GEOSTROPHIC CIRCULATION OR SHALLOW MARINE TURBIDITY CURRENTS? THE DILEMMA OF PALEOFLOW PATTERNS IN STORM-INFLUENCED PROGRADING SHORELINE SYSTEMS[1]

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ABSTRACT: In ancient storm-influenced prograding shoreline sequences, sole marks (mainly tool marks) from hummocky cross-stratified storm deposits are commonly oriented normal to paleoshoreline and the trend of paleobathymetric contours in the basin. Asymmetrical tool marks typically indicate flows directed offshore. Several workers have attributed their formation to storm-generated, shallow marine turbidity currents. This interpretation conflicts with observations from modern shelves, where storm-driven circulation generally is geostrophically balanced, and time-averaged bottom currents approximately parallel bathymetric contours and the local shoreline.

The resolution of these apparently conflicting observations may lie in the realization that tool marks (and many other small paleoflow indicators) form almost instantly as the result of *instantaneous* flow conditions very near the bed. Beneath storm-generated flows in the shallow ocean, instantaneous and time-averaged characteristics of the bottom boundary layer generally exhibit little similarity. Storm-generated tool marks are formed by the movement of large tools within the thin (less than 1 m) inner boundary layer resulting from the superimposition of waves and currents. The orientation of the peak instantaneous shear stress moving large tools under such combined flows mainly reflects wave-orbital motions, which typically are normal to shore. The magnitude of stress is greatly increased in the offshore direction (and decreased in the onshore direction) by superimposition of a steady current with an offshore component of flow, but the direction of stress is only slightly affected.

In ancient storm-influenced sequences, therefore, shore-normal tool marks generally were not formed by turbidity currents; rather, their orientation is best attributed to shoaling waves approaching the coast at a very high angle. Asymmetrical tool marks are directed offshore due to enhanced shear stress on the offshore stroke of waves superimposed on a geostrophic current with an offshore flow component. Tool marks do not reflect the time-averaged bottom-flow direction; in fact, they provide almost no information concerning steady bottom currents.

In contrast, high-angle cross-beds (formed in coarser sediment by the migration of dunes and sandwaves), although relatively rare in offshore storm deposits, generally reveal approximately shore-parallel flows in ancient systems. Cross-beds closely reflect the time-averaged flow direction in the outer boundary layer of a geostrophic current, for three reasons: 1) the net transport direction for sand moving as bed load beneath a combined flow lies between the directions of peak instantaneous shear stress and time-averaged shear stress; 2) large ripples disrupt the thin inner boundary layer; and 3) long time intervals (relative to wave-induced velocity oscillations) are required to form large ripples.

INTRODUCTION

Oceanographic investigations on modern shelves have led to the recognition that geostrophically balanced coastal downwelling (driven by coastal set-up or "storm surge") is the primary mechanism for the seaward transport of sediment during storms. Process-oriented stratigraphic investigations have enhanced our understanding of ancient storm deposits and effects but have given rise to numerous unanswered questions. Principal among these is one which is the focus of an ongoing debate in the sedimentological community: Were ancient storm deposits emplaced by flows similar to the storm-generated flows observed in modern settings, or is the geologic evidence sufficient to suggest that they were emplaced by some wholly different means—specifically, storm-generated turbidity currents? The background to this uniformitarian dilemma is presented below.

Observational Inconsistencies

Much uncertainty exists concerning the hydrodynamic significance of paleocurrent indicators in ancient storm-influenced shallow marine deposits from epicontinental and pericontinental seas. Certain aspects of this uncertainty have been summarized by Walker (1984a, 1984b), who points out that geologists working in ancient deposits and oceanographers working in modern environments have amassed apparently contradictory data sets concerning the qualitative nature of storm-generated flows in shallow seas.

The "geological viewpoint" (Walker 1984b) is based primarily upon two major lines of evidence from numerous studies of ancient storm-influenced prograding shoreline sequences:

Vertical Facies Sequences.—The inferred offshore deposits in these ancient systems typically form thickening- and coarsening-upward successions of mudstones interbedded with sandstones. Sandstone beds deposited lower in the succession commonly exhibit complete or partial Bouma sequences. Higher up, sandstones exhibit hummocky cross-stratification, flat lamination, and wave ripples.

Paleocurrent Data.—The orientations of sole marks, current ripples, and other small paleocurrent indicators from hummocky cross-stratified and flat-laminated sandstone beds commonly reflect storm-generated flows directed offshore, essentially normal to the ancient shoreline trend. In most instances, the underlying Bouma sequences also exhibit shore-normal sole marks and current ripples.

Note that the determination of paleoflow patterns in ancient shallow marine systems is in general a difficult task, in that it requires independent determinations of

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paleocurrent direction and the paleoshoreline trend. Each of these determinations involves various uncertainties. Nevertheless, the accumulated evidence from many detailed stratigraphic investigations continues to support the generalizations of Walker (1984b). For example, Leckie and Krystinik (1989a, 1989b) have recently summarized paleoflow patterns in several ancient shoreline systems in the Western Interior of North America; they concluded that sole marks, parting lineations, and asymmetrical ripples from hummocky cross-stratified, proximal offshore storm deposits are in each unit oriented normal to shore, forming angles of 70 to 90° with the best estimates of the ancient shoreline trends. Where Bouma sequences are present, they likewise exhibit offshore-directed, shore-normal paleocurrent indicators.

A common (but by no means universal) interpretation of these geological observations suggests that powerful storm-generated flows in the proximal offshore zone (specifically, the lower shoreface to inner shelf) of ancient shallow seas were directed essentially normal to shoreline, down the inferred paleoslope, and were driven by gravity acting upon the density difference between turbid bottom water and overlying clear water. Excess density in the bottom flow most likely resulted from sediment suspended by turbulence; thus, these storm-generated flows were turbidity currents. In shallow offshore water depths (above effective storm wave base), strong oscillatory fluid motions formed hummocky cross-stratification and wave ripples. In greater depths (typically identified as being below effective storm wave base), Bouma sequences were formed under waning, purely unidirectional flows. This interpretation has been advanced (with varying levels of enthusiasm) in studies of numerous ancient units, including those of Hamblin and Walker (1979), Wright and Walker (1981), Dott and Bourgeois (1982), Graham (1982), Leckie and Walker (1982), Wu (1982), Walker (1983a, 1983b, 1984a, 1984b), and Walker et al. (1983).

In contrast, the "oceanographic viewpoint" (Walker 1984b) holds that powerful storm-generated turbidity currents (apparently absent in modern shallow seas) could not have been responsible for the emplacement of many ancient storm deposits. Gravitational acceleration of sediment suspended during storms is not believed to produce large-scale fluid motion over relatively flat shelves: the slopes are too low to achieve autosuspension. Strong unidirectional flows *are* generated by modern storms; however, the depth-averaged steady flow component in the bottom boundary layer typically is directed approximately parallel to bathymetric contours and the local shoreline. In these flows, downwelling fluid motion is driven by a horizontal pressure gradient resulting from set-up along the coast. At equilibrium, this pressure force is balanced primarily by the Coriolis force, required in an Earth-based coordinate system to reconcile relatively weak forces on the rotating planet. The Coriolis force is responsible for the alongshore deflection of storm-driven circulation on modern shelves. Set-up along a coast in the northern hemisphere results in alongshore flows to the right (looking offshore), whereas flows are to the left in the southern hemipshere (see further discussion below).

Proponents of the "oceanographic viewpoint" argue on uniformitarian grounds that storm-generated flows in most ancient shallow marine systems must have been qualitatively similar to the flows observed in modern settings. This reasoning has been repeated by numerous workers, including Hunter and Clifton (1982), Mount (1982), Swift et al. (1983, 1987), DeCelles (1987), and Duke et al. (1990). As compelling as this argument is, it offers no explanation of the shore-normal, offshore-directed paleocurrent indicators and vertical facies sequences observed in many ancient systems.

Previous attempts to reconcile modern observations with specific ancient systems have not proved fully satisfactory. For instance, off-shore-directed sole marks in the Cretaceous Blackhawk Formation of Utah represent yet another example of what D. J. P. Swift (pers. comm., 1988) refers to as "the paleocurrent problem." These structures were attributed by Swift et al. (1987) to nearly shore-normal flows generated on the shoreface during peak storm conditions, when geostrophic veering of these high-speed flows would have been minimized. In this scenario, the offshore-directed pressure-gradient force driving shallow storm flows would have been balanced mainly by frictional forces, rather than by the Coriolis force; additionally, the peak current would be accelerating, and thus the pressure-gradient force would not be fully balanced (see further discussion below). While such an interpretation is fully acceptable for sole marks generated by accelerating flows in very shallow water depths, it generally cannot be called upon to explain those formed in deeper water, on the lowermost shoreface and shelf; further, it cannot be invoked for waning-flow indicators (such as current and parting lineations or asymmetrical ripples) formed in any offshore setting.

Similarly, Duke et al. (1990) encountered nearly shore-normal sole marks in storm- and tide-influenced deposits from the Silurian Medina Group of New York and Ontario. They attributed this orientation to a combination of three factors: 1) high-speed jetting of storm flows from nearly shore-normal tidal channels on the upper shoreface; 2) extremely shallow basinal water depths, in which friction would be unusually effective in minimizing geostrophic veering; and 3) a low-latitude depositional setting, where the magnitude of the Coriolis parameter was relatively small. While the combined effects of these factors may plausibly have acted to inhibit geostrophic veering of storm currents in the Medina basin, they clearly do not constitute a generally applicable resolution of "the paleocurrent problem."

The difficulty is compounded when one examines the sense of deviation of offshore paleocurrent indicators from a true shore-normal geometry. In their survey of ancient shoreline systems, Leckie and Krystinik (1989a, 1989b) found angular deviations of no more than 20° from a true shore-normal orientation; importantly, however, the sense of deviation in some of these northern-hemisphere occurrences commonly was to the left, in a manner inconsistent with coastal set-up and geostrophic veering (Leckie and Krystinik 1989a). Although angular relationships of 20° or less might be discounted by some workers as within the margin of error inherent in stratigraphic investigations, the trend is nonetheless disturbing.

Despite these difficulties, proponents of the "oceanographic viewpoint" can point to certain evidence from the stratigraphic record which strongly supports the concept of geostrophically balanced storm circulation in ancient systems. Not all offshore storm deposits exhibit hummocky cross-stratification. Those formed in upper fine and coarser sandstones typically reveal both different internal structures and a much different pattern of flow in the offshore zone. In these coarser deposits, the dominant internal structure is high-angle cross-bedding, including both trough and planar-tabular cross-bedding. Although such relatively coarse offshore sandstones apparently are much less common in the stratigraphic record, they generally reveal flows in the offshore zone directed more-or-less parallel to paleobathymetric contours and the ancient shoreline. Examples from the North American Western Interior have been described by Campbell (1971; but see reinterpretation of Bergman and Walker 1987), Berg (1975), Cotter (1975), Spearing (1976; see also Harms et al. 1975, chapter 6), Brenner (1978), Boyles and Scott (1982), Rice and Shurr (1983), Parrish et al. (1984), Tillman and Martinsen (1984), Brenner et al. (1985), and Nummedal and Swift (1987).

Alongshelf flows revealed by cross-bedding in these deposits are now generally considered to represent geostrophically balanced storm circulation. The sense of flow in the occurrences above is consistent with geostrophic circulation resulting from set-up along the adjacent shoreline.

Statement of the Problem

The situation detailed above leads to the identification of certain critical questions that must be addressed in any attempt to reconcile observations from ancient prograding shoreline systems and modern shelves:

1) If the concept of shallow marine turbidity currents is untenable in view of observations from modern environments, how are we to account for offshore-directed paleocurrent indicators (mainly tool marks and other small structures) preserved in lower shoreface and inner shelf storm deposits in many ancient sequences? By what mechanism were such indicators deflected slightly to the left of a true shore-normal geometry in several northern hemisphere occurrences?
2) Why are only larger paleocurrent indicators (mainly trough and planar-tabular cross-beds) so clearly consistent with the model of geostrophically balanced storm circulation derived from studies of modern shelf dynamics? Were these slightly coarser deposits emplaced under flows qualitatively different from those of their finer counterparts?
3) By what means were Bouma sequences formed in ancient storm-dominated prograding shoreline systems? More importantly, how can we explain the shore-normal paleoflow indicators exhibited by many of these thin sandstone beds?

In the present paper, I address the first two of these questions only. I shall suggest that the different patterns of paleoflow indicators described above form under qualitatively similar geostrophically balanced flows but that their different orientations reflect varying substrate response to conditions in the bottom boundary layer. The equally important issues of question 3 will be addressed in a companion paper. The results of this study have been presented previously in an abstract by Duke (1990).

THE BOTTOM BOUNDARY LAYER UNDER STORM-GENERATED GEOSTROPHIC FLOWS

Figure 1 diagrammatically illustrates the equilibrium response of the shelf water column to an idealized storm-induced set-up along a straight shoreline in the northern hemisphere. The general form of this response is illustrated in a vertical section normal to shore (Fig. 1A). The effects of strong onshore wind shear, wave shaling, barometric pressure differences, and astronomical tides can combine to drive surface water onshore, thus deforming the sea surface such that it is elevated along the coast. This coastal set-up results in static pressure differences along any horizontal plane below the sea surface. The resulting horizontal pressure gradient acts to drive bottom water offshore in a manner that partially compensates the onshore transport of surface water. With time, an equilibrium condition can be achieved in which downwelling water circulates through an elevated but essentially stable coastal water prism.

Figure 1A also shows that the sea floor in relatively shallow depths is affected by two superimposed (and interacting) boundary layers: The steady flow exerts an offshore-directed shear stress at the bed, whereas wave-induced oscillatory motions exert reversing onshore-offshore bottom stresses. Beneath large storms on modern shelves, either of these two superimposed flow components alone would be adequate to mobilize sand at depths well over a hundred meters.

Were it not for the effects of Earth's rotation, Figure 1A would be adequate to represent the basic structure of the storm-driven circulation system. The pattern of flow is substantially modified by planetary rotation, however, as is illustrated in Figure 1B. This figure shows a plan view of the mid-depth reference horizon drawn in Figure 1A. Initially, the horizontal pressure-gradient force accelerates water seaward. Frictional forces are insignificant along this mid-depth horizon, and the horizontal pressure force on any particle of fluid is balanced mainly by the

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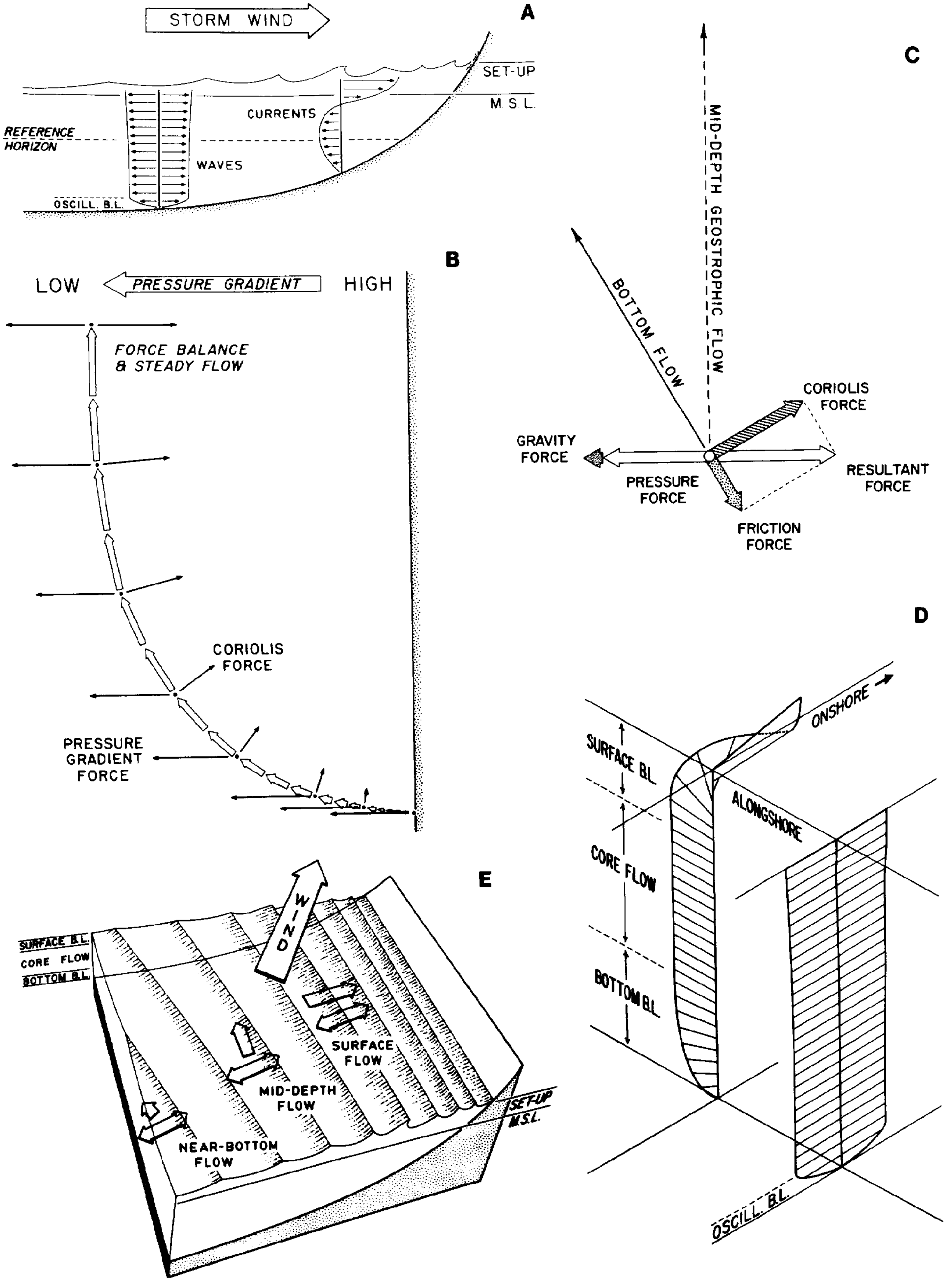
FIG. 1.—Diagrams illustrating basic pattern of storm-driven geostrophic circulation beneath shallow-water storm waves over the lower shoreface and inner shelf in the northern hemisphere. See text for explanation.


A
STORM WIND
SET-UP
M.S.L.
CURRENTS
REFERENCE HORIZON
WAVES
OSCILL. B.L.
B
LOW
PRESSURE GRADIENT
HIGH
FORCE BALANCE & STEADY FLOW
CORIOLIS FORCE
PRESSURE GRADIENT FORCE
C
MID-DEPTH GEOSTROPHIC FLOW
BOTTOM FLOW
CORIOLIS FORCE
GRAVITY FORCE
RESULTANT FORCE
PRESSURE FORCE
FRICTION FORCE
D
ONSHORE
SURFACE B.L.
ALONGSHORE
CORE FLOW
BOTTOM B.L.
OSCILL. B.L.
E
WIND
SURFACE B.L.
CORE FLOW
BOTTOM B.L.
SURFACE FLOW
MID-DEPTH FLOW
NEAR-BOTTOM FLOW
SET-UP
M.S.L.

Coriolis force oriented orthogonally (and to the right) of the fluid trajectory. The Coriolis force increases as the fluid accelerates and veers to the right under the net effect of both forces. Ultimately, a balance between the pressure-gradient force and the Coriolis force is achieved as the fluid trajectory parallels the shoreline and the fluid ceases to accelerate. At this point, fluid at this horizon is travelling at its maximum flow speed.

The same process occurs at all horizons between the surface and bottom boundary layers. Thus, under a fully developed geostrophic flow, non-shearing mid-depth currents oriented roughly parallel to shore are typical of the entire offshore zone. Shore-parallel flows may extend from the edge of the shoreface (in water scarcely 10 m deep and 1 or 2 km from shore) to the shelf break (in water 200 m deep and 200 km from shore). On the modern Atlantic shelf, for example, storms typically result in dominantly along-shelf water movement over the lower shoreface (e.g., Lavelle et al. 1978a, 1978b) and across the entire width of the shelf (e.g., Vincent et al. 1981).

Figure 1C qualitatively illustrates the *time-averaged* balance of forces near the boundary under a shore-parallel geostrophic flow. Proximity to the bottom necessitates the introduction of a significant friction term in the force balance; this force alone is adequate to deviate the resulting near-bottom flow offshore by as much as a few tens of degrees (e.g., Swift 1976). In addition, a small gravity force has been included in Figure 1C. Storm flows are known to suspend large concentrations of sand particles at least as high as a meter above the bed (Clarke et al. 1982); gravity acts upon the excess density of this turbid bottom water. Gravitational acceleration of the bottom fluid is directed normal to isobaths, parallel to the horizontal pressure-gradient force.

On a perfectly flat basin floor, a horizontal gravity force due to a vertical concentration gradient would of course be absent; however, a *horizontal* concentration gradient would produce a gravity force, even over a flat surface. As summarized above, numerous modern oceanographic investigations suggest that the gravity forces produced by storm-induced sediment-concentration gradients are probably miniscule on the very gentle slopes characteristic of the lower shoreface and inner shelf. Nevertheless, *all* the forces acting near the sea floor are relatively weak; thus it may be necessary to include a significant gravity term to approximate more closely the true force balance, especially on shorefaces with unusually steep slopes. As sketched in Figure 1C, the gravity force is much smaller than the pressure force and does not significantly affect the resulting bottom-flow trajectory. (If it were much larger, the equilibrium flow would be faster and thus the friction force would be increased, resulting in increased offshore deflection of the bottom current.) Although a relatively small gravity force clearly is characteristic of storm-generated bottom flows on modern shelves, the degree to which gravitational acceleration may enter into the bottom force balance has not been adequately investigated; note, however, that L. O. Wright et al. (unpubl. data) provide new data concerning gravity forces during a storm over the shoreface, in water 8 m deep.

It must be emphasized here that in relatively shallow water (on the shoreface, inner shelf, and upper middle shelf), storm waves cause intense oscillatory motions to be superimposed upon the steady bottom flow depicted in Figure 1C. However, forces due to wave-induced oscillatory motions have not been included in Figure 1C, under the assumption that they are symmetrically disposed in the onshore-offshore direction and would not significantly affect the time-averaged force balance. Note that this assumption is not strictly true, for at least two reasons: 1) the bottom stresses exerted during each half-stroke of oscillation are not equal beneath steep, shallow water waves, and 2) stresses generated by wave-induced oscillations and a steady current do not combine arithmetically; rather, second-order nonlinear interactions between the separate flow components yield asymmetrical stresses dependent upon their relative orientations (see further discussion below). However, the addition of wave forces probably would not substantially modify the qualitative representation of the time-averaged force balance in Figure 1C. The two superimposed, interacting vertical profiles of horizontal fluid velocity have been sketeched in Figure 1D.

As shown in Figure 1D, E, the shelf water column can be divided into three separate regions of storm-driven quasi-steady circulation: the turbulent upper and lower boundary layers (which overlap in shallow water) are separated in deeper water by a core region of non-shearing ("slab-like") geostrophic flow. Due to the Coriolis force, currents near the surface (in the Ekman layer) typically are rotated a few to several tens of degrees to the wind direction; this angle (and the thickness of the layer itself) varies with wind speed, water depth, and latitude (Csanady 1982, chapter 1). To further complicate matters, this entire upper boundary layer is "rafted along" by the underlying core flow, and this advection contributes to the resultant near-surface flow directions. As an approximate empirical rule, however, the mean surface current during storms is oriented about 45° to the wind (D. J. P. Swift, pers. comm., 1989), as drawn in Figure 1E.

Note that both the lower and upper boundary layers are rotary (Fig. 1D). Such boundary layers differ from a two-dimensional boundary layer in that they may exist with a constant thickness (Csanady 1967). Thus, neither boundary layer expands to encompass the entire shelf water column, and the bottom boundary layer typically is confined to about 10 m above the bed (Swift 1976; Swift and Nummedal 1987).

This paper is mainly concerned with the bottom boundary layer on the shoreface and inner shelf, which can be further subdivided into an inner and outer boundary layer when wave-induced oscillatory motion also is considered. The inner boundary layer is that region where the thin, oscillatory, wave-generated boundary layer interacts with the much thicker unidirectional, current-generated boundary layer (Fig. 1D); it typically is confined to the lowest few to several decimeters of the water column (see below). The outer boundary layer constitutes the remainder of the bottom boundary layer. Note that the oscillatory inner boundary layer of combined flows is somewhat thicker than the boundary layer generated by equivalent waves in isolation; it approaches a thickness of 1 m under highly energetic conditions (Davies et al. 1988). Also note that refraction of shallow water waves causes them to approach a shore-parallel configuration as they shoal (Fig. 1E); large storm waves begin to "feel bottom" and refract far from shore, on the middle to outer shelf. Thus, large storm-generated sea or swell waves along a straight shoreline exhibit nearly shore-parallel crests across much of the inner shelf and lower shoreface (Fig. 1E), as has been observed in numerous modern investigations (e.g., Lavelle et al. 1978b).

The time- and depth-averaged flow conditions in the bottom boundary layer clearly are significant when considering transport of sediment suspended relatively high above the bed, in the outer boundary layer. However, it is not so obvious how these quantities may be related to sediment moving more-or-less as bedload. To examine tractional sediment transport, which bears significantly upon the origin of sedimentary structures, we must consider instantaneous flow conditions in the inner boundary layer.

The Inner Boundary Layer Under Geostrophic Flows

Davies et al. (1988) have presented numerical simulations of instantaneous flow conditions in the inner boundary layer of combined flows resulting from the superimposition of a steady, uniform, unidirectional current and a symmetrical, uniform, unimodal (or monochromatic), oscillatory flow. Their simulations (which assumed a flat, hydraulically rough, rigid bottom) involved variously oriented flow components.

Although the work of Davies et al. (1988) was designed to model superimposed waves and tides in water 10 m deep, their results may be extended to approximate the similarly thick bottom boundary layer of a geostrophic storm flow in deeper water. Their simulations involved a unidirectional current which in isolation from waves would exert a bottom stress of 33.8 dyn/cm^2 and a flow speed of approximately 30 cm/s at a height of 20 cm above the bed (or approximately 50 cm/s at 100 cm above the bed).

These values are fairly typical of time-averaged bottom shear stresses and near-bottom flow speeds produced by storm-driven geostrophic flows on the lower shoreface to middle shelf (Table 1). In fact, such values are rather high (for all but the most extreme storm conditions) for depths greater than 10 m; however, the modelled values represent maxima appropriate to the aims of this paper. To illustrate, consider that the steady currents modelled by Davies et al. (1988) possessed maximum speeds of about 80 cm/s at the water surface, 10 m above the bed. In our extension of their model, this speed would correspond approximately to the mid-depth flow speed within the non-shearing core of a geostrophic current. Over modern shelves, storm-generated geostrophic currents typically achieve maximum speeds of only about 30 to 80 cm/s (see data summaries of Swift et al. 1983 and Swift and Nummedal 1987). Note, however, that somewhat higher current speeds are not unknown (Table 1).

The oscillatory component of the combined flows modelled by Davies et al. (1988) possessed a period of 8 s and a maximum bottom orbital speed (measured just outside the wave-formed boundary layer) of 100 cm/s. In the modelled water depth of 10 m, the stable shallow-water waves producing such a flow would be about 2.4 m tall. The same bottom flows could be generated by steeper waves in deeper water, however. Thus, in 30 m water depth, stable 8-s waves 8.6 m tall would produce roughly the same bottom-flow speed. The modelled flow parameters can therefore be taken as roughly representative of storm-generated sea or swell waves over a lower shoreface and inner shelf exposed to the open ocean. In fact, both storm seas and swell waves commonly produce longer, faster oscillatory flows, but the modelled values represent conservative minima which again are appropriate to the aims of this paper. The reader is referred to the study of Lavelle et al. (1978b) for a record of storm-induced bottom flows which correspond closely to the model parameters (see data summary in Table 1).

TABLE 1.—*Characteristic parameters (measured near the sea floor) of some storm-generated combined flows on modern shelves (depths greater than 10 m). Strong tidal currents and pronounced bottom topography were absent. All values are approximate means obtained over several wave cycles during peak storm flows*

Shelf Location	h, m	z, cm	U_c, cm/s	U_w, cm/s	T, s	Data Source
Washington	50	300	80	—	—	Smith and Hopkins (1972)
	50	300	70	—	—	
	50	300	50	—	—	
	80	300	54	—	—	
	80	300	58	—	—	
North Carolina	27	100	50	—	—	Hunt et al. (1977)
Virginia	20	37	30	—	—	Swift et al. (1977)
Texas	21	305	150	—	—	Forristall et al. (1977)
New York	21	150	60	—	—	Lavelle et al. (1978a)
	21	150	40	—	—	
New York	10.5	100	39	80	10	Lavelle et al. (1978b)
Texas	17	200	70	—	—	Smith (1978)
New York	30	100	50	—	—	Young (1978)

h = water depth at measurement location; z = height above substrate at which measurements were obtained; U_c = speed of near-bottom unidirectional current; U_w = maximum near-bottom wave-orbital speed; T = period of wave-induced velocity oscillations; — = not reported.

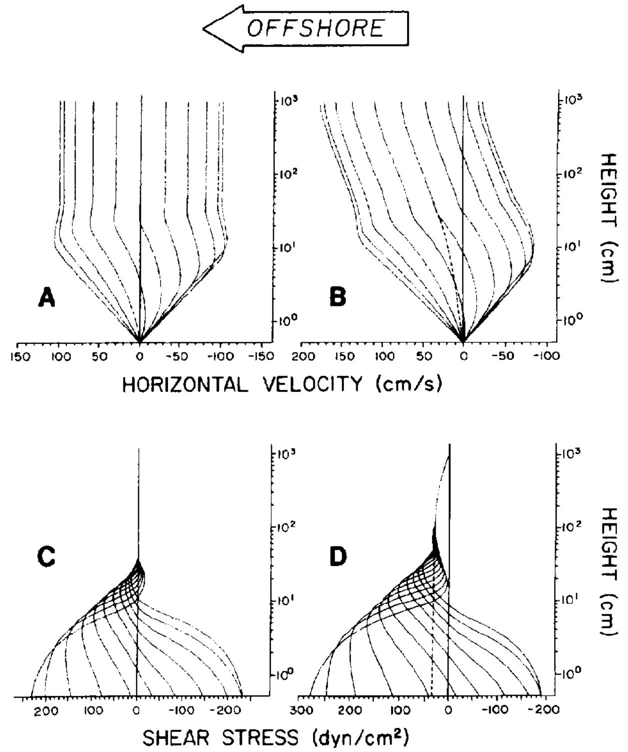


FIG. 2.—Vertical profiles of instantaneous horizontal velocity and shear stress for shallow-water waves in isolation (A, C) and for waves with a superimposed colinear current (B, D) which is steady when averaged over many wave cycles. Waves are propagating onshore, whereas current is flowing offshore. Each profile is plotted for successive time intervals of 0.05 T, where T = period of wave-induced oscillatory motion; thus, each set spans one half-stroke of oscillation. Profiles in each set proceed in time from left to right, representing the shoreward stroke of orbital motion. Dashed lines in (B) and (D) represent solutions for the current in isolation, which merge with combined-flow solutions several decimeters above the bed. After Davies et al. (1988, figs. 2 and 4). See text for further discussion.

Figure 2 reproduces certain results of the simulation by Davies et al. (1988) for colinear flow components, roughly equivalent to storm flows in very shallow upper shoreface settings very near shore, where the pressure-gradient force driving the accelerating bottom current is only partly balanced and friction represents the dominant retarding force. Results are presented both for waves in isolation and for waves superimposed on the current. Note that the combined-flow simulations of Davies et al. (1988) involved waves travelling in the same direction as the current; however, due to the symmetry of the oscillatory component, the solution is the same if the wave propagation direction is reversed. The maximum offshore-directed bottom stress (280 dyn/cm^2) is much larger than the maximum onshore-directed stress (190 dyn/cm^2) in this combined flow. Due to the high-order dependence of sediment-transport rate upon bed shear stress, the net transport of sediment offshore would be much greater under the combined flow than under the steady component alone.

Figure 3 reproduces equivalent results of the simulation by Davies et al. (1988) for a combined flow in which the separate components in the bottom boundary layer are oriented at approximately 45° to one another. This geometry might correspond to the situation at the sea floor under a fully developed geostrophic flow (compare with Fig. 1C, D, E). Note that the maximum alongshore component of bed shear stress is less than 30 dyn/cm^2, whereas the maximum offshore and onshore components are approximately 270 and 210 dyn/cm^2, respectively. Similar alongshore/offshore ratios of maximum horizontal velocity obtain from the bed to a height of about a decimeter above the bed. In this combined flow, the direction of peak instantaneous boundary shear stress deviates from the orientation of wave-induced orbital motion by only 7° (Fig. 3).

It should be recollected that the model parameters of Davies et al. (1988) underplay wave motions and overemphasize the steady current component, relative to most storm conditions on the shelf (see previous discussion). Nevertheless, Figures 2 and 3 show that fluid motions near the bed are overwhelmingly dominated by the wave-induced oscillatory component of these combined flows. The contribution of the steady current to the peak instantaneous values of both near-bed flow speed and boundary shear stress is roughly one order of magnitude less than the contribution from the orbital wave motion. These conditions are due to the relative thinness of the oscillatory boundary layer and the resultant steep vertical gradient in the wave-induced horizontal velocity profile near the bed.

This characterization is confirmed by careful inspection of various data records (including those listed in Table 1) of modern storm-generated waves and bottom flows over the lower shoreface and inner shelf. Indeed, it appears to be a physically inescapable conclusion that all storm-induced bottom flows well above wave base are strongly dominated by oscillatory components of motion. Previous workers have voiced similar generalizations (e.g., Swift and Nummedal 1987 suggested that storm-generated bottom flows are oscillatory-dominant as far out as the middle shelf).

INFERRED SUBSTRATE RESPONSE TO THE BOTTOM BOUNDARY LAYER OF COMBINED FLOWS

Inferred Origin of Sole Marks and Other Small Paleoflow Indicators

Laboratory studies in flumes and stratigraphic studies of deep-water turbidite sequences have elucidated the formation of physical sole marks under unidirectional flows (see, for example, summaries provided by Allen 1982, chapter 13, and Reineck and Singh 1975, p. 64–74). Sole marks include flute casts and tool marks. These latter markings are formed nearly instantaneously, by the impact on the muddy substrate of a relatively large tool (such as a shell fragment) carried by the flow in the lower portion of the boundary layer. Typically, these tools move through traction, saltation, or intermittent suspension,

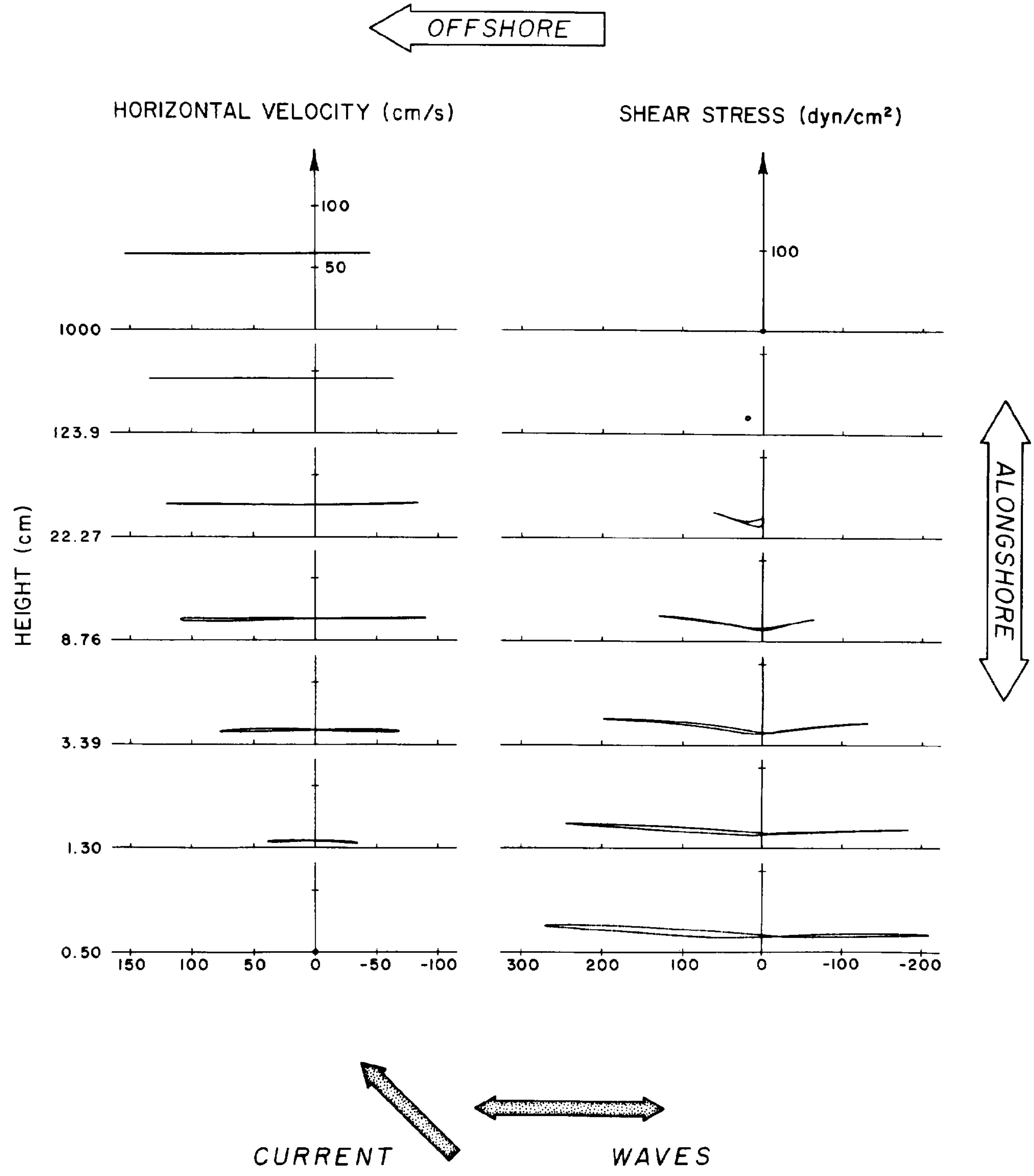


FIG. 3.—Plan-view representations of instantaneous horizontal velocity and shear stress loci for onshore-propagating waves superimposed on a current flowing obliquely offshore (at an angle of about 45 degrees to the coast, as drawn at bottom of figure). Results are plotted for seven different levels above the bed. The magnitude and direction of each instantaneous vector is traced by a loop representing one complete wave cycle. At the bed (where the velocity is zero) and at the top of the outer boundary layer (where the stress is zero), the loci collapse to a single point. After Davies et al. (1988, fig. 10). See text for further discussion.

traveling little more than a few centimeters above the bed. Various types of tool-generated marks are recognized. These include symmetrical forms, yielding flow orientations only, and asymmetrical forms, from which flow direction can also be obtained.

For the most part, the bases of shallow marine storm deposits in ancient siliciclastic sequences exhibit only small symmetrical tool marks (mainly small grooves). Asymmetrical prod marks are less common, and well-developed flute casts generally are absent or quite rare. Occurrences of such tool marks have been reported and figured by numerous workers.

Based upon our knowledge of the formation of these features under unidirectional currents, it is reasonable to suggest that most physical sole marks from ancient storm deposits were formed by the nearly instantaneous impact of tools carried in the combined-flow inner boundary layer. In most cases, the tools probably were small shells perhaps a few centimeters long. Typically, tools of this size clearly were the largest clasts moved by the flow, and it is likely that they were mobilized by only the strongest instantaneous flow in the inner boundary layer. Inspection of Figure 3 shows that the directions of peak instantaneous velocity and shear stress in combined-flow boundary layers are nearly identical to the direction of wave-generated oscillatory motion in isolation. Thus I suggest that sole marks from ancient storm deposits typically possess shore-normal orientations (within observational limitations) because the refraction of shoaling waves typically causes them to approach the shoreline at a very high angle.

Further, *directional* sole marks typically are directed offshore because bottom shear stress on the offshore stroke of waves is substantially increased by even a small offshore-directed component of unidirectional flow superimposed on the wave-generated oscillatory motion; it is similarly decreased on the onshore stroke by such a superimposition (see Figs. 2 and 3). Thus, large tools on the bed should be preferentially moved in the offshore direction beneath geostrophic flows superimposed upon shallow water waves.

Support for this inferred origin is provided by the observation of numerous bipolar, bimodal prod marks (attributed to wave-induced oscillatory motion) from the bases of storm-deposited sandstone beds and gutter casts in Triassic and Jurassic strata in Germany (Bloos 1982, fig. 5; Aigner 1982, fig. 3; Aigner 1985, fig. 44) and Ordovician strata in Ontario (W. L. Duke, unpubl. data). These occurrences may represent the exception that proves the rule: Firstly, they provide strong evidence that powerful oscillatory flows are capable of forming tool marks on the bases of hummocky cross-stratified storm beds. Secondly, the scarcity of reversing prod marks in the stratigraphic record and the relative abundance of offshore-directed prod marks suggest that powerful storm-generated waves typically are accompanied by at least a weak offshore-directed current component. In most cases, the relatively weak offshore current probably was produced by geostrophically balanced coastal downwelling.

Additional support for tool-mark generation beneath an inner boundary layer dominanted by wave-induced orbital motions can be found in a large majority of hummocky cross-stratified sequences with which the author is familiar. This support derives from observations of tool-mark orientations on relatively extensive exposures of the bases of beds. These exposures do not generally reveal well-aligned tool marks but rather exhibit marks with a wide spread of orientations (which nevertheless typically are clustered around a mean orientation normal to the inferred shoreline). Such a pattern is inconsistent with a near-bottom flow dominated by a steady unidirectional current (whether generated by a turbidity current or geostrophic circulation). In contrast, this pattern *is* consistent with unsteady reversing flows associated with a multidirectional wave spectrum. A good example of weakly aligned tool marks from the base of a storm-deposited sandstone bed has been figured by Gray and Benton (1982).

This generative scenario furnishes a simple explanation for slight deviations of sole marks from a true shore-normal orientation. Leckie and Krystinik (1989a, 1989b) report deviations as great as 20°; additionally, the sense of deviation in their northern hemisphere examples is commonly to the left (looking offshore). Within the context of the present interpretation, these slight angular deflections clearly represent wave-propagation directions at angles slightly less than 90° to shore. Further, assuming that the wave-propagation direction was roughly coincident with the dominant wind direction, the leftward deviation of sole marks is consistent with the generation of coastal set-up along the adjacent shoreline: just as the Coriolis force deflects deep flows driven by pressure differences, it also deflects surface flows driven by frictional coupling with the wind (see previous discussion). In the northern hemisphere, therefore, winds approaching the shoreline from the left (as indicated by leftward-deflected sole marks) would accordingly generate surface-water flow directed onshore, thus producing the coastal set-up required to form both the storm deposit and its sole marks (Fig. 4A). In contrast, winds approaching from the right (Fig. 4B) would commonly generate surface flows directed alongshore or offshore, and no coastal set-up or storm deposit would be produced; instead, upwelling flow would transport offshore muds landward over sand. Thus, the leftward deviation of sole marks, emphasized by Leckie and Krystinik (1989a) as inconsistent with geostrophic circulation, is actually an expected attribute of geostrophically balanced flows in the generative scenario advanced herein.

Much of the above reasoning can also be applied to other small paleocurrent indicators present at or above the bases of many storm-deposited sandstone beds. These indicators include current and parting lineations and large oriented or imbricated clasts. Although the somewhat smaller sand grains would be mobilized throughout a large portion of the wave cycle, small structures preserved in this sand would generally be aligned with the peak instantaneous transport direction. A grain-fabric study of storm-deposited sandstones (Cheel 1991) has recently provided strong observational support for this inference.

The hydrodynamic significance of other small paleocurrent indicators in these sequences is questionable. Elongate, straight to sinuous gutter casts are very common from the bases of storm-deposited sandstone beds; likewise, isolated sand-filled gutter casts encapsulated by mudstone also are common. Where present, gutter casts commonly possess orientations very similar to those of associated tool marks (e.g., Duke et al. 1990), and they commonly exhibit a laterally accreted sandstone fill (for examples, see Aigner 1982, fig. 9A; Aigner 1985, figs. 57B and 68D; Duke 1985b, figs. 5–39). Unfortunately, little is known of the genesis of these enigmatic features, and a complete discussion of their origin is beyond the scope of this paper. A hydrodynamic analysis of gutter casts will be presented elsewhere, however.

Other types of small paleocurrent indicators are derived mainly from the tops of storm-deposited sandstones. Small asymmetrical ripples cap many storm-deposited sandstone beds; they are generally thought to record waning, unidirectional, storm-generated currents (e.g., Hamblin and Walker 1979; Dott and Bourgeois 1982; Swift et al. 1987). The nature and origin of these bed forms is essential to the interpretation of Bouma sequences in storm deposits from deeper water, and the discussion of their generation is thus deferred to the companion paper.

Inferred Origin of High-Angle Cross-Bedding

As discussed previously, storm-generated dunes and sandwaves (and associated high-angle cross-bedding) in both modern and ancient shallow shelf systems typically yield approximately alongshore paleocurrent directions (consistent with the local sense of downwelling geostrophic circulation). I suggest that large ripples roughly reflect the time-averaged flow direction of storm-induced combined flows for three reasons:

Direction of Net Transport of Sand Moving as Bed Load.—As discussed above, the largest clasts transported by a combined flow (such as shell fragments) might be expected to move only under the peak instantaneous bottom shear stress, but smaller sand grains should be mobilized throughout a longer portion of the wave cycle. Thus, the direction of net sand transport for bed load moving over the stoss side of a large ripple should lie between the shore-normal peak stress direction and the shore-oblique direction of time-averaged shear stress.

Disruption of Inner Boundary Layer.—Laboratory and field experiments have elucidated the range of morphological and scalar variation in asymmetrical ripples formed under unidirectional flows and have defined the equilibrium stability fields of these different ripple forms (see summary by Harms et al. 1982). A hierarchy of superimposed trains of asymmetrical ripples, each scaled to overlapping unidirectional-flow boundary layers of different thickness, is common in deeper flows (see analysis by Smith 1970 and additional discussion by Middleton and Southard 1984, chapter 7).

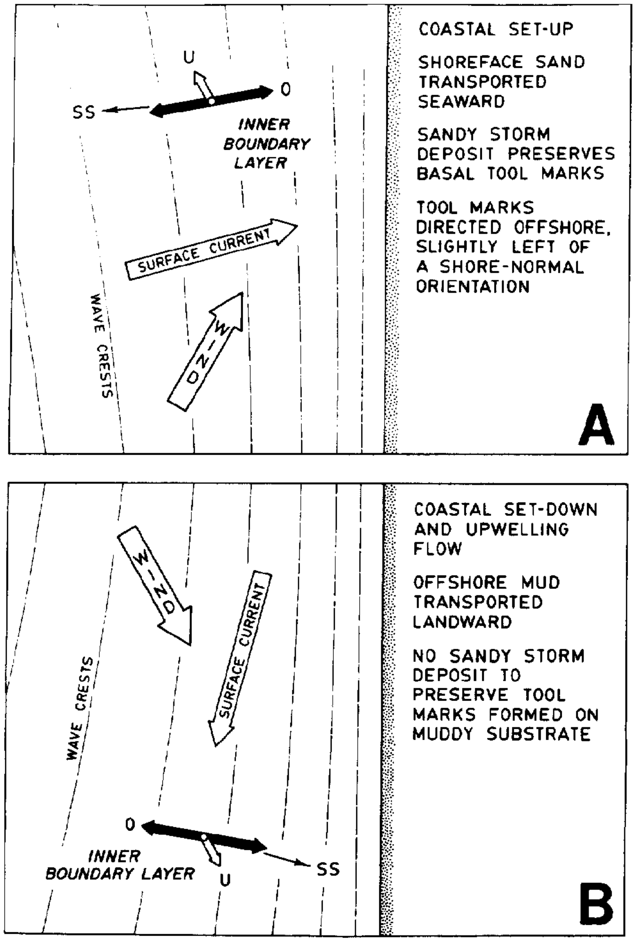


FIG. 4.—Wind and surface-water flow along a straight shoreline in the northern hemisphere, and qualitative representations of flow in the inner boundary layer. A) Onshore wind from the left (looking offshore). B) Onshore wind from the right (looking offshore). U = unidirectional component of bottom flow. O = oscillatory component of bottom flow. SS = direction of maximum instantaneous boundary shear stress and bottom-flow velocity. Note in (A) that the angular relationships between the bottom-flow components are such that the direction of maximum instantaneous shear stress is partially rectified (with respect to the shoreline) relative to the propagation direction of waves. Note also that coastal set-down commonly is small compared to coastal set-up; thus, the unidirectional current in the configuration of (A) typically is greater than that in (B). See text for further discussion.

In both modern and ancient storm-influenced deposits, cross-bedding formed by the migration of large ripples typically is much larger than the scale of the combined-flow inner boundary layer. This is true of both planar-tabular cross-bedding formed by sandwaves (the two-dimensional dunes of Ashley et al. 1990) and trough cross-bedding formed by dunes or megaripples (the three-dimensional dunes of Ashley et al. 1990). On the modern Atlantic shelf of North America, sandwaves typically possess heights ranging from several decimeters to over 7 m, and spacings of tens to hundreds of meters; their stoss sides typically are mantled by smaller dunes (Swift et al. 1979). Medium-scale cross-bed sets preserved in ancient sequences commonly are several tens of decimeters thick (e.g., Spearing 1976), implying formation of bed forms at least this tall. These include both planar-tabular sets and trough sets.

These dimensions suggest that large offshore ripples formed by storm-generated combined flows strongly modify or dirsupt the thin inner boundary layer. Indeed, the largest ripples could perhaps disrupt the entire bottom boundary layer. Turbulent eddies shed from these large bed forms place suspended sand high above the bed, well into the outer boundary layer or even the lower part of the core-flow region; here, the sand moves with the geostrophic current (compare with Fig. 1D and Fig. 3). Thus, the orientation of these large bed forms most likely develops as a response to the current-generated outer boundary layer, with which they are scaled.

Time to Development of Equilibrium.—By virtue of their size and the large mass of relatively coarse sand contained in individual bed forms, large ripples are relatively immune to modification by short-term deviations in flow characteristics, even if these are relatively energetic. Additionally, they require long periods of time (of the order of hours to perhaps years, depending on their size) to develop to their equilibrium geometry. Thus, large ripples represent the response of the substrate to the cumulative effects of flows much longer than a single half-stroke of a wave oscillation. The geometry of these ripples must therefore be controlled by the long-term average characteristics of all sediment-transporting flows to which they are exposed (rather than by instantaneous flow conditions), a conclusion previously reached by studies of large ripples on modern shelves (e.g., Swift et al. 1979). Clearly, therefore, the net transport direction of sand over an eddy-producing field of large ripples *must* be alongshore under typical storm-generated combined flows. This issue will be discussed more fully elsewhere.

As a result of these robust temporal and spatial characteristics of large ripples, paleoflow measurements obtained from cross-bedding in ancient storm-influenced shallow marine sequences probably provide the most accurate available approximation of the long-term time-averaged flow direction in the outer boundary layer.

Some Possible Tests of These Inferred Relationships

Angular relationships between various paleoflow indicators from a depositional sequence of inferred storm origin may provide stratigraphically based tests of the hydrodynamic relationships suggested above. As summarized in Figure 5 (left-hand bed), small structures from hummocky cross-stratified siltstones and finer sandstones should commonly exhibit shore-normal patterns reflecting the peak instantaneous flow direction of wave-induced oscillatory-dominant bottom flows. The sense of the *time-averaged* bedload-transport direction might be obtained only from the laterally accreted fill of gutter casts (where such infilling geometries are present).

As an aside, note that the hypothetical depositional process suggested herein is fully consistent with the origin of hummocky cross-stratification indicated by certain previous field and laboratory investigations. Various very different observations and lines of reasoning strongly suggest that this structure is generated beneath purely oscillatory flows or combined flows with unidirectional current components that are, in most instances, exceedingly small (e.g., Duke 1985a, 1985b, 1987; Leckie 1988; Southard et al. 1990; Arnott and Southard 1990; Cheel 1991). Within the context of the present scenario, the low-relief topographic features that produce hummocky cross-strata would be completely immersed within the strongly oscillatory-dominant inner boundary layer of combined flows. A more complete discussion of the genesis of hummocky cross-stratification is beyond the scope of the present paper but will be presented elsewhere.

In contrast, high-angle cross-bedding in coarser offshore sandstones should reflect nearly shore-parallel currents flowing obliquely offshore, as is characteristic of time-averaged bottom flows beneath geostrophic currents (Fig. 5, right-hand bed). However, tool marks from the bases of these sandstones, formed nearly instantaneously, should again be oriented at a high angle to the ancient shoreline. Similarly, current and parting lineations preserved on relatively flat laminae from the stoss sides of large ripples (or interbedded flat-laminated intervals) should also exhibit a nearly shore-normal orientation.

The generalizations above should only apply to storm beds deposited in ancient settings where 1) local bathymetric contours were essentially straight and parallel to shore, 2) oscillatory bottom flows were much faster than superimposed bottom currents, 3) waves were refracted to a nearly shore-normal propagation direction, and 4) the slowly varying bottom current was directed obliquely offshore. These conditions probably are most common on the lowermost shoreface and inner shelf. In shallower (upper shoreface) water depths, storm-generated currents locally are very intense and generally are oriented more nearly normal to shore. In greater (middle to outer shelf) water depths, wave-induced oscillatory motions commonly are weak relative to geostrophic currents, and storm waves are only partially rectified by refraction. Thus, the first tests of the inferred relationships shown in Figure 5 should be conducted in relatively shallow, proximal offshore storm deposits exhibiting abundant wave-formed vortex ripples with crests aligned parallel to an independently verified, straight shoreline trend. If these relationships prove successful under these circumstances, they have the potential to demonstrate a strong wave influence in deposits where vortex ripples happen not to be preserved; likewise, they might be used to obtain an estimate of the local shoreline trend in situations where it cannot be determined by other means.

Finally, note that current ripples from the tops of storm-deposited sandstone beds have not been represented in Figure 5, for two reasons. 1) It is probable that the uppermost parts of many beds were reworked after deposition by relatively weak flows associated with swell waves, tides, and/or geostrophic currents of variable orientation (see Fig. 4b). For this reason, paleoflow indicators capping storm deposits should not be included in the tests proposed above, except where vortex-ripple orientations are required to establish an approximate paleoshoreline trend. 2) As previously discussed, a consideration of issues surrounding the genesis of asymmetrical ripples at the tops of storm-deposited sandstone beds has been deferred to

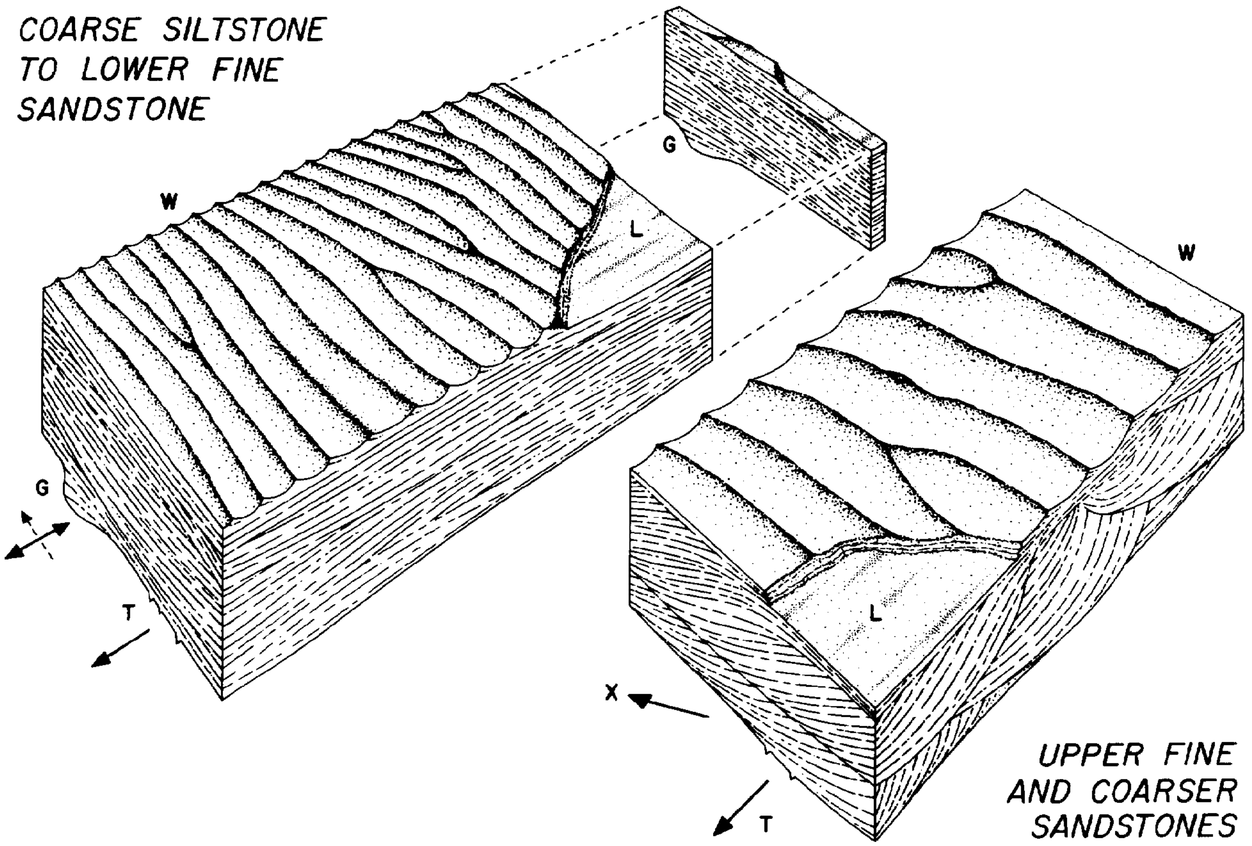


FIG. 5.—Hypothetical relationships between various paleoflow indicators in shallow marine storm beds deposited in the northern hemisphere. Angular relationships between the structures shown are herein considered to be diagnostic of deposition beneath combined flows resulting from the superimposition of shallow-water waves and a geostrophic current. G = gutter cast. L = current and parting lineations. T = tool marks. W = wave-formed vortex ripples. X = medium-scale high-angle cross-bedding (either planar-tabular or, as drawn here, trough cross-bedding). Note sense of direction of lateral accretion in the fill of the gutter cast. Also note that foresets within vortex ripples commonly (but not always) reveal shoreward translation of the ripple form, as drawn here. See text for further discussion.

a companion paper. One preliminary observation concerning bed-capping ripples is appropriate at this time, however. Leckie and Krystinik (1989b) reported numerous occurrences of vortex ripples with internal foresets indicating seaward translation of the ripple form (their "combined-flow ripples"). In my own experience, onshore-migrating vortex ripples, as drawn in Figure 5, also are fairly common (e.g., Duke 1985b, fig. A2–14; Duke et al. 1990, fig. 21). The landward translation of these latter ripples may have resulted from velocity asymmetry beneath shoaling waves, in which case a combined-flow origin need not be invoked.

SUMMARY

Abundant geological evidence clearly shows that sole marks (mainly tool marks) in most ancient storm-influenced prograding shoreline sequences do not reflect the time-averaged flow direction close to the bed under a geostrophically balanced current. Geostrophic flows are essentially shore-parallel, whereas the ancient tool marks are essentially shore-normal and directed offshore. This situation has led several workers to suggest that many ancient storm deposits were emplaced by storm-generated turbidity currents. Paradoxically, however, storm-induced turbidity currents are absent or rare on modern shelves, and thus it is highly unlikely that they could have been major depositional agents in ancient shallow marine systems.

Herein I suggest an alternative interpretation of storm-generated, shore-normal tool marks (and many other small paleocurrent indicators). In the proposed scenario, these structures reflect the dominant orientation of maximum *instantaneous* bed shear stress and near-bottom flow velocity under unsteady combined flows. These flows result from the superimposition of a steady or slowly varying geostrophic current and strong oscillatory fluid motions induced by shallow-water surface gravity waves. The direction of peak instantaneous bed shear stress and bottom velocity beneath oscillatory-dominant combined-flow events is essentially the same as that induced by waves in isolation from the current. Because large shoaling waves typically approach the shoreline at a very high angle, the orientation of maximum bottom shear stress and velocity is nearly shore-normal. Additionally, the magnitude of this stress and velocity is greatly increased on the offshore stroke of waves (and reduced on the onshore stroke) by superimposition of a unidirectional current with even a weak offshore component of flow (such as a geostrophic flow). This offshore flow enhancement accounts for the direction of asymmetrical tool marks on the bases of storm-deposited sandstone beds.

Thus, tool marks from storm-influenced shallow marine sequences tell us virtually nothing about either time- or depth-averaged storm currents in ancient shallow seas. However, their orientation *is* useful in determining local wave-propagation directions during storms.

It therefore is not necessary to invoke turbidity currents to explain small storm-generated structures with offshore-directed orientations (such as tool marks). Instead, the characteristic orientation and inferred mode of genesis of these small paleoflow indicators is fully consistent with the model of geostrophically balanced storm circulation developed from studies of modern shelf dynamics. Uniformitarianism thus compels us to accept this model as the norm for similar ancient systems.

Further support for geostrophic circulation in ancient systems is derived from coarser offshore storm deposits exhibiting medium-scale cross-bedding. Typically, these cross-beds indicate storm currents directed alongshore. Because large dunes and sandwaves disrupt the combined-flow inner boundary layer, suspending sand high above the bed, and because they require time periods greatly in excess of a single wave cycle to attain equilibrium, their orientation should reflect the time-averaged flow of the outer boundary layer. Beneath a geostrophic current, time-averaged flow in the outer boundary layer is directed approximately alongshore.

Pending further field and laboratory studies of substrate response to complex combined flows, the predicted angular relationships between various paleoflow indicators in ancient storm deposits may serve as stratigraphically based tests of the hydraulic relationships proposed herein.

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