TEMPESTITE DEPOSITION

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ABSTRACT: **A model is developed to explain the wide range of sedimentary structures found in ancient storm-deposited beds. The model predicts the nature and association of internal sedimentary structures and sole marks that correspond to various storm flow conditions. Despite recent studies that reveal the signature of ancient storms with geostrophic flow systems like those documented from the modern, nonactualistic storm processes are needed to explain the unusual thickness and wider cross-shelf distribution of ancient tempestites. Mechanisms for storm transport of sediment onto the shelf are best recorded in sole marks, which appear to show a range of predepositional conditions from purely oscillatory flow to combined flow to purely unidirectional flow. The depositional phase of tempestites is also highly variable both from bed to bed and from basin to basin, as reflected in the wide range of vertical stratification sequences in the ancient.**

Most recent authors have considered excess-weight (density-induced) forces to have been relatively unimportant in ancient storm deposition. This view results from a major leap in understanding of modern storm processes, particularly the dynamics of combined-flow bottom boundary layers, during the last 15 years. It also comes from the unsubstantiated view that because the bottom slopes and measured storm-generated near-bottom sediment concentrations of modern shelves are presumably too low for autosuspension, such forces are unimportant. Experiments on the interaction of waves and density flows define the conditions under which mixing forces destroy density stratification, and also raise the possibility that with high Richardson numbers, wave-generated shear stresses may enhance turbulence just enough to raise sediment concentrations in the boundary layer and thus facilitate transport by excess-weight forces. We also believe that excess-weight forces are potentially important for the following reasons: (1) sediment concentrations during peak storms conditions exceed 1000 mg/l on inner shelves, and may therefore be nonnegligible and important for cross-shelf transport with or without currents and waves; (2) one cannot rule out catastrophic introduction of sediment by river floods, earthquakes, or other events that caused liquefaction during ancient storm events, particularly given the significant difference in maximum thickness between ancient and modern storm-generated beds; (3) the slopes of modern continental shelves may be anomalously low as a result of Holocene sea-level rise, and therefore poor analogs for many ancient storm-influenced settings. Higher slopes may have been the norm in a wide variety of ancient tectonic settings, thus providing greater offshore-directed driving force for sediment-rich, storm-generated suspensions.

INTRODUCTION

The last decade and a half has seen the refinement of facies models for tempestite deposition, with particular emphasis on hummocky cross-stratification (HCS) (e.g., Hamblin and Walker 1979; Kreisa 1981; Dott and Bourgeois 1982; Leckie and Walker 1982; Swift et al. 1983; Craft and Bridge 1987; and many others). Considerable advances have been made in understanding the origin of HCS through experimental work (Arnott and Southard 1990) and through study of grain fabric (Cheel 1991). Detailed interpretation of the stratification of individual storm-deposited beds is still difficult, and many questions remain unanswered. These questions bear heavily on the mechanisms responsible for sediment transport across shelves. The extent to which the observations of oceanographers and marine geologists are applicable to ancient storm-deposited sandstone beds still needs to be evaluated. If ancient tempestites represent nonactualistic events, as suggested by their greater thickness and wider distribution than their modern counterparts, then explanations are required that must be grounded in plausible fluid-dynamic and sediment-transport processes. This paper presents a model for storm-deposited beds that emphasizes the range of potential storm processes and attempts to link a correspondingly wide range of sedimentary structures, including sole markings, to these processes.

DYNAMICS OF STORM FLOW

Recent advances in theoretical, experimental, and field studies in oceanography have provided a solid conceptual background and quantitative framework for understanding storm flows. Strong storm winds produce waves and surface currents. The effect of the Earth's rotation produces Ekman veering: the net transport of surface waters is approximately 90° to the wind, to the right of the wind in the Northern Hemisphere. If wind and shoreline orientations are such that surface waters are deflected landward, superelevation of the sea surface or coastal setup results. The combined effects of the resulting offshore-directed pressure gradient and the Coriolis force produces a nearly shore-parallel geostrophic current. Ignoring the important seasonal effects of temperature and salinity stratification, during storms the water column is composed of three layers: a highly turbulent upper surface layer, an effectively inviscid interior or core flow layer, and a bottom boundary layer (Fig. 1; Swift and Niedoroda 1985; Trowbridge and Nowell 1994). The geostrophic core flow moves parallel to the isobaths and exerts shear stress on the sea floor, resulting in a bottom boundary layer. The effect of bottom friction on the force balance produces offshore veering up to several tens of degrees in the bottom boundary layer (Cacchione and Drake 1990).

The bottom boundary layer, which is critical to an understanding of storm sediment transport, consists of boundary layers produced by waves and currents. It can be viewed as a thin (< 1 m) wave-dominated boundary layer nearest the bottom that exerts high instantaneous shear stresses on the bed, overlain by a thicker (up to ~ 20 m) current-dominated boundary layer. The lower part of the bottom boundary layer is actually a combined-flow boundary layer, in which waves and currents interact nonlinearly to produce bottom shear stresses higher than the sum of each component (Grant and Madsen 1979; Dyer and Soulsby 1988; Cacchione and Drake 1990). The temporal changes in orientation and magnitude of shear stresses during each oscillation in a combined flow is described by Davies et al. (1988) and Cacchione and Drake (1990, fig. 16), and is discussed later in more detail with regard to the production of sole markings.

Balance of Forces

All storm depositional models are defined in part by their dependence on one or more storm-related processes to transport of sediment out onto the shelf. Three kinds of forces can be important during storms (Fig. 2): (1) offshore pressure gradient due to coastal setup or setdown; (2) the Coriolis force, at 90° to the direction of water movement; (3) bottom friction, acting opposite to the direction of water movement; and (4) the downslope component of the excess weight of sediment-rich dispersions, here termed the "excess-weight force". The magnitude of the pressure gradient

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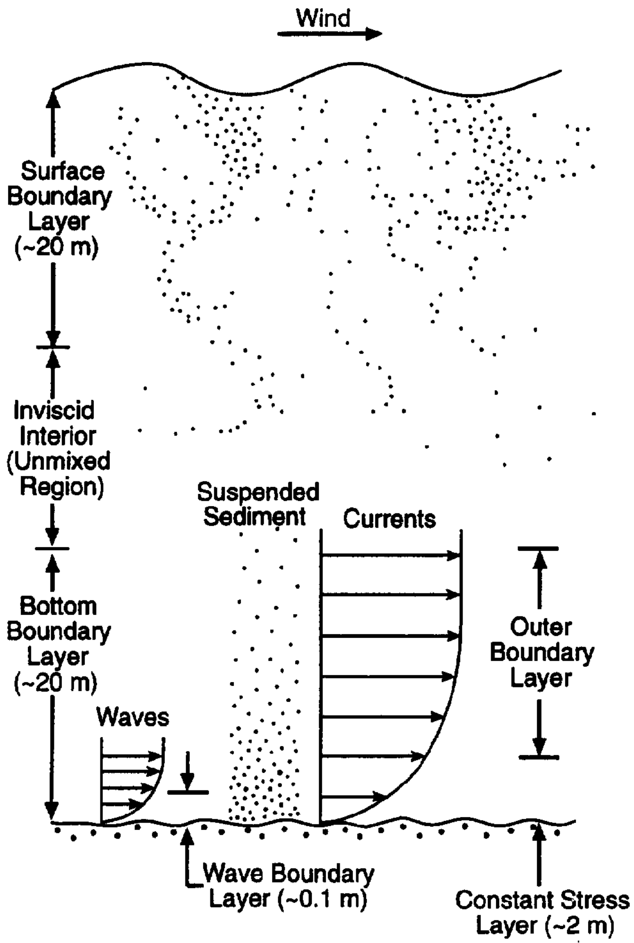

FIG. 1.—Subdivision of water column during storms into three layers: a highly turbulent upper boundary layer, an inviscid interior or core flow layer, and a bottom boundary layer. The latter consists of a thin wave-boundary layer and a thicker boundary layer produced by currents. Modified from Trowbridge and Nowell (1994).

depends upon the size of the coastal setup, which is directly related to the intensity, orientation (relative to the shoreline), and duration of the storm winds, as well as geomorphic aspects of the shoreline and shelf. The magnitude of the excess-weight force is a function of the excess weight per unit volume of the sediment suspension (relative to clear water) and the bottom slope. Given a nonnegligible bottom slope, large excess-weight forces require suspension of a considerable mass per unit volume of suspended sediment. These might develop from storm-generated waves and currents and/or from unusual events that would add large concentrations of sediment to the coastal water column.

Other things being equal, offshore transport is aided by high pressure gradient, high excess weight, and low Coriolis force. Both Coriolis force and friction force depend on velocity, but whereas Coriolis force increases as the first power of velocity, friction force increases approximately as the second power. An important consequence is that for weak flows with small driving forces (pressure gradient and excess-weight force) the friction force is small relative to the Coriolis force, but for strong flows with large driving forces, the friction force greatly exceeds Coriolis force (Fig. 2; Swift et al. 1987; Duke 1990). As a result, all other factors being equal, weaker "relaxation" currents—those that result from coastal setup—should be nearly shore-parallel, whereas stronger relaxation currents should be directed at a larger offshore angle.

STORM DEPOSITIONAL MODELS

Early storm depositional models derived from the study of ancient deposits focused on excess-weight forces, because many ancient storm deposits closely resemble turbidites (Hamblin and Walker 1979; Wright and Walker 1981; Leckie and Walker 1982; Walker 1984) and because the bulk of ancient deposits indicate sediment transport nearly perpendicular to shore for long distances (see Leckie and Krystinik 1989). Implicit in this model is the need to mobilize large quantities of sand at the shoreline to create dense suspensions upon which gravity acts in the downslope (offshore) direction. Such processes would be nonactualistic and record very rare storm events (recurrence intervals of tens of thousands of years), presumably significantly different, quantitatively if not qualitatively, from those studied in the modern oceans. Evidence cited for shelf turbidity currents includes storm sand transport more than 100 km offshore, and high velocities (> 1 m/s) at these great distances from shore (Walker 1984; Brenchley 1985; Leckie and Krystinik 1989). Additionally, many workers have concluded, from case studies, that strong unidirectional flow dominated the erosional and initial depositional flow conditions of tempestite beds (Walker 1984; Craft and Bridge 1987; Myrow 1992a, 1992b). Finally, the lower facies in some upward-shoaling storm-influenced deposits consist

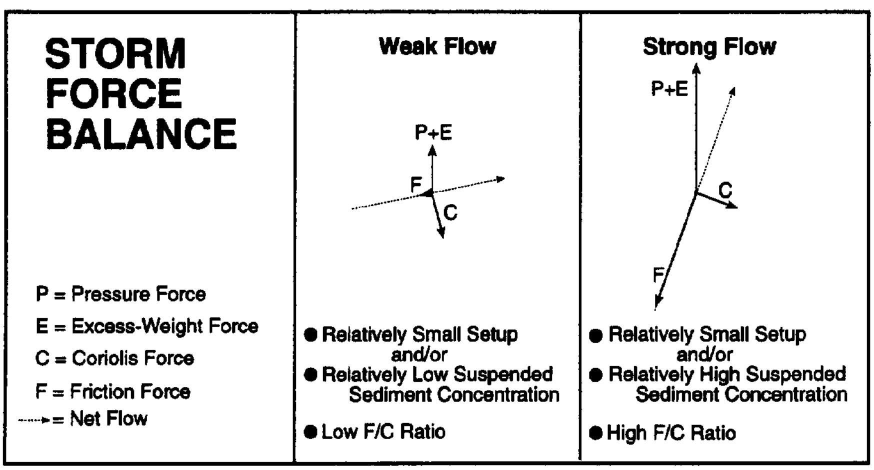

FIG. 2.—Balance of forces during storms. Shoreline is oriented from left to right with offshore towards top of page.

of turbidite-like beds with flutes and asymmetrical ripples (e.g., Hamblin and Walker 1979).

This view of storm deposition has been criticized by oceanographers who emphasize that modern storms generate geostrophic bottom flows (Swift et al. 1986; Snedden et al. 1988) that form when currents created by pressure gradients associated with coastal setup or setdown are deflected into a nearly shore-parallel orientation by the Coriolis force. Two aspects of ancient tempestites need explanation with regard to their origin from geostrophic flows: (1) only a handful of ancient examples exist in which paleocurrents from tempestites are oriented parallel to shore (Nøttvedt and Kreisa 1987; Snedden and Swift 1991; Winn 1991), and (2) there is an apparent inability to transport sediment at great distance offshore at high velocities.

Duke (1990) and Duke et al. (1991) have tried to resolve some of these problems by suggesting that ancient deposits were formed—similarly to modern storm deposits—under combined flows in which storm waves are superimposed on a geostrophic current oriented at a low angle to shore. They believe that the paleocurrent indicators reflect the direction of maximum instantaneous shear stress in the thin boundary layer created by the oscillatory-flow component of the combined flow. The net addition of the offshore component of force of the geostrophic current to the storm waves during their seaward stroke results in an asymmetry of shear stress (Davies et al. 1988; Snedden et al. 1988; Cacchione and Drake 1990; Cacchione et al. 1994), supposedly yielding offshore sediment transport and unimodal sole marks. Outcrop and grain-fabric studies indicate that combined flows were important in deposition of some examples of storm-deposited hummocky cross-stratification, but several questions still linger with regard to the universal applicability of this model.

First, experimental work (Arnott and Southard 1990) and grain-fabric analysis (Cheel 1991) suggest that isotropic HCS, which is common in the rock record, is formed by purely oscillatory flows or oscillation-dominated combined flows. The existence of thick storm deposits with such stratification places strong constraints on all storm depositional models, including those that rest mainly on combined flow. Specifically, it requires storms to transport large volumes of sand considerable distances across shelves and then deposit the sand under the influence of oscillatory or oscillation-dominated combined flows.

If one believes that in most cases ancient tempestites were deposited in single episodes, then transport by combined flow across a shelf might be accomplished by differential offshore-directed mass transport during passage of individual waves. In other words, individual grains would mainly move back and forth under the more powerful influence of waves but would be translated farther during seaward-oriented wave strokes because of the added offshore component of the geostrophic flow. Bed shear stress is greater during the offshore-directed part of the oscillation wave cycle, so net transport of sand is obliquely offshore (see Cacchione et al. 1994, fig. 7). Settling lag effects would enhance this asymmetry of transport. It is unlikely, however, that this mechanism can account for both the volume and distance of transport of sediment necessary to explain ancient deposits.

Deposition of thick beds with *isotropic* HCS is difficult to explain by any mechanism. This requires rapid deposition of a large volume of sand to be transported to the site of deposition, presumably with a component of unidirectional flow, and a subsequent rapid deceleration of the unidirectional flow component to allow for reworking during deposition of the suspended sediment load by complex oscillatory flow or oscillation-dominated combined flow. This deceleration could be "hidden" in the lower, parallel-laminated parts of some storm-generated sandstone beds. In this case, the oscillatory component of the progressively more oscillation-dominated flow would alone be strong enough to maintain upper-plane-bed conditions during this stage.

An alternative to considerable cross-shelf transport in single events would involve incremental sand transport by a succession of storms (Swift et al. 1983; Brenchley et al. 1990; Brenchley et al. 1993), in which case the stratification preserved in tempestites would record either the latest stage of storm deposition or any number of earlier stages. In many cases, lateral tracing of thick hummocky cross-stratified "beds" reveal that they consist of many amalgamated beds (Brenchley et al. 1990; Summa 1993), although it is still unclear whether this is true of most thick tempestites in the rock record; more tracing of individual storm-deposited beds laterally in outcrop is needed to resolve this. In any case, the unusual thickness and considerably greater cross-shelf distribution of ancient deposits, relative to modern deposits, suggests that some aspects of ancient storm deposition are nonactualistic.

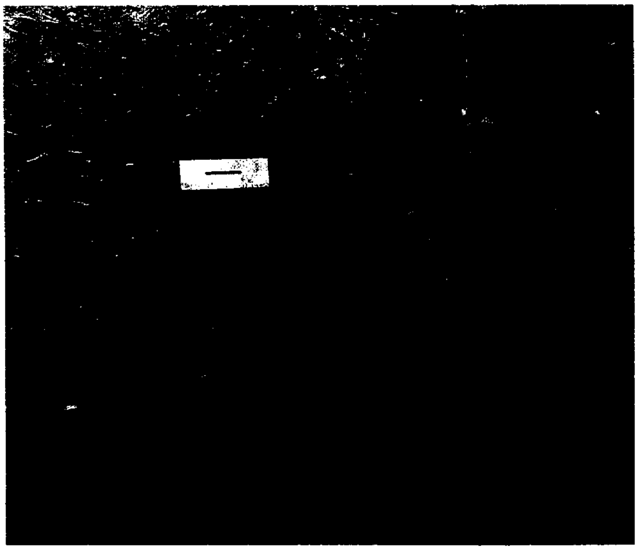

FIG. 3.—V-shaped sole marking with one curved arm and one straight arm from the Proterozoic Vingerbreek Formation, Nama Group, Namibia. Associated prod marks show polymodal orientations. Scale is 1 cm.

Tests of the various models of storm transport and deposition are difficult to construct, but these will probably rest on detailed studies of individual well-exposed and extensive storm-deposited beds, particularly along cross-shelf transects. Sole markings of storm-generated sandstone beds have received considerably less attention than internal stratification. These sole markings, which include a wide variety of current- and tool-formed structures, hold special potential for testing of many of the hypotheses concerning the importance of particular storm depositional processes. Such sole marks are analyzed below, with emphasis on hydrodynamic interpretation.

SOLE MARKS

The hydrodynamic interpretation of sole marks is of prime importance for reconstructing the process of sediment transport onto shelves. Most sole marks on tempestite beds appear to be linear grooves, various tool markings including prod marks, and flutes. Bidirectional and multidirectional orientations of prod and groove marks (Benton and Gray 1981; Bloos 1976; Duke 1990) have been used to indicate the importance of waves, and possibly combined flows.

Recent work by Martel and Gibling (1994) and Beukes (1996) reveals a poorly understood class of sole marks that presumably were formed by combined flows. These U-shaped, V-shaped (Fig. 3), and quasi-sinusoidal sole marks imply that in some cases the earliest stage of tempestite deposition is by combined flow. Are these poorly recognized features common in the rock record, or are they rare and hence record unusual conditions? A wide spectrum of initial conditions are theoretically possible for storms, defined largely by the velocities, orientations, and relative strengths of the unidirectional and oscillatory flow components (Myrow and Southard 1991). In addition, the time history of each component may be irregular,

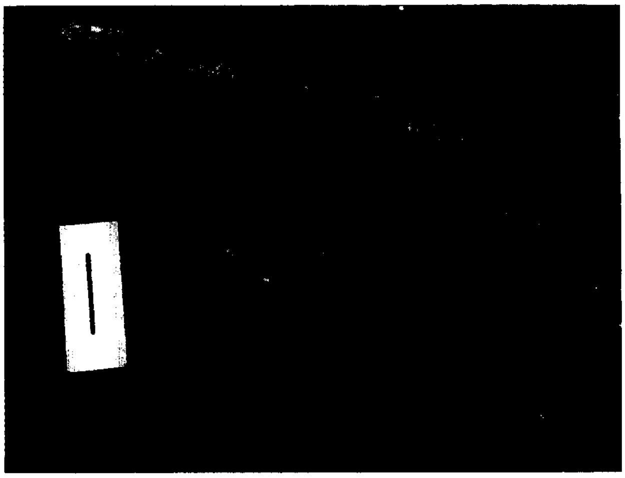

FIG. 4.—Cast of current crescent from base of tempestite in member 2 of the Precambrian–Cambrian Chapel Island Formation, southeast Newfoundland. Pebble obstacle is preserved in specimen; flow is to upper right. Scale is 1 cm.

so that in combination with varying extent of bed-configuration disequilibrium, the depositional record of storm flows is potentially highly variable. Of particular interest with regard to sole markings is the degree to which the early erosional phase of storms may be highly variable with regard to flow components from storm to storm and/or basin to basin.

Clearly there are features that, if present, are diagnostic of oscillatory or combined flow, but are there features that are diagnostic of unidirectional flow? Potential structures include sinuous gutter casts with helical grooves, pot casts with snail-like geometries, and flutes (Myrow 1992b). Current crescents are additional unidirectional-flow features found in tempestites (Fig. 4; Myrow 1987), albeit rarely. Despite claims to the contrary (e.g., Seilacher and Aigner 1991, p. 253), flutes are present and sometimes abundant in some ancient storm-influenced deposits (e.g., Hamblin and Walker 1979; Leckie and Krystinik 1989, fig. 2a; Myrow 1992a, fig. 8). In these cases they show generally unimodal orientations (Fig. 5). We know of no examples of sole markings with bidirectional or multidirectional flutes. Myrow (1992b, 1994) emphasized the wide range of geometries, paleoenvironments, and possible modes of origin of pot casts and gutter casts. Many geometries of gutter casts are compatible with formation by waves, and examples exist with bimodal prod marks, attesting to either oscillatory flow or combined flow. However, analysis of pot casts and sinuous gutter casts associated with tempestites bearing flute marks indicates formation by storm-generated flows in which the early stages were dominated by unidirectional flow. It has never been shown experimentally that flute marks, sinuous gutter casts, or pot casts can form under oscillatory or combined flows. Additionally, generation of these features, particularly flutes, by combined flows would have to take place under considerably limiting conditions, defining the "erosional window" problem.

The Erosional Window Problem

According to Duke (1990) and Duke at al. (1991), sole marks, including flutes, are formed during periods of maximum bed shear stress associated with the offshore-directed stroke of each passing storm wave in a combined flow. A secondary peak in bed shear stress occurs during the onshore-directed stroke (Duke 1990; Davies et al. 1988; Cacchione et al. 1994). Therefore, the formation and preservation of current-generated, directionally oriented structures (e.g., flutes) under combined flows requires considerable asymmetry between the offshore- and onshore-directed peak shear stresses of each passing wave so that weaker onshore-directed flows do not cause erosion. As Myrow (1992b, p. 1005) pointed out, "This is a considerable constraint, given that current-eroded structures that would form during each offshore-directed stroke would have a hydrodynamically smooth shape (e.g., flutes or potholes) that would be in equilibrium with this component of flow. Such structures would likely be deformed or eliminated with landward-directed flow on alternate wave oscillations under significantly lower shear stresses than those needed to produce the flute". As a result, there is a "window" of shear stresses allowable for the creation of features such as flutes under combined flows (Fig. 6). Maximum offshore-directed shear stresses must exceed the critical shear stress for the underlying sediment, but the maximum onshore-directed shear stresses of alternate oscillations must not exceed the critical shear stress for erosion (or partial erosion) of structures with a form in hydrodynamic equilibrium with flow oriented directly offshore. More powerful waves cause both greater onshore- and offshore-directed maximum shear stresses (Davies et al. 1988). Therefore, in order to keep the peak onshore-directed flow from causing erosion, the unidirectional component of flow must be very rapid

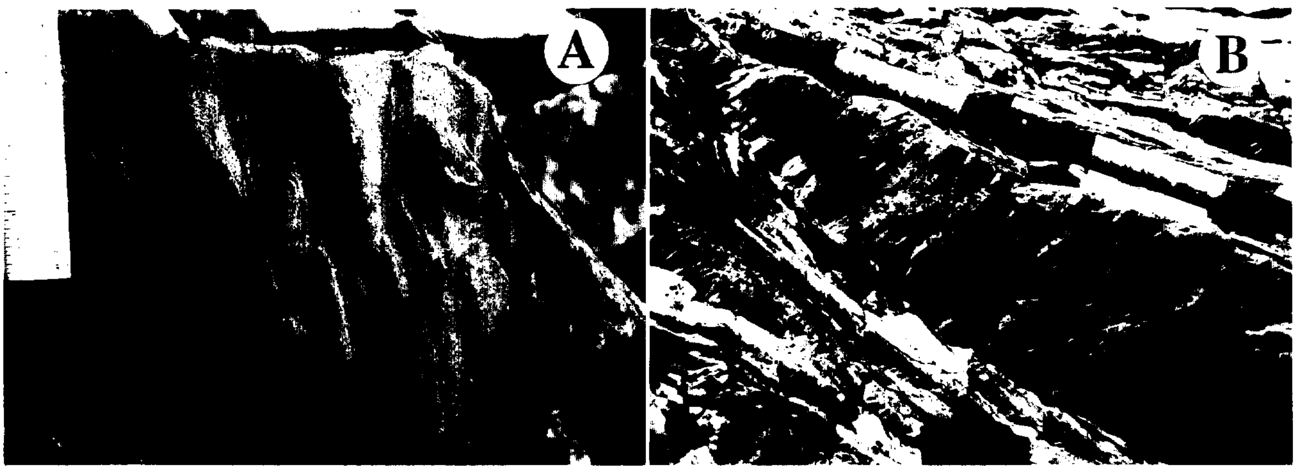

FIG. 5.—Flute marks from shallow marine storm-influenced deposits. **A**) Well-developed flute marks from the Kliphoek Member of the Dabis Formation (Nama Group), Aar Farm, Namibia. Scale is in centimeters. **B**) Elongate well-oriented flutes from sole of shallow subtidal tempestite member 2 of the Precambrian–Cambrian Chapel Island Formation, southeast Newfoundland. Divisions of Jacob's staff 10 cm.

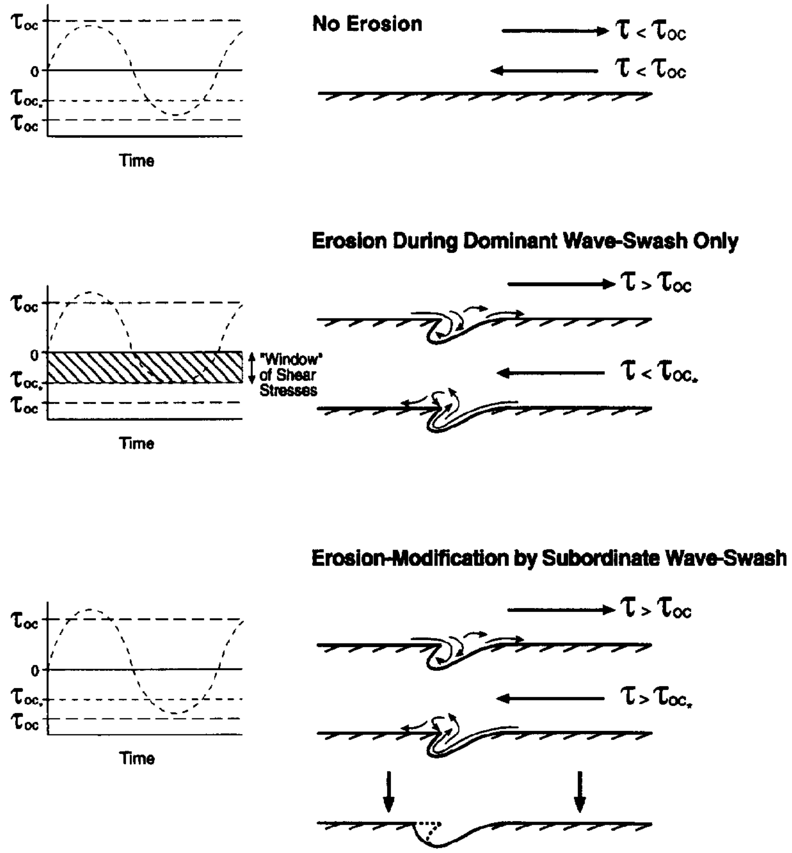

FIG. 6.—Erosional Window Problem. In the first case, shear stresses associated with onshore and offshore wave swashes are equal and below that critical for erosion ($\tau_0 c$). In the second case, shear stresses exceed $\tau_0 c$ during a dominant wave swash (e.g., offshore stroke when waves are enhanced by offshore component of geostrophic flow) causing erosion (e.g., flute mark), but weaker wave swash does not exceed $\tau_0 c$ or even $\tau_0 c^*$, the shear stress needed to cause erosion of the sculpted sea surface in equilibrium with the dominant wave swash. The last case shows erosion during both wave swashes. The shear stresses exceed $\tau_0 c$ during a dominant wave swash only, but exceed $\tau_{oc}{}^*$ during the subordinate wave swash so erosional modification of the flute mark occurs.

and/or highly oblique to the shoreline, or the combined flow must be such that the offshore-directed maximum shear stresses only *minimally* exceed the critical shear stress of the underlying sediment.

ROLE OF DENSITY MODIFICATION

For most ancient storm-influenced nearshore and shelf deposits, water depth is only generally constrained, and typically such constraint comes from a combination of facies distributions, paleohydraulic interpretations of sedimentary structures, and the thickness and nature of facies transitions. Notwithstanding, it is readily apparent from study of ancient tempestites that beds several tens of centimeters thick were commonly deposited in at least several tens of meters water depth.

Modern oceanographic studies indicate that during storms suspended sediment is not evenly distributed throughout the water column but is concentrated in the bottom boundary layer, especially in the wave boundary layer (Trowbridge and Nowell 1994; Wiberg et al. 1994). If vertical gradients of sediment concentration were strong during ancient storms, then the importance of excess-weight forces may not be negligible. Several experimental studies of the effects of wave-generated turbulence on a density current have attempted to define and quantify the effects of boundary mixing and predict the conditions under which flows are transformed from purely gravity currents to ones dominated by turbulent diffusion. Diffusion of a gravity-driven dispersion into overlying ambient fluid, and ultimately the degree to which turbidity currents lose character, can be modeled with the Richardson Number Ri, which relates inertial forces to mixing forces (Fischer et al. 1979; Noh and Fernando 1992): $\mathrm{Ri} = B_m h^*(\cos\theta)/s^2$, where B_m is the maximum buoyancy of the cloud, h^* is the maximum thickness of the buoyant cloud, θ is the angle of the sloping bed, and s is the root mean square (rms) of the background turbulent velocity fluctuations. A consequence of this equation is that although the gentle bottom slopes typical of modern shelves hinder generation of turbidity currents, the gentle slopes hinder turbulent diffusion of wave-modified turbidity currents once the currents are set in motion. Growth of a turbulent cloud under the influence of waves results from turbulent diffusion across the upper surface of the flow: $h^* = (Kt)^{1/2}$, where K is the eddy diffusivity near the boundary and t is time (Fischer et al. 1979). Turbulent diffusion can be related to wave parameters and bed geometry through the equation $K = C_1 fSd$ (Phillips et al. 1986; Noh and Fernando 1992), where C_1 is a constant, f is the wave frequency, S is the orbital diameter of the wave oscillations, and d is the size of the roughness elements.

A variety of experimental approaches have been used to study boundary mixing in gravity flows in the presence of background turbulence, mainly using saline gravity currents. In these studies, background turbulence was generated by vertically oscillating mesh grids (Simpson 1987; Thomas and Simpson 1985), bubbling of gas from below the flow (Linden and Simpson 1986), and oscillation of beds with roughness elements (Phillips et al. 1986; Noh and Fernando 1992). A nondimensional measure of turbulence under these conditions is given by the ratio of the rms wave-induced velocity fluctuation U' to the velocity U of the density-current head. Thomas and Simpson (1985, fig. 6) showed that when $U'/U < 0.05$ the mixing rate is nearly identical to that of a standard gravity current, and when $U'/U > 0.5$ the mixing rate is determined by eddies generated by background turbulence and is independent of flow speed. These experimental results, from a horizontal flume, were replicated on an inclined plane by Noh and Fernando (1991). Boundary mixing was shown to decrease the velocity of density current heads and the density of the buoyant clouds in both saline solutions (Thomas and Simpson 1985; Simpson 1987) and sediment suspensions (Noh and Fernando 1992).

It is unclear, however, how the experimental results described above apply to the conditions of a hypothetical shelf turbidity current with superimposed background turbulence generated by wind-generated gravity waves. Problems include: (1) the applicability of saline solution experiments, which are free of natural complications such as changing suspension densities that result from particle entrainment and settling; (2) the artificial manner of introducing background turbulence; and (3) the unnatural slopes involved, which were generally too low (0°, Simpson 1987; Linden and Simpson 1986) or much too large (9.4°, Phillips et al. 1985; 24°, Noh and Fernando 1992).

Semiquantitative experimental studies on ocean disposal of fly ash by Foster and Stone (1963) suggest that for wave energy less than that for diffusion throughout the water column, turbulence added by waves tends to enhance turbidity-current flow. The carrying power and lateral persistence of ash slurries along a sloping bed in a flume 36.6 m long were increased by the superposition of shallow-water waves relative to runs in still water. They suggested that the turbulence added by waves reduces deposition from suspension, and thus maintains elevated density and hence driving force. In addition, they noted that at low to moderate wave intensities, the layer of interfacial mixing at the top of the turbidity current was not thicker than in similar runs in still water, but that the boundary between this layer and the clear fluid above was much sharper and was relatively planar. This was attributed to destruction of macroscopic vortices by turbulence generated by the waves. Lack of published data from these experiments makes it difficult to compare their results with other studies of the interaction of waves and turbidity currents. The speed of the turbidity current (0.03 m/s), and the grain size (silt) and density (1.5–2.35 g/cm^3; mean = 2.0 g/cm^3) of the sediment in the experiments were lower (particularly the speed) than those that, from field evidence, would have characterized flows on ancient shelves. As mentioned above, many of the controlling parameters in better documented experimental studies are extreme relative to geologically feasible conditions. There is therefore great need for rigorous experiments on turbidity currents and wave-generated turbulence under conditions comparable to those expected under natural conditions, aimed at determining whether hypothetical shelf turbidity currents would generally be destroyed by boundary mixing or whether they would actually be enhanced by added turbulence.

Swift (1985) has argued against the existence of shelf turbidites, on the basis of the conditions necessary for autosuspension and on the feasibility of mechanisms to generate such flows. As he correctly points out, the threshold sediment concentrations for autosuspension—about 1000 mg/l (Middleton 1966; Lowe 1982)—are generally higher than concentrations measured in modern geostrophic flows (50–150 mg/l; Swift 1985, table 3), and the slopes on modern shelves are so low that ignition is unlikely. However, peak storm concentrations on inner shelves do exceed 1000 mg/l (Madsen et al. 1993), and even at sediment concentrations and bottom slopes smaller than necessary for turbidity-current autosuspension, excess-weight forces may be important in cross-shelf transport of sediment in tandem with storm-generated currents and waves. In addition, the possibility exists that sediment concentrations in ancient storm events were significantly higher than those measured in modern environments in which most of the suspension is produced only by resuspension by storm waves and currents (e.g., Clark et al. 1982; Wiberg et al. 1994). Catastrophic introduction of sediment by river floods, earthquakes, or other liquefaction events, although not documented at the scale necessary to explain the thickness and extent of many ancient tempestites, is still potentially important geologically. In addition, the equilibrium slopes of many ancient continental shelves may have been much higher than those of modern shelves, which strongly reflect the influence of Holocene sea-level rise. This would be particularly true for ancient active tectonic settings such as foreland basins and other collisional margins.

PREDICTIVE MODEL OF TEMPESTITE SOLE MARKS AND STRATIFICATION

Early models for ancient tempestites were based on deposition from turbidity currents (e.g., Hamblin and Walker 1979), whereas more recent studies have appealed to combinations of storm waves and geostrophic flows (e.g., Midtgaard 1996). Emphasis on one process over another may be stifling a greater appreciation of the complexity of storm processes from event to event and from basin to basin. We believe that the potential multiplicity of storm processes has been lost, in part, through advocacy of particular depositional models at the expense of others. The following is a predictive model for the origin of tempestite features, particularly sole markings, within a framework of possible combinations of storm processes.

A range of possible processes, and magnitudes of processes, may be involved in any particular storm. In a simplified way, the spectrum of possibilities can be shown using a triangular diagram (Fig. 7) in which the three corners represent the following processes: (1) geostrophic currents, (2) wave oscillations, and (3) density-induced flow. Stratification in storm deposits was modeled by Myrow and Southard (1991) for a full range of combined flows between purely unidirectional and oscillatory end members. They emphasized the potential variability in initial storm conditions and the time history of each flow component. Adding a third component, density-induced flow, makes the potential history of a storm event, and resulting deposits, even more variable. Understanding of the stability of various bed configurations under simple combined flows is not well known (Arnott and Southard 1990), and virtually nothing is known about the three-part system involving density flows. A further complication concerns the origin of suspended sediment responsible for the excess-weight forces. For clarity in the ensuing discussion, we distinguish between sediment-equilibrium cases, in which all of the sediment in suspension is in equilibrium with the waves and currents acting at and near the bed, and sediment-disequilibrium cases, in which excess suspended sediment results from unusual events or processes (discussed in a later section) that are unrelated to, or only secondarily derived from, typical storm processes. The distinctiveness of the end member for density-induced flow in Figure 7 becomes blurred as waves and/or currents act to suspend sediment and thus generate all (in the sediment equilibrium case) or part (in the sediment disequilibrium case) of the gravity force.

Initial bottom-flow conditions at any location during a hypothetical storm can be plotted as a point in Figure 7, and any curve representing the temporal evolution of a storm flow can be drawn through the diagram with time as a parameter. Since even simplistic bed-configuration stability diagrams do not exist for the three-part system shown in Figure 7, and because of the extremely large combination of mean velocities and orientations of the components, even a first-order discussion of the range of vertical stratification sequences would be difficult. Representative vertical stratification sequences are provided in Figure 7 simply to guide discussion of the range of potential features reasonable under the general conditions of each flow region.

Purely Density-Induced Flow

One end-member case in Figure 7 represents purely turbidity-current flow. The viability of shelf turbidity currents has been dismissed mainly because of the generally low slopes of continental shelves and the difficulty of rapidly entraining large volumes of sediment. Bottom slopes are such that autosuspension (Bagnold 1962, 1963) and development of self-sustaining turbidity currents (Pantin 1979; Parker 1982) is unlikely (Swift 1985), but sediment gravity flows, especially those without a yield strength such as turbidites and liquefied flows, can flow on extremely low slopes. In addition, in many inner-shelf settings, particularly those associated with large marine deltas, slopes are steeper than are typical for shelves.

A pure turbidity current on a shelf would represent the most extreme disequilibrium condition (described earlier), in which none of the sediment in suspension is derived from the action of waves and currents. Such con-

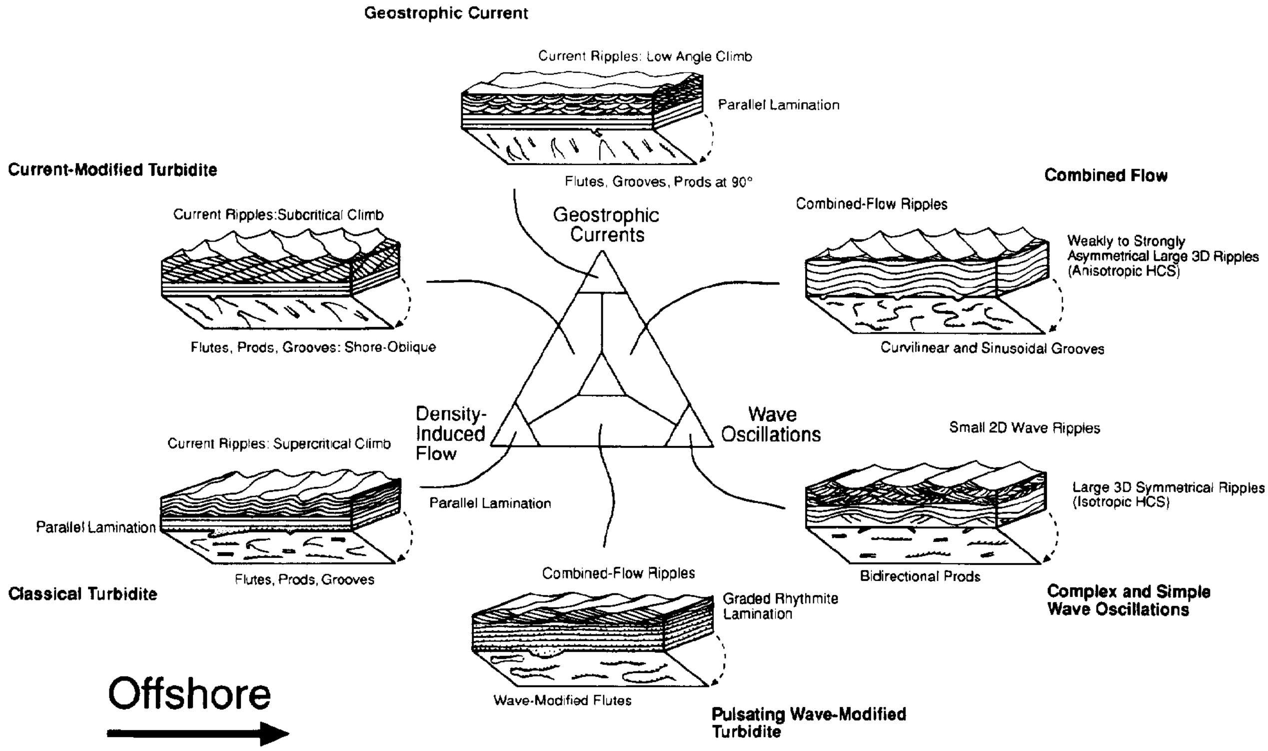

FIG. 7.—Predictive model of the origin of stratification and sole markings for various possible combinations of storm processes. The triangular diagram has three corners representing density-induced flow due to excess-weight forces, geostrophic currents, and wave oscillations.

straint essentially defines non-storm conditions, however. The only possibility for generating storm-related shelf turbidity currents in the absence of waves and currents might be in deltas where river floods debouch directly into the ocean (see Higgs 1990). This would require the flood water to be very dense and/or cold to sink below ocean water and thus provide a strong offshore-directed gravity force. Lack of waves and currents is not common in the modern; most rivers, even those with high sediment concentrations, form dense buoyant plumes. Settling of sediment from these plumes into the underlying sea water would enhance the density stratification produced by the salinity contrast and produce a gravity-driven underflow, but Swift (1985) argues that such currents are not dense enough to form strong turbidity currents and are not observed in the modern. Nonetheless, if we assume that powerful density currents are possible from river discharge, then absence of waves and currents would require a time lag between the storm and the sea state it produces, and on the other hand, discharge of the bulk of runoff generated by the storm in the watershed. Cacchione and Drake (1990, their fig. 8) documented such a time lag for the Russian River in Northern California, although in that case there was some overlap in time between the decaying sea state and the arrival of fluvial suspended sediment.

If the conditions imposed by the need for high shelf gradients, high sediment concentrations, and time lags between waves/currents and density flows are met, then the features of the deposits of such flows, including sole marks and internal stratification, would be essentially identical to classical turbidites at the outcrop scale.

Density-Induced Flow and Wave Oscillations

Discussions of the existence of shelf turbidites have generally neglected the effect of waves. As discussed earlier, superposition of wave-generated oscillatory flow on a turbidity current may have a range of effects. At modest levels, wave-generated shear stresses may enhance the natural turbulence of the density flow, thus facilitating turbidity-current transport. At low Richardson numbers, elevated turbulence causes a breakdown of the turbidity current and suspension of sediment through a large part of the water column (Noh and Fernando 1992).

Walker (1984) suggested that liquefaction of a shoreface, or other source of sand at a shoreline, due to cyclic wave loading, would hold potential to rapidly suspend large volumes of sediment, thus leading to a shelf turbidity current superimposed by waves. Catastrophic failure of sandy shoreline environments along retrogradational slides have been described from modern fjords (Andresen and Bjerrum 1967). The lack of storm-generated currents in these conditions would occur in locations along the shelf, and at times during storms, in which the relationship between the orientation of storm winds and shoreline are such that surface currents do not produce coastal setup and geostrophic flow. Such conditions would also form under shore-parallel winds in equatorial regions (see "Wave Oscillation" section below). Although sediment failures of the scale required to explain the thickness and distribution of many ancient tempestites are not documented for modern storm-influenced shorelines, nonactualistic large-scale events are both plausible, and in agreement with, estimates of recurrence intervals of thousands to tens of thousands of years from ancient deposits (Walker 1984, table 2; Einsele 1993, fig. 13).

Storm beds deposited in the flow field corresponding to a combination of density-induced flow and wave oscillations (Fig. 7) might range from those essentially identical to classical turbidites to those showing strong influence of waves. Internal stratification might range from classic Bouma sequences to anisotropic HCS formed from large, asymmetric three-dimensional (3D) dunes. Wave superposition on a turbidity current could cause considerable pulsation of the flow, which might be expressed as graded lamination within parallel or (anisotropic) hummocky lamination. Some types of graded rhythmites (Gadow and Reineck 1969; Reineck and Singh 1972, 1980; Dott and Bourgeois 1982; Myrow 1992a, fig. 6) may also result from pulsation of turbidity currents, with the overall grading representing long-term deceleration of the turbidity-current component of flow, and the individual graded laminae reflecting the periodic accelerations and decelerations induced by waves. Clearly the number of graded laminae in graded rhythmites cannot reflect deposition from each individual wave oscillation in a storm. Individual laminae might instead represent deposition during particularly powerful wave oscillations that were followed by one or more abnormally weak ones, defining episodic aggradation events. Sole marks of beds formed in the wave/turbidity current field might range from well-formed flutes, grooves, and prods with unimodal downstream orientations, to wave-modified sole marks and, towards the wave-oscillation corner, minor upstream-oriented prod marks.

Density-Induced Flow and Geostrophic Currents

Coastal superelevation of the sea surface, which produces geostrophic flows, is generally accompanied by waves. Geostrophic currents move along the entire width of shelves in some instances (Beardsley and Butman 1974) and hence may affect regions of the outer shelf below storm wave base, or where storm waves have little effect on sedimentation. The combination of density-induced flow and geostrophic currents would probably require nonequilibrium introduction of sediment, because it is not likely that the shear stresses associated with a geostrophic current in the absence of waves could generate suspended sediment concentrations large enough for significant excess-weight forces, especially far offshore of the shoreface zone of active downwelling.

Deposits from this flow region (Fig. 7) would not differ significantly from those of a classical turbidite in that the addition of a geostrophic current would change only the orientation of the density-induced flow, not the nature of the flow itself. The difference in orientation would be reflected in the orientation of sole marks and bed-form migration directions as preserved in cross-stratification and form sets.

Geostrophic Flows

Storms generate a variety of ocean currents, including wind-driven currents, storm-surge ebb currents, rip currents, and geostrophic currents. Although storm-surge ebb currents have been suggested as the mechanism of deposition of some ancient deposits (e.g., Mount 1982), and are locally quite strong (Drake et al. 1980; Flather and Proctor 1983), these evolve into shore-parallel geostrophic shelf currents (Swift et al. 1986). Steady-state geostrophic flows are the only kind of ocean current that might account for the vast majority of ancient sandy tempestites. Because of the abundance of shore-perpendicular paleocurrents, it has been argued that without wave oscillation effects (Duke 1990) these could not transport sediment to any great distance away from shore (Leckie and Krystinik 1989). In most instances geostrophic currents would coexist with storm waves, but we would predict that, considered separately, such flows would accelerate and decelerate more slowly than turbidity currents. The internal structure of beds in this field would be more uniform and weaker normal size grading. Slower deceleration would lessen the flux of sediment to the bed, so that climbing-ripple stratification, a common feature in turbidites, would be absent or show a low angle of climb. Bottom scour would probably be minimal and hence sole marks might be poorly developed. If well-developed, they would be nearly parallel to shore, with slight offshore orientation due to Ekman veering in the bottom boundary layer.

Geostrophic Currents and Wave Oscillations

Many studies in both the modern and the ancient have speculated on the sedimentological effects and products of combined flows, in particular the combination of high-frequency storm-generated waves and wind-driven geostrophic flows. As with wave-modified turbidity currents, the combination of intense, short-term, wave-produced boundary shear stresses on the mean-flow boundary layer causes greater eddy diffusion (Vincent et al. 1982) and increased suspended load (Grant and Madsen 1979).

Hummocky and swaly bed configurations in shelf (Swift et al. 1983) and shoreline (Greenwood and Sherman 1986) environments have been interpreted as combined-flow features. Probable ancient analogs are slightly asymmetrical 3D hummocky beds (e.g., Nøttvedt and Kreisa 1987). Such bed configurations probably form under conditions of relatively weak current speeds relative to wave orbital speeds (Arnott and Southard 1990). Internal stratification of beds formed under combined-flow conditions might range from highly to slightly anisotropic HCS, corresponding to strongly asymmetrical large 3D dunes (current-dominated combined flows) to weakly asymmetrical large 3D dunes (oscillation-dominated combined flows).

Sole markings formed under combined flows might reflect all or part of regular to irregular curvilinear tool motions (Martel and Gibling 1994; Beukes 1996). A number of factors, such as substrate consistency, size and shape of tools, and temporal changes in the speed and orientation of near-bottom flow during full wave cycles, may result in formation of tool marks (mainly prods and grooves) only during the peak shear stresses of the offshore-directed wave strokes (Duke 1990). In this case, mostly unimodal tool-mark orientations would be produced, and if current-generated erosional structures such as flutes are formed, these should contain evidence for modification by waves.

Wave Oscillations

Depending on shoreline orientation, directions of movement of storm tracks and associated winds, and other factors, coastal setup and setdown may not develop and as a result no geostrophic currents are generated. In such areas, wind-driven waves and long-period swell would impinge on the sea floor with little or no superposition by currents. Near the Equator the Coriolis effect is too weak to produce geostrophic flow, so in this region storm-generated currents may be unimportant relative to storm-wave processes. Of course, downwelling currents that result from coastal setup (relaxation currents) can still form at the Equator if winds are nearly perpendicular to shore, so purely wave-influenced storm events require shore-parallel winds. It might be argued that since relaxation currents do not tend to become parallel to shore near the Equator, they are weaker than their geostrophic counterparts. The offshore-directed pressure gradient is directly and efficiently relieved in these cases, whereas at higher latitudes the offshore transport of water consequent upon coastal setup is accommodated by continuous shore-oblique offshore "leakage" near the bottom from requisitely more rapid, dominantly shore-parallel flow. In terms of the geologic record, it should be noted that in equatorial regions (doldrums) large-scale storms with regionally strong winds are rare.

Internal structures of storm beds formed solely under oscillatory flow would probably include one or more of the following: planar lamination, isotropic HCS, and small-scale 2D and 3D ripple stratification (see Myrow and Southard 1991, fig. 6). Sole markings on such beds would contain grooves and prods showing bimodal or polymodal orientations depending on whether the directional spectrum of bottom oscillatory flow is narrow or broad, respectively.

Center Triangle

The flow field corresponding to subequal effects of density-induced flow, geostrophic currents, and wave oscillations may represent the flow conditions under which many ancient tempestites were deposited. Such a wide range of features are possible that we refrain from presenting a representative deposit in Figure 7. Certainly in nonequatorial regions geostrophic currents and wave oscillations are an almost certain result of coastal storms.

It is unclear whether, for large storms with sediment-equilibrium conditions, suspended sediment concentration is commonly sufficient to generate significant excess-weight forces. Data on sediment concentration gradients on shelves during large storms are sorely needed. Obviously, processes that lead to sediment-disequilibrium conditions will alter flow conditions such that storms that initially plot in the combined-flow region in Figure 7 shift into the center triangle.

The combined effects of a geostrophic current and excess-weight forces would be a single flow whose magnitude and orientation would be represented by the vectorial addition of each component, probably at an intermediate angle away from shore. Addition of waves to such a current would probably produce strongly asymmetric hummocky bed forms at intermediate to high velocities. The stratification of a bed deposited in the center triangle would probably be similar to that in the combined-flow field, but the dune-scale stratification would reflect even more asymmetric bed-form geometries and evidence throughout the bed for higher sedimentation rates (e.g., higher angles of climb of bed forms). Sole markings in these conditions might be intermediate between pure end-member density-induced flow and combined density-induced–wave-oscillation flow, namely mildly modified flutes and grooves. The oblique orientations of the combined DIF-GC flow component and the wave trains, assuming the very simplest case of uniform shore-parallel refracted waves, might produce asymmetries in the wave-modifying patterns of current- and tool-formed features such as grooves and flutes. Such asymmetries in the wave modifications might be useful for reconstructing ancient wave-approach orientations. The curvilinear grooves presumably produced by combined flows might also be possible in the center triangle. However, the more powerful combination of density-induced flow and geostrophic currents would probably overpower wave effects, so that the curvilinear pattern might be highly asymmetric, in which case once again the wave approach might be discernible from an ancient storm bed.

DISCUSSION OF MODEL

In the storm-deposition scheme represented in Figure 7, sole markings and representative vertical stratification sequences are shown for hypothetical tempestite beds formed under a range of storm conditions. These cartoons are highly generalized guides to potential products for each flow region. Depending on rates of change of each flow component, lag effects, including those associated with bed-form equilibrium and other complexities, various processes may or may not be recorded in the nature of sole marks and in the styles and vertical sequences of stratification. The strongest predepositional flow conditions during storms determine the nature of sole marks. We suggest that in flows in which these conditions are dominated by excess-weight forces unimodally oriented marks will develop, including well-formed flute marks. With increasing influence of waves or combined flow (lower to middle part of diagram), modified grooves and flutes may form. The geometry and flow conditions under which such structures might form are almost completely unknown; extensive experiments on erosion of muddy substrates under a variety of complex flows is badly needed. Bimodal or polymodal tool marks are expected under simple and complex purely oscillatory flow, respectively. Similar features may also form under combined flow (Duke 1990). Where present, combined-flow-diagnostic sole marks such as curvilinear grooves allow for differentiation from purely oscillatory flows.

One must wonder, however, about the apparent rarity of combined-flow-diagnostic sole marks. Assuming that their rarity is not simply due to non-recognition by sedimentologists, one might appeal to: (1) rarity of storms in which the substrate was directly affected by combined flow; (2) infrequency of proper preservational conditions or particular tools; or (3) other, as yet unknown, vagaries associated with the erosion by combined flows.

Styles of stratification and vertical stratification sequences for the end-member cases of purely turbidity-current flow and purely oscillatory flow are relatively straightforward (see Myrow and Southard 1991, fig. 6). The effect of adding turbulent energy to a turbidity current through weak to moderate-strength waves would probably result in a pulsating turbidity current. The internal stratification of deposits of pulsating wave-modified or combined-flow-modified turbidity currents would be difficult to predict, but such features as anisotropic HCS and graded rhythmites might be expected. Density currents modified by wave oscillations should produce features more closely resembling a turbidite—better grading and more current scour at the base—than a combined flow involving waves and geostrophic currents. Addition of an excess-weight force to a combined flow (thereby creating an excess-weight-affected flow in our terminology)—central triangle field of Figure 7—would be resolved as a four-part force problem involving pressure gradient, excess weight, Coriolis, and friction forces. In such cases, a flow would show an increase in offshore-directed maximum bed shear stresses and an offshore rotation in mean flow compared to a combined flow with no augmentation by excess weight.

An attempt to determine the degree to which the various flow types or regions in Figure 7 may be reflected in the rock record, and paleoenvironmental conditions under which such flows may have formed, might start with an analysis of individual tempestites in well-exposed cross-shelf transects. This would allow reconstruction of the temporal and spatial variations in the orientation and relative magnitude of various storm processes. Figure 8 attempts to represent the temporal history of the four storm-related forces—pressure gradient, excess-weight, friction, and Coriolis—for two positions on a cross-shelf transect during a hypothetical storm. It is a two-dimensional simplification that does not reflect the inevitable and significant longshore variability during storms (Héquette and Hill 1995). In the example shown, a geostrophic flow is generated on the inner shelf and sediment-equilibrium conditions prevail. The lengths of vectors for friction, Coriolis, and pressure-gradient forces for the nearshore position in Figure 8 (Table 1) were calculated by assigning a length of 10 to the Coriolis force at T_1 and using assigned offshore angles between 10° and 60°. Sediment suspension by waves and currents produce negligibly weak to moderate excess-weight forces which act parallel to, and are shown lumped in with, the pressure gradient. Excess-weight forces were ignored for the calculation of vector lengths; their addition would act to veer the flows offshore. The diagram shows the following: (1) temporal increase then decrease in the magnitude of all four forces, (2) larger changes in friction force than in the others, (3) seaward then landward rotation of flow direction away from shore-parallel, and (4) weaker flow conditions at all times in the offshore location.

It would be especially difficult to predict spatial changes in the excess-weight force across the shelf in modern storms. On the inner shelf, strong wave-generated oscillatory flow at the bed would suspend more sediment, thereby increasing the excess-weight force, but it is also a region more likely to produce flows with low Richardson numbers and therefore greater upward turbulent diffusion of suspended sediment. Farther offshore, diffusion may be weaker, but this would be offset by weaker oscillatory flow and progressive loss of suspended sediment by deposition from the offshore-moving flow. In a sediment-disequilibrium case of the same hypothetical storm, the sudden introduction of a high concentration of suspended sediment in the nearshore would produce a dominantly gravity-driven flow that would move offshore, possibly to depths below the influence of waves. Although the "sediment disequilibrium" case is one in which more sediment is in suspension than would be accounted for by waves and currents alone, the sum of the various forces would remain close to being in balance. An additional vector for excess-weight force would be added to the pressure gradient force thus rotating the flows offshore.

The temporal and spatial changes in storm forces shown in Figure 8 do not, however, illustrate the role and influence of waves. Triangular diagrams, with the flow regions from Figure 7, are shown in Figure 9 to show how the relative importance of waves, geostrophic currents, and density-induced flow changes through time in a cross-shelf transect. The temporal

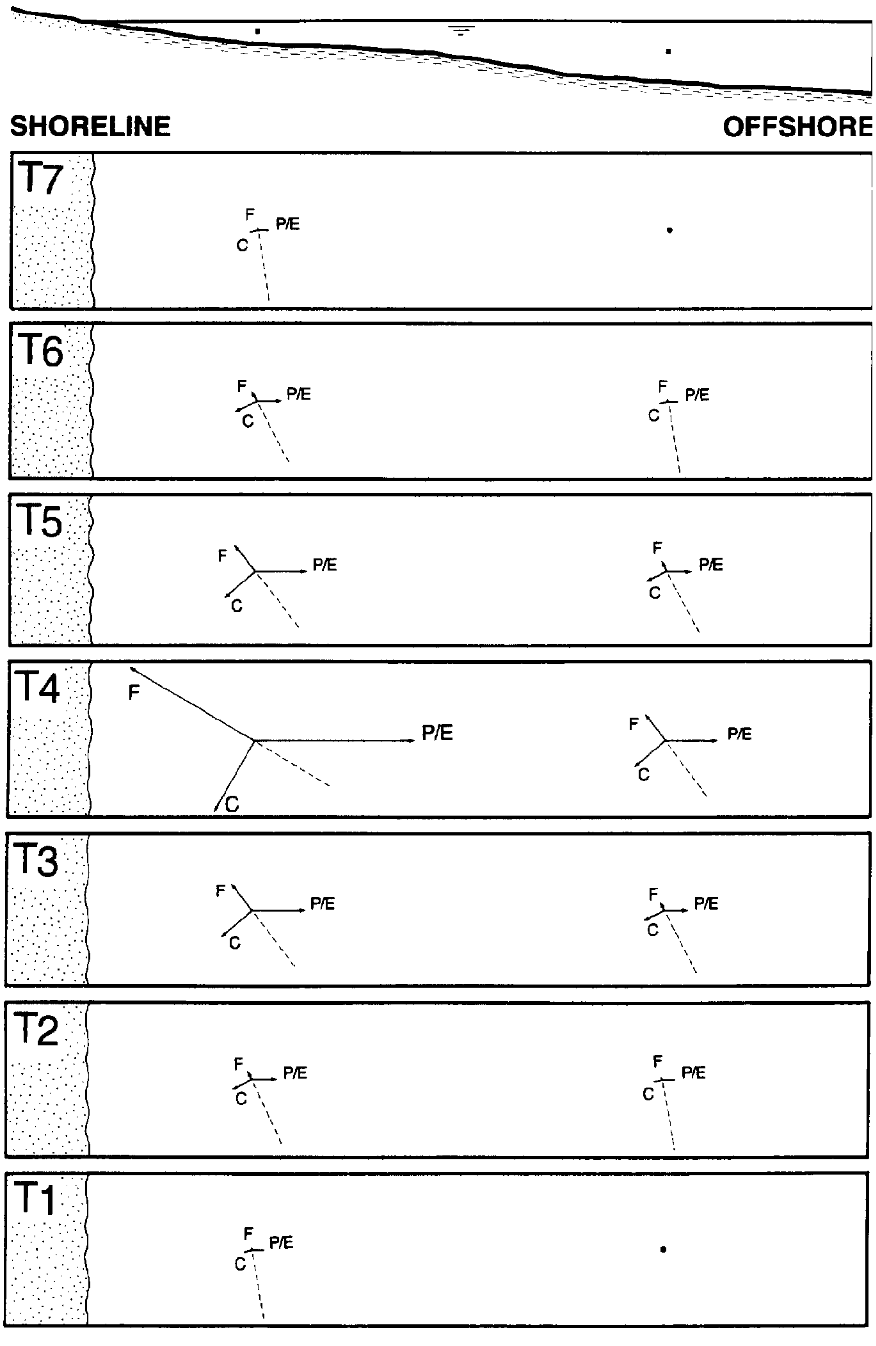

FIG. 8.—Temporal history for two locations on a shelf during a hypothetical storm, showing the four storm-related forces: pressure gradient (P), friction (F), excess-weight force (E), and Coriolis force (C). The example assumes sediment-equilibrium conditions for a storm that systematically increases then decreases in intensity, with concomitant changes in the strengths of forces and the orientation of the resulting flow. Lengths of vectors for the nearshore position (Table 1) were calculated by assigning a length of 10 to the Coriolis force at T_1 and using assigned offshore angles between 10° and 60°.

TABLE 1.—*Lengths of vectors for friction, Coriolis, and pressure-gradient forces for flows with different orientations (θ) relative to shoreline*

Time	Offshore Angle	Coriolis Force	Friction Force	Pressure Gradient
T_1/T_7	10°	10	1.8	10.2
T_2/T_6	24°	25	11.0	27.3
T_3/T_5	40°	47	39.1	61.1
T_4	60°	98	170.0	194.3

* The length of vectors was calculated by arbitrarily assigning a length of 10 to the Coriolis force at Time 1. Values used for construction of Figure 9.

history of three hypothetical event is shown for three locations (X_1–X_3) across the shelf by a line drawn within each triangle with time as a parameter. The predepositional phase of the storm is shown as a solid line, and the depositional phase as a dashed line. Equilibrium conditions are shown in the first two cases. In the first case, the concomitant development of waves and geostrophic flow occurs in the nearshore positions (Triangle X_1) as the storm begins, and with progressive suspension of sediment and the establishment of strong concentration gradients, the curve passes into the central triangle. The waning stages of flow in the nearshore setting shows a late-stage shift toward the wave-oscillation field as the setup dissipates and residual wave swell reworks the sediment surface. The magnitude of

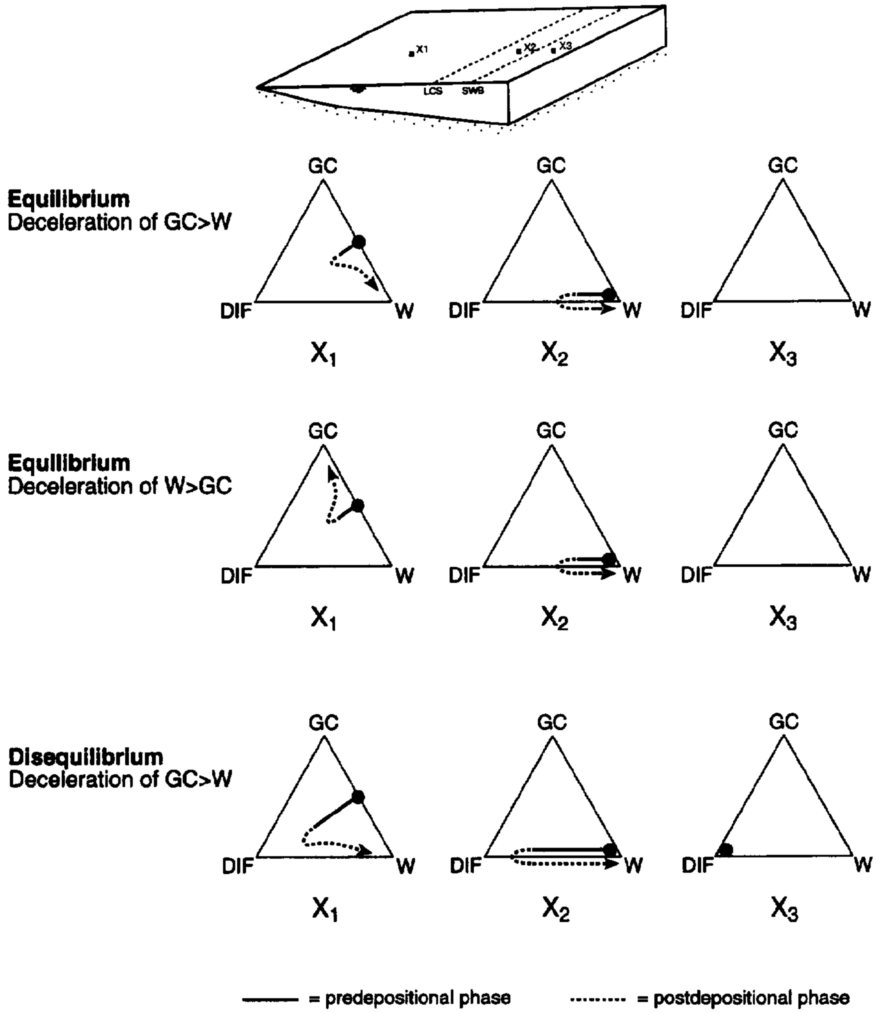

FIG. 9.—Triangular diagrams with the flow regions from Figure 7 that show the temporal history of three hypothetical event for three locations (X_1–X_3) across a shelf. The relative importance of waves, geostrophic currents, and density-induced flow is shown by a line drawn within each triangle with time as a parameter. The predepositional phase of the storm is shown as a solid line, and the depositional phase as a dashed line. Equilibrium conditions are shown in the first two cases and disequilibrium conditions for the last case. The pressure-gradient force tapers off seaward at a position corresponding to the intersection of the sloping surface of setup with the flatter offshore sea-surface profile, here labeled LCS for "limit of coastal setup". Storm wave base (SWB) is also shown on the block diagram.

the pressure-gradient force that drives the geostrophic flow is independent of depth but tapers off seaward at a position corresponding to the intersection of the sloping surface of setup with the flatter offshore sea-surface profile. Beyond this position, represented by Triangle X_2, the influence of geostrophic flow is negligible and only the influence of waves, and the progressive increase then decrease in the effects of a strongly gravity-driven flow, are recorded. Below storm wave base a purely turbidity-current flow would be recorded (Triangle X_3). Given the inherent difficulties in achieving autosuspension on a shelf (Swift 1985), such flows would probably not be sustained for any great distance below storm wave base. The second case is nearly identical, but in this case the deceleration of waves occurs quickly relative to the geostrophic flow, so the X_1 position shows a shift away from the wave corner of the triangle. The third case shows disequilibrium conditions with more rapid deceleration of geostrophic flow relative to waves and in all three triangles the greater influence of excess-weight forces relative to the two equilibrium cases.

SUMMARY

Storm deposits are highly variable, reflecting a wide variety of erosional and depositional processes. Ancient tempestites are unusually thick, and indicate much greater cross-shelf transport relative to modern deposits, thus indicating nonactualistic processes. Mechanisms for considerable cross-shelf transport are not evident from modern oceanographic studies and are difficult to deduce from the rock record. The best record of transport mechanisms may come from sole marks, which record the latest predepositional phase of storms. Tempestite sole marks are not all straightforward to interpret, but in various ancient deposits they appear to record a range of predepositional conditions from purely oscillatory flow to combined flow to purely unidirectional flow. The depositional phase of tempestites is also highly variable both from bed to bed and from basin to basin, as reflected in their wide range of vertical stratification sequences. The model presented herein attempts to make sense of the known variation in tempestites and predict the nature and associations of particular storm-generated features that would correspond to various flow conditions (regions of the ternary diagram in Figure 7).

Excess-weight forces have been dismissed as unimportant for ancient storm deposition. This comes from a greater understanding and appreciation of how modern storms operate, particularly combined-flow bottom boundary layer dynamics. It also comes from the false assumption that because the bottom slopes of modern shelves and the measured near-bottom sediment concentrations are presumably too low for autosuspension such forces are unimportant. We believe that dismissing the potential importance of excess-weight forces is premature, on three grounds. (1) Sediment concentrations during peak storms conditions exceed 1000 mg/l (Madsen et al. 1993) on inner shelves, and may therefore be nonnegligible and important for cross-shelf transport with or without currents and waves. (2) One cannot rule out catastrophic introduction of sediment by river floods, earthquakes, or other events that cause liquefaction for ancient storm events, particularly given the significant difference in maximum thickness between ancient and modern storm-generated beds. (3) The slopes of modern continental shelves may be anomalously low as a result of Holocene sea-level rise, and therefore poor analogs for many ancient storm-influenced settings. Higher slopes may have been the norm in a wide variety of ancient tectonic settings, thus providing greater offshore-directed driving force for sediment-rich, storm-generated suspensions.

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