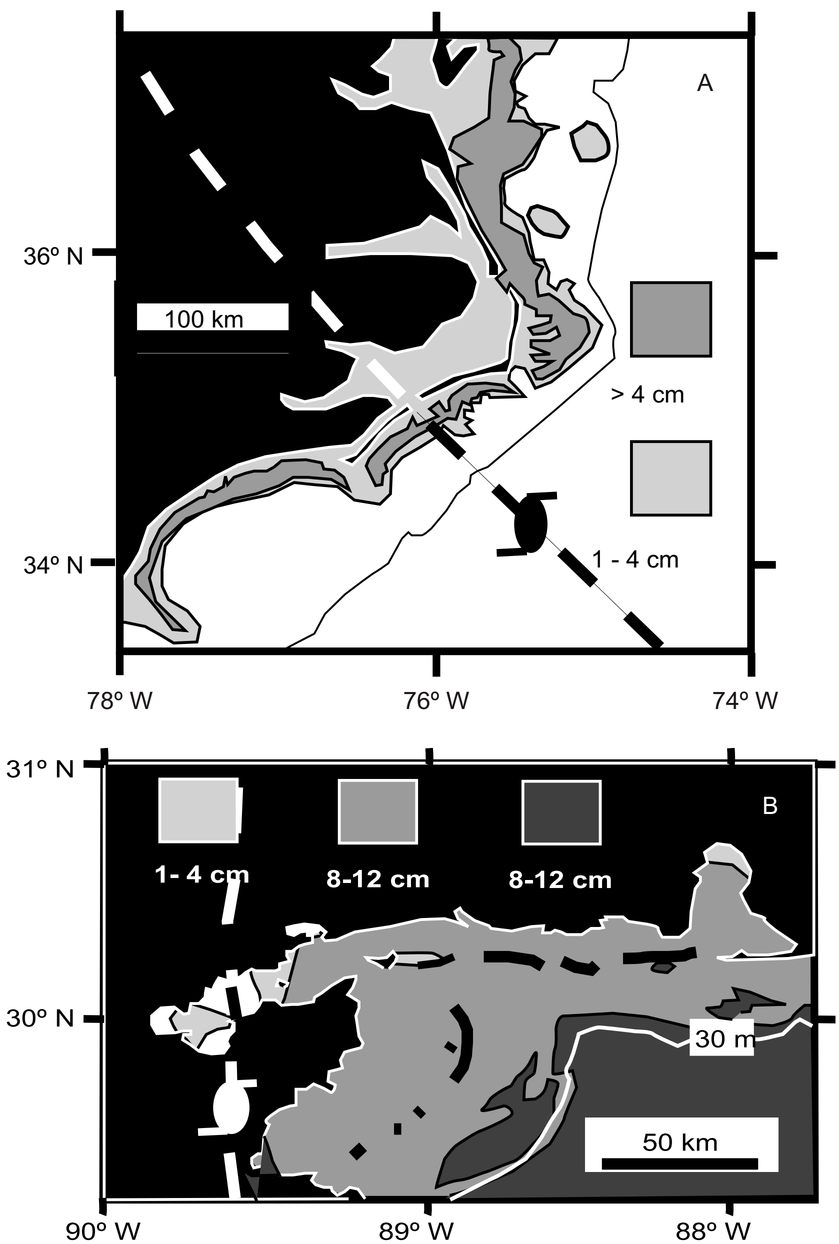

Fig. 6. Contour maps of predicted storm bed thickness. (A) Tropical Storm Isabel, which made landfall on the Outer Banks of North Carolina. The storm bed approximately follows the 30 m isobath (the thin line is the 100 m isobath). The maximum thickness is 8 cm near landfall. (B) Hurricane Katrina, which made landfall just east of New Orleans, Louisiana, in the northern Gulf of Mexico. The thickest bed is predicted seaward of the 30 m isobath where large storm waves occurred. The deepest water in the study area is < 100 m except in the extreme southeast corner. The storm tracks are indicated with dashed lines and land, including barrier islands, is black.

simulated Katrina bed exceeded 4 cm throughout the sound whereas the Isabel bed was thinnest behind the barriers and remained less than 6 cm. These two storm beds demonstrate some of the problems of interpreting ancient storm beds but they also help define the variability that can be expected.

RELATING MODERN STORM BEDS TO THE ROCK RECORD

Hurricane Katrina produced an event bed with a known origin and a thickness of the same order of magnitude as those observed in the geological record. This knowledge can be used to constrain some of the uncertainties about the deposition and preservation of ancient storm beds. Observations and modelling of modern storm beds indicate that they are 0.1–50 cm thick and consist of sandy layers less than 50 cm thick overlain by mud. They can be entirely amalgamated, cannibalized, or preserved in their entirety, depending on physical and biological reworking. Resuspension beds have been observed in water depths of 13–30 m and both measurements and models suggest that they are also generated in depths of $\approx$100 m. The Katrina storm bed extends at least 350 km west from landfall. This is consistent with model results as well.

However, there are several assumptions implicit in applying knowledge of a modern storm bed to the stratigraphic record: (1) the geological and oceanographic factors during severe storms in the Holocene are similar to those in the past such that modern beds can be compared to ancient deposits for which the storm type is unknown; (2) the thickest beds are deposited near the storm track; and (3) the mechanism for producing a storm bed is the same for sandy or muddy sediments. The previous sections of this paper have discussed the initial fabric of storm beds and the processes that generate them. This section will examine the recurrence interval for storm beds and their preservation potential.

Recurrence interval

Elsner *et al.* (2006) estimate a return period of 21 years for major hurricanes for the entire Gulf coast but, in order to compare the modern shelf data to the geological data, it is necessary to focus on a smaller area. Historical track data (NOAA, 2007) for Category 3–5 hurricanes passing within 100 km of typical locations within the northern Gulf of Mexico (Fig. 7) are useful for this purpose. The database spans 154 years (1851 to 2005). The small sample size for these 200 km circles prevents the use rigorous statistical methods but the return period can be estimated for each location. The shortest return period is for Waveland (19.25 years) and the longest occurs at Tampa (51.33 years). The coastline from Tampa to Brownsville is 1500 km long and Waveland is near the centre of its length. The largest numbers of major hurricane landfalls occur within north-central Gulf of Mexico because of the interaction of the west-northwest storm tracks with steering lows over North America. Thus, there is a strong atmospheric control on landfalls, which would apply to past climatic intervals as well.

For comparison with the modern Gulf of Mexico, the Western Interior Seaway during the Turonian

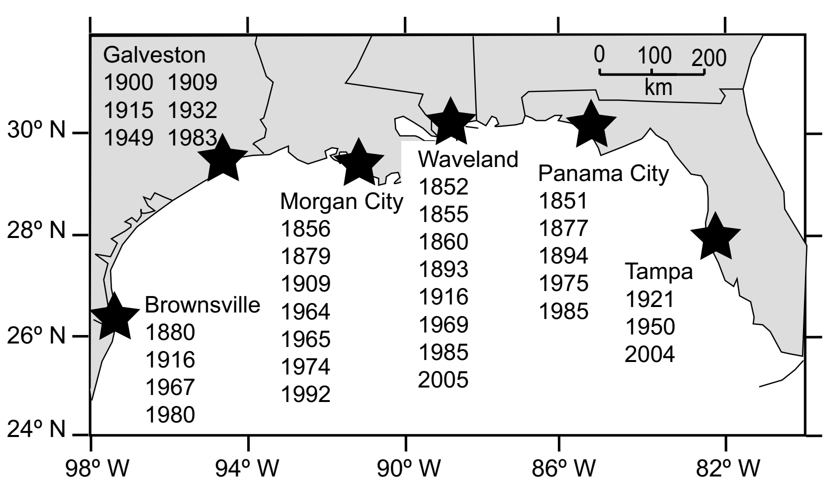

Fig. 7. Map of northern Gulf of Mexico, showing example locations (stars) for category 3–5 hurricanes that made landfall within a 100 km radius given by the years in which they occurred. The data for Tampa include eastward-travelling hurricanes only. The total, including those that remained over land, is 8.

(≈88.5–91 Ma) was possibly 4000 km long and oriented parallel to meridians. It would have had substantial variations in climate as well as geography along its extent. It is possible that the northern seaway would have been subjected to frequent extratropical cyclones whereas the southern margin could have been impacted by less common tropical cyclones. The assumption that storm bed generation during these two types of severe storms is similar is necessary to estimate the recurrence interval within ancient basins. It is necessary to also assume that the frequency of storm-bed deposition by such storms in the past was similar to the modern Gulf of Mexico; i.e. at decadal time scales. This estimate could be improved if a database of the occurrence of especially strong extratropical cyclones like the "Halloween" storm of 1991 (Cardone *et al.*, 1996) were available.

Preservation potential

The preservation potential of a storm bed is a function of its initial thickness, subsequent burial rate, and bed reworking by physical and biological mechanisms. The impact of these factors on the preservation potential of storm beds will be examined by comparing previous results within the Mississippi Bight (Bentley *et al.*, 2002; Keen *et al.*, 2004) to the storm beds from Hurricanes Katrina and Rita on the Louisiana shelf.

Physical reworking

The impact of physical reworking on bed preservation can be classified as three cases: (1) amalgamation occurs if the depth of reworking exceeds the combined thickness of a prior storm bed (sand layer plus mud drape) in addition to any intervening sediment; (2) cannibalization is the process whereby a younger bed includes part of an older storm bed in addition to intervening sediment; and (3) preservation occurs if none of the older storm bed is incorporated into the younger storm bed, although part of the intervening fair-weather sediment may be. All three of these cases can be found in both synthetic and seafloor cores from Mississippi Sound (Fig. 8A), which contain storm beds from a 1947 hurricane and Hurricane Camille. Amalgamation of the 1947 bed with that from Camille occurred at site 1 (Ship Island), where no evidence of the older bed is found (Fig. 8B). The older storm bed was cannibalized by Camille at Dog Key Pass (Fig. 8C), but the sandy layer was preserved at Bay St. Louis (Fig. 8D) and the inner shelf (Fig. 8E).

The core from site 1 on the Louisiana shelf in January 2006 (Fig. 4B) contains a single sand layer that resembles amalgamation (compare to Ship Island in Fig. 8B). The samples from 2006 do not reveal cannibalization but the core from site 2 (Fig. 4C) is similar to a core in which the older bed is preserved (e.g. Bay St. Louis in Fig. 8D).

Biological reworking

The preservation potential of a storm bed is also dependent on the activity of burrowing organisms that constantly rework the upper 10–20 cm of sediment. These infaunal communities are robust and quickly recover after severe storms (Hernandez-Arana *et al.*, 2003; Yannarell *et al.*, 2007). Thus, the original storm-generated characteristics of a storm bed less than 10 cm thick will be destroyed by bioturbation. A bioturbation model that disrupts primary depositional fabric has been applied to the simulated cores described by Keen *et al.* (2004). These synthetic disturbed cores, (the middle sections in Fig. 8B-E) can be compared to the x-radiographs (rightmost columns in Fig. 8B-E). For example, the x-radiograph from Ship Island (Fig. 8B) shows extensive bioturbation and all primary fabric has been destroyed. However, the bioturbated synthetic core is not completely disturbed because the amalgamated Camille storm layer is too thick. At Dog Key Pass (Fig. 8C) the upper parts of two identifiable beds are preserved in both the x-radiographs and the synthetic disturbed cores. Similar preservation is both seen and predicted at Bay St. Louis (Fig. 8D) but with more distinct bedding because of the higher contrast between the sandy layers and mud. The Camille bed reveals similar preservation in both the x-radiograph and synthetic core from the inner shelf (Fig. 8E) but the results for the older bed are ambiguous because of an observed shell lag that is absent from the synthetic core.

The cores taken from the Katrina and Rita beds were taken too soon after deposition for bioturbation to have destroyed their primary fabric. The impacts of bioturbation and burial on the preservation potential of these beds can be evaluated using the model of Bentley *et al.* (2006), which computes the preservation quotient q as a function of burial rate, bioturbation depth, and a depth-dependent bioturbation rate. Figure 9 displays four simulations of an event layer 10 cm thick, buried by

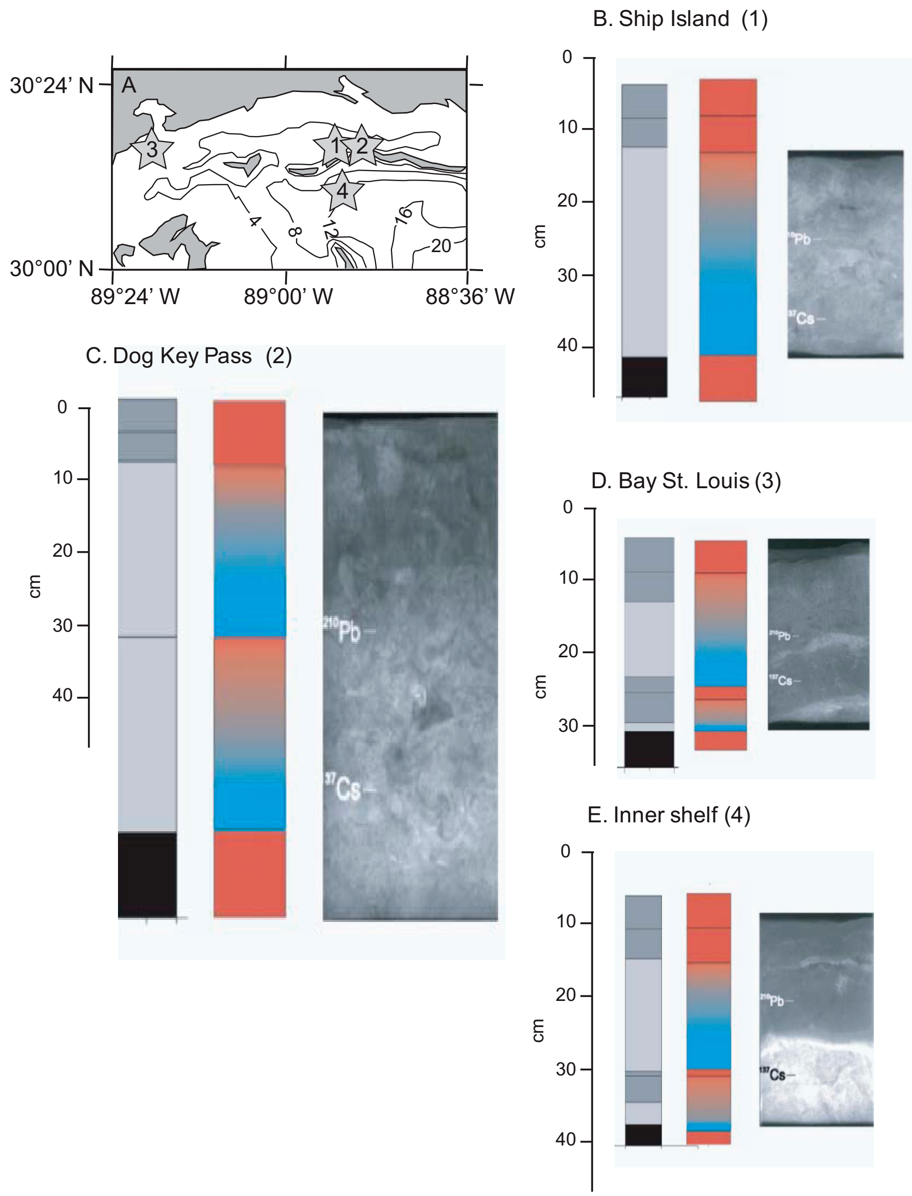

Fig. 8. Storm beds within Mississippi Sound for a 1947 hurricane and Hurricane Camille (1969). (A) Location map for cores discussed in text and this figure (location shown in Fig. 3). Synthetic cores (left column), synthetic cores with bioturbation (middle column) and x-radiographic negatives of real cores for the Mississippi Bight: (B) Ship Island; (C) Dog Key Pass; (D) Bay St. Louis; and (E) the inner shelf. The synthetic cores contain pre-storm mud (black), storm beds (light shade) and fair-weather mud (darker shade). The degree of preservation of the original fabric for the bioturbated synthetic cores is indicated by colour; blue is original fabric and red is completely disrupted (Keen *et al.*, 2004). ^{210}Pb and ^{137}Cs represent core dating presented in Keen *et al.* (2004).

sedimentation rates of 2 and 10 cm yr^{-1}, and bioturbated to a depth of 20 cm by bioturbation mixing rate/depth regimes that are typical of shelf settings (i.e. rapid-shallow and slow-deep). The models were run until the event-bed surface was buried below the maximum bioturbation depth. In each case, the bed surface has been completely bioturbated, and primary fabric in basal portions of the event beds is only partially preserved, with more complete preservation under conditions of more rapid burial. These results suggest that event beds thinner than approximately 10 cm have little chance of preservation under such conditions whereas thicker beds, perhaps formed closer to

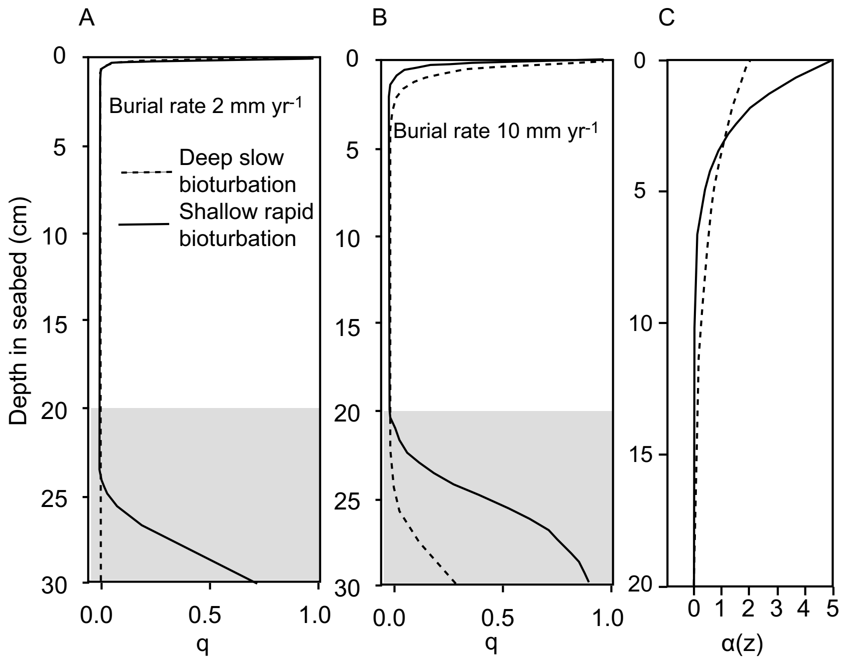

Fig. 9. Event-layer preservation potential modelled with respect to varied conditions of bioturbation and burial acting on a bed 10 cm thick. The preservation quotient q represents the fractional sediment volume (0–1) retaining primary depositional fabric. (A) burial rate = 2 mm yr^{-1} for 100 yr; (B) burial rate = 1 cm yr^{-1} for 25 yr; (C) depth-dependent first-order bioturbation rates [α(z)] for deep, slow mixing (dotted line) and shallow, more rapid mixing (solid line), in each case to maximum depth of 20 cm. See Bentley *et al.* (2006) for more detail.

the storm track or buried more rapidly by either steady sedimentation or episodic deposition have a greater potential for preservation and recognition in the rock record.

Storm bed frequency in the Cretaceous

It is useful to consider the character and frequency of ancient storm sequences in light of these observations of modern storm beds. As an example, this section will apply the previous discussion of the initial fabric, causative processes, and recurrence interval of modern storm beds to an ancient storm-dominated sequence from the Campanian (≈83.5–70.6 Ma) Spring Canyon Member of the Blackhawk Formation in the Book Cliffs of central Utah (Hampson, 2000; Hampson & Storms, 2003). These storm beds were deposited during a sea-level high stand as part of the Sowbelly parasequence (Kamola & van Wagoner, 1995).

The Sowbelly parasequence

The Sowbelly parasequence (Fig. 10) is bounded below by a marine flooding surface. The lowermost sediments are bioturbated marine mudstones intercalated with decimeter-thick, very fine-grained, hummocky cross-stratified sandstones like those of Fig. 1B. These storm beds become thicker, slightly coarser-grained, and amalgamated over approximately 20 m of stratigraphic section. They are succeeded by large-scale trough cross-stratified sandstones produced by bidirectional dune migration. These dunes are overlain by wedge-shaped sets of plane-parallel laminated lithic arenites that are rooted at the top and capped by coal. The lack of either deeper marine sediments or landward facies within the parasequence is consistent with its boundaries, which are minor stratigraphic discontinuities. The Sowbelly parasequence records 10 km of seaward progradation of a storm-dominated sandy shoreface during approximately 100,000 years (Hampson & Howell, 2005; Hampson, 2010), which gives an average rate of progradation of 1 km per 10,000 yr (0.1 m yr^{-1}).

Sowbelly deposition rate

The average rate of deposition for the Sowbelly parasequence can be found as follows. The muddy sediments at the bottom of the succession in Fig. 10 were deposited on distal lower shoreface of the inner shelf and the rooted, plane-parallel laminated lithic arenites at the top were constructed on the foreshore. Hampson & Storms (2003) estimate the horizontal distance from the foreshore to the distal lower shoreface to be 2 km. Thus the vertical succession at any one location (e.g. Fig. 10) was deposited as the shoreline moved seaward 2000 m, which would have taken 20,000 years if a constant rate of progradation

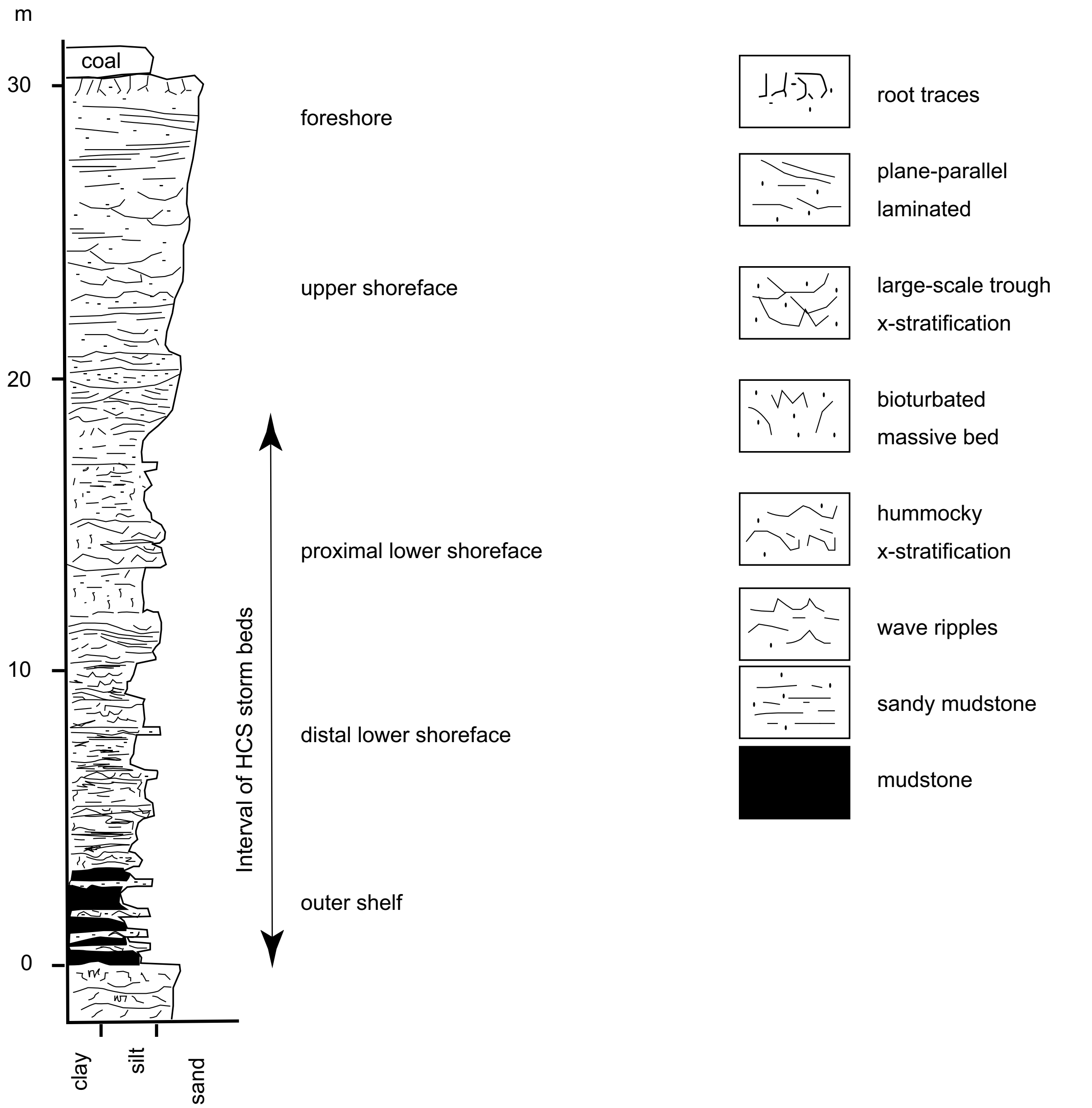

Fig. 10. Graphic log of the Campanian-age Sowbelly parasequence, Spring Canyon Member, Blackhawk Formation in Gentile Wash, Utah (39 42' 56.31" N; 110 52' 28.74" W). The sequence was deposited as a storm-dominated sandy shoreline prograded approximately 10 km ESE over approximately 100,000 years. Approximately 75 identifiable discrete hummocky cross-stratified (HCS) storm beds are preserved in the section.

of 0.1 m yr^{-1} is assumed, as discussed in the previous section. The average sedimentation rate for the Sowbelly sediments is, therefore, 30 m in 20,000 yr or 1.5 mm yr^{-1}, which is of the same order as for the Mississippi Bight (2.9–4.7 mm yr^{-1}). It is important that the overall sedimentation rate, and thus burial rate, be similar in order to apply the Gulf of Mexico recurrence interval estimate to the Sowbelly sediments.

Preservation rate

The apparent recurrence interval of identifiable storm beds can be termed the preservation interval (Tamura & Masuda, 2005). The Sowbelly parasequence in Gentile Wash contains approximately 75 discrete storm beds on the order of 20 cm thick. Using the above estimate of 20,000 years for deposition of these sediments, the preservation interval for bed-producing storms would have been 266 years. This preservation interval is a maximum estimate for recurrence interval because both physical and biological reworking would have removed multiple beds for each bed preserved. Approximately 40 cm of sediment would have been deposited between beds if the storm recurrence interval were 266 years. The average thickness of sediment per storm bed is 27 cm (i.e. 20 m divided by 75 beds). If 20 cm is subtracted for the thickness of an average bed, the remaining 7 cm of bioturbated mud should be fair-weather sediment deposited between storms. This is substantially less than the 40 cm that was estimated from the deposition rate. This simple mass-conservation estimate suggests that the preservation interval does not represent the recurrence interval for these storm beds.

Fine-grained Holocene storm beds deposited during shoreline progradation coeval with early marine regression reveal measured preservation intervals of 83–250 years (Tamura & Masuda, 2005), which are similar to the estimate for the Sowbelly parasequence. Since these Holocene beds were deposited in a climate that was similar to that existing today, it is reasonable to assume that the recurrence interval for large storms would have been similar to the Gulf of Mexico. Furthermore, if bioturbation depths were similar to those for the Gulf of Mexico, a similar preservation rate can be expected. The similarity of the Holocene and Cretaceous preservation intervals allows a preservation rate to be estimated using the storm recurrence interval from the Gulf of Mexico. Here the preservation rate is defined to be the ratio of the preservation interval to the recurrence interval. Using a recurrence interval of 20–50 years, the estimated preservation rate is 0.075–0.187. In other words, 7–19% of the storm beds would be preserved if the assumptions listed above are correct.

SUMMARY AND CONCLUSIONS

One of the basic tenets of the geological sciences is uniformitarianism. All of the evidence indicates that the climate of the past varied from that of today, but that physical, biological, and chemical processes were consistent with what is known from modern settings. As observations accumulate from the modern ocean, it is becoming possible to test the assumptions implicit in uniformitarianism with respect to processes within the coastal ocean. Observations and modelling of historical severe storms indicate initial thickness on the order of centimetres and horizontal scales of hundreds of kilometres with the thickest beds near the storm centre. These modern storm beds consist of sand layers interbedded with mud and both graded bedding and HCS have been observed. They are produced in water depths of 13–100 m and consist of mixed resuspended and transported sediment. These observations and model results are consistent with ancient storm beds. Storm beds are deposited in a dynamic environment and many of them are only temporary repositories within the marine sand sheet, especially on autochthonous shelves like the MAB. The seabed of the inner shelf and shoreface is constantly reworked to ≈10 cm by both physical and biological mechanisms. Seafloor resuspension by storms also extends to this approximate depth.

This knowledge of modern storm bed generation can be used to constrain the generation and preservation of storm beds in ancient shelf sequences. The apparent recurrence interval for storm beds within the Sowbelly parasequence from the Book Cliffs of Utah is 266 years but this is not consistent with the deposition rate and observed storm bed thickness and number from this section. This discrepancy can be physically explained by the reworking of storm beds. The preservation rate can be estimated by assuming that the storm recurrence interval is similar to modern equivalents. Thus, the preservation interval can be divided by the recurrence interval estimated from modern storm beds to find the preservation rate, which for the example given is less than 20%.

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