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## STORM DEPOSITS

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Large storms have wide-ranging effects in a spectrum of environments from outer shelves to coastal plains. The most common deposits of storms in the rock record are sandstone beds deposited under powerful near-bottom water motions produced by waves and currents. Early studies of the effects of storms on modern shelves (e.g., Hayes, 1967) sparked interest in finding analogues in the rock record. This resulted in the development of storm facies models, with particular emphasis on hummocky cross-stratification (HCS) (Walker, 1984). The origin and dynamics of the depositing flows were considered controversial (see Swift *et al.*, 1983; Walker, 1984) and initial models relied on cross-shelf transport by turbidity currents (Hamblin and Walker, 1979). Actualistic models of storm dynamics subsequently constructed by oceanographers and marine geologists largely focussed on nearly shore-parallel geostrophic currents. Duke (1990) suggested that ancient shallow-marine storm deposits (tempestites) were deposited by geostrophic combined flows and subsequent work indicates that combined flows are in fact recorded in ancient sandy tempestites (e.g., Midtgaard, 1996). However, many ancient storm-deposited sandstone beds show greater thickness and cross-shelf distribution than their modern counterparts (Leckie and Krystinik, 1989; Myrow and Southard, 1996). In addition, the time between successive beds in many deposits in the rock record may be many orders of magnitude too large to explain as a simple series of storm events.

The stratification preserved in tempestites, particularly HCS, has been studied experimentally (Arnott and Southard, 1990) and through the analysis of grain fabric (Cheel, 1991). Such studies, and those of modern shelves (e.g., Amos *et al.*, 1996), confirm that HCS forms as a result of complex oscillatory flow or combined flow (waves and currents). A wide range of vertical stratification sequences is possible within individual storm-deposited beds (Myrow and Southard, 1991). Three processes operate during storms to produce the wide range of tempestites encountered in the sedimentary record:

geostrophic currents, wave oscillations, and excess-weight forces (density-induced flow) (Myrow and Southard, 1996). The relative importance of these three processes may change during individual events and between events both within and between basins. Thus considerable variability is possible in the character of individual beds, although most beds display graded bedding and evidence for flow deceleration.

Geostrophic flows are near-shore-parallel flows that result from Coriolis deflection of water masses that are driven offshore in response to pressure gradients associated with coastal setup. Combined flows result from the superposition of storm-generated waves with these flows. Because these flows are oriented slightly obliquely offshore, instantaneous bed shear stresses in the combined-flow boundary layer show asymmetry in the offshore direction (Duke, 1990). Sediment transport results from the nonlinear addition of the two components of flow in the boundary layer, with the net result that wave oscillations are stronger in the offshore direction and thus preferentially move sediment in that direction. Whether this asymmetry in transport can account for significant cross-shelf transport is unclear. Regardless of transport mechanisms, most tempestite successions show patterns of decreased bed thickness and evidence for less powerful currents from onshore to offshore. An exception to this rule occurs in areas of nearshore sediment bypass (Myrow, 1992).

In many cases, ancient deposits contain evidence for powerful offshore-directed flow, which is at odds with deposition under combined flows. Such flow is possibly driven, at least in part, by excess-weight forces. These forces result from high suspended sediment concentrations (SSCs) near the bed. High SSCs can result from resuspension of shoreline sand by storm processes. A number of studies indicate that very high SSCs (up to 4 g/L) are produced on shorefaces and inner shelves and that this leads to powerful seaward-directed sediment-laden flows (e.g., Wright *et al.*, 1994). Plumes associated with fluvial discharge events may also produce hyperpycnal (bottom-hugging) flows, and such flows are termed oceanic floods (Wheatcroft, 2000). These could be pre-ignited with regard to autosuspension, but this is unnecessary for significant cross-shelf transport because storm

waves can provide the extra turbulence needed to maintain flow. Results of both oceanographic (e.g., Cacchione *et al.*, 1999) and modeling experiments of the northern California coast indicate that gravity driven underflows associated with ocean floods are an important factor for cross-shelf transport of fine-grained sediment. Such flows have high SSCs (up to 2.5 g/L) even at mid-shelf depths (50 m to 70 m).

The sequence-stratigraphic context of tempestites may have a strong control on their abundance, nature, and stratigraphic distribution. Transgressive to early highstand conditions may have higher accommodation space and thus greater potential for Coriolis effect to produce geostrophic flow, whereas late highstand conditions promote greater bottom friction and more offshore-directed flow (McKie, 1994). Late highstand to early lowstand systems tracts of third- or higher order sequences tend to have abundant tempestites due to mobilization of coastal sand during relative sea level fall (Einsele, 1996). Sediment supply by rivers, or *in situ* carbonate production, has a first-order control on tempestite thickness and abundance. More work is needed to better constrain the recurrence intervals of ancient deposits. Comparison of these data to those from the Modern will help to establish the degree to which actualistic models apply to the ancient.

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### Cross-references

Bedding and Internal Structures  
 Coastal and Shallow Wave-Dominated Marine Environments  
 Facies Models  
 Gutter and Gutter Casts  
 Hummocky and Swaley Cross-Stratification  
 Paleocurrent Analysis  
 Sands and Sandstones