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Origin of hummocky and swaley cross-stratification— The controlling influence of unidirectional current strength and aggradation rate

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Origin of hummocky and swaley cross-stratification—The controlling influence of unidirectional current strength and aggradation rate

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ABSTRACT

A series of wave-tunnel experiments was conducted to investigate the conditions under which hummocky and swaley cross-stratification form. Isotropic 3-dimensional (3-D) hummocky bed forms were generated under long wave periods (~8–10 s) and moderate oscillatory velocities (U_o ~50–90 cm/s) with very weak (< 5 cm/s) to no unidirectional flow. Hummocks became anisotropic with the addition of only a small unidirectional current (5–10 cm/s), and began to resemble unidirectional dunes when the unidirectional current was increased above 10 cm/s. Synthetic aggradation of the hummocky bed forms at high (4.2 mm/min) and low (1 mm/min) rates generated stratification resembling hummocky and swaley cross-stratification, respectively. Based on these findings, we suggest that hummocky cross-stratification optimally forms above (but near) storm wave base where aggradation rates during storms are high enough to preserve hummocks but unidirectional current speeds are sufficiently low to generate low-angle, isotropic cross-stratification. Swaley cross-stratification is also hypothesized to be deposited by an aggrading hummocky bed between fair-weather and storm wave base, but in shallower water where aggradation rates are low enough to cause preferential preservation of swales.

Keywords: shallow marine, combined flow, bed forms, hummocky cross-stratification, swaley cross-stratification.

INTRODUCTION

Over the past few decades two sedimentary structures have been widely reported from the shallow-marine sedimentary record—hummocky cross-stratification (Harms et al., 1975) and swaley cross-stratification (Leckie and Walker, 1982) (Fig. 1). Hummocky cross-stratification and swaley cross-stratification are thought to be genetically related (e.g., Leckie and Walker, 1982). Swaley cross-stratification commonly occurs above hummocky cross-stratification in upward-coarsening shallow-marine sedimentary successions, and resembles amalgamated hummocky cross-stratification, but without the hummocks (Duke, 1985; Leckie and Walker, 1982; Tillman, 1986; Walker, 1982). There is general consensus that both hummocky and swaley cross-stratification form during storms (e.g., Cheel and Leckie, 1993; Dott and Bourgeois, 1982; Duke, 1985; Harms et al., 1982; Leckie and Krystinik, 1989; Swift and Figueiredo, 1983; Walker et al., 1983). However, workers still disagree about how hummocky cross-stratification and swaley cross-stratification form. Are they generated by purely oscillatory flow (e.g., Dott and Bourgeois, 1982; Walker et al., 1983), unidirectional-dominated combined flow (e.g., Allen, 1985; Greenwood and Sherman, 1986; Swift and Nummedal, 1987), or oscillatory-dominated combined flow (e.g., Allen, 1993; Arnott and Southard, 1990; Cheel and Leckie, 1993; Duke, 1987; Duke et al., 1991; Higgs, 1990; Leckie and Krystinik, 1989; Midtgaard, 1996; Molgat and Arnott, 2001; Nottvedt and Kreisa, 1987)? Are hummocky and swaley cross-stratification scour-and-drape structures (e.g., Dott and Bourgeois, 1982; Harms et al., 1982; Midtgaard, 1996), or are they deposited by a dynamic bed form (e.g., Arnott and Southard, 1990; Duke et al., 1991; Leckie, 1988; Nottvedt and Kreisa, 1987; Southard et al., 1990; Swift and Figueiredo, 1983; Walker et al., 1983)?

The environment where hummocky and swaley cross-stratification form is yet another source of debate. Hummocky cross-stratification was originally proposed to form between fair-weather and storm wave bases in open-marine environments (Dott and Bourgeois, 1982). However, since then, it has been reported in fetch-limited settings (e.g., Eyles and Clark, 1986; Greenwood and Sherman, 1986), and at depths as shallow as the surf zone and foreshore (DeCelles and Cavazza, 1992; Greenwood and Sherman, 1986; Yang et al., 2005). Swaley cross-stratification is thought to form between fair-weather and storm wave base above hummocky cross-stratification but below beach deposits (e.g., Arnott, 1992; Duke, 1985; Plint and Walker, 1987; Tillman, 1986; Walker, 1982).

This experimental study was designed to define conditions (oscillatory and unidirectional velocities, oscillation period, grain size) under which hummocky bed forms are generated (Fig. 2). The effects of the addition of weak unidirectional flow (above a few cm/s) and of an increase in aggradation rate were then tested on the resulting hummocky bed forms. The purpose of this study was to answer some of the questions surrounding the debate on the origin of hummocky cross-stratification and swaley cross-stratification and to investigate the potential genetic link between these two enigmatic sedimentary structures.

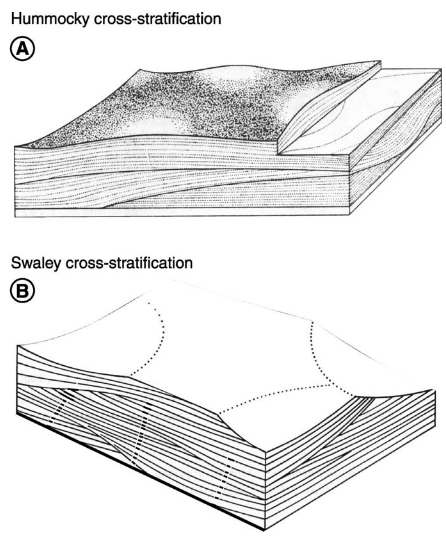

Figure 1. A: Hummocky cross-stratification (HCS) was first described by Harms et al. (1975) as gently dipping (<15°), cross-stratification in coarse siltstone to fine sandstone characterized by presence of both hummocks (convex-up, meter spacing, decimeters high) and swales (convex-down), and by erosional lower contact. Internal lamination is nearly parallel but also fluctuates in dip, giving fan-like appearance. Low-angle truncation surfaces are common but may become conformable when traced laterally. Cross-strata dip directions are scattered, and structure is isotropic in three dimensions. B: Swaley cross-stratification (SCS) was introduced by Leckie and Walker (1982, p. 143) to describe "a series of superimposed concave-upward shallow scours about 0.5–2 m wide and a few tens of centimeters deep" observed in fine to medium sandstone. In addition, basal surfaces are erosive, laminae rarely dip more than 10°, and structure is isotropic in three dimensions.

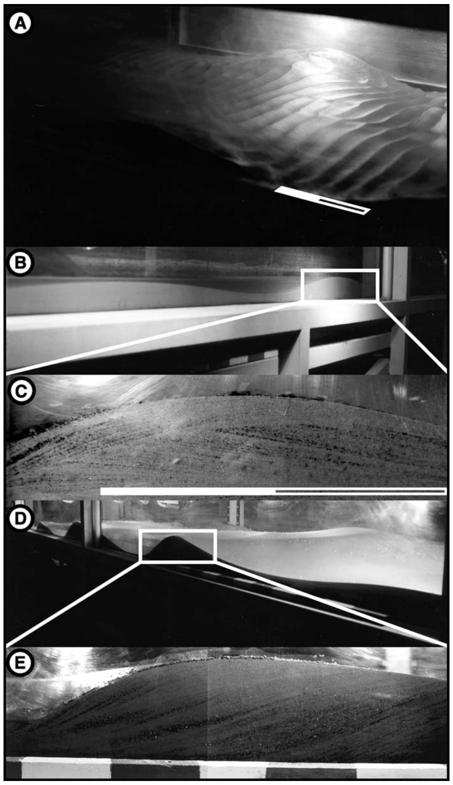

Figure 2. Hummocky bed forms generated in laboratory; scale bar divisions: 10 cm; grain size: 0.11 mm (very fine sand). Unidirectional current is from right to left. A: Oscillatory velocity (U_o) is 45 cm/s, unidirectional velocity (U_u) is 0 cm/s, oscillatory period (T) is 7 s. Note superimposed small-scale ripples. B: U_o = 65 cm/s, U_u = 5 cm/s, T = 9.4 s. C: Close-up view of stratification in B; note isotropic low-angle cross-stratification and bidirectionality of dip direction characteristic of low U_u hummocky cross-stratification (HCS). D: U_o = 65 cm/s, U_u = 10 cm/s, T = 9.4 s. E: Close-up view of stratification in D; note anisotropic nature of cross-stratification and single dip direction indicating migration with unidirectional current. This stratification style is intermediate between anisotropic hummocky cross-stratification (for its sigmoidal foresets and lee-face dip angle below angle-of-repose) and high-angle cross-stratification (for its single downstream dip direction).

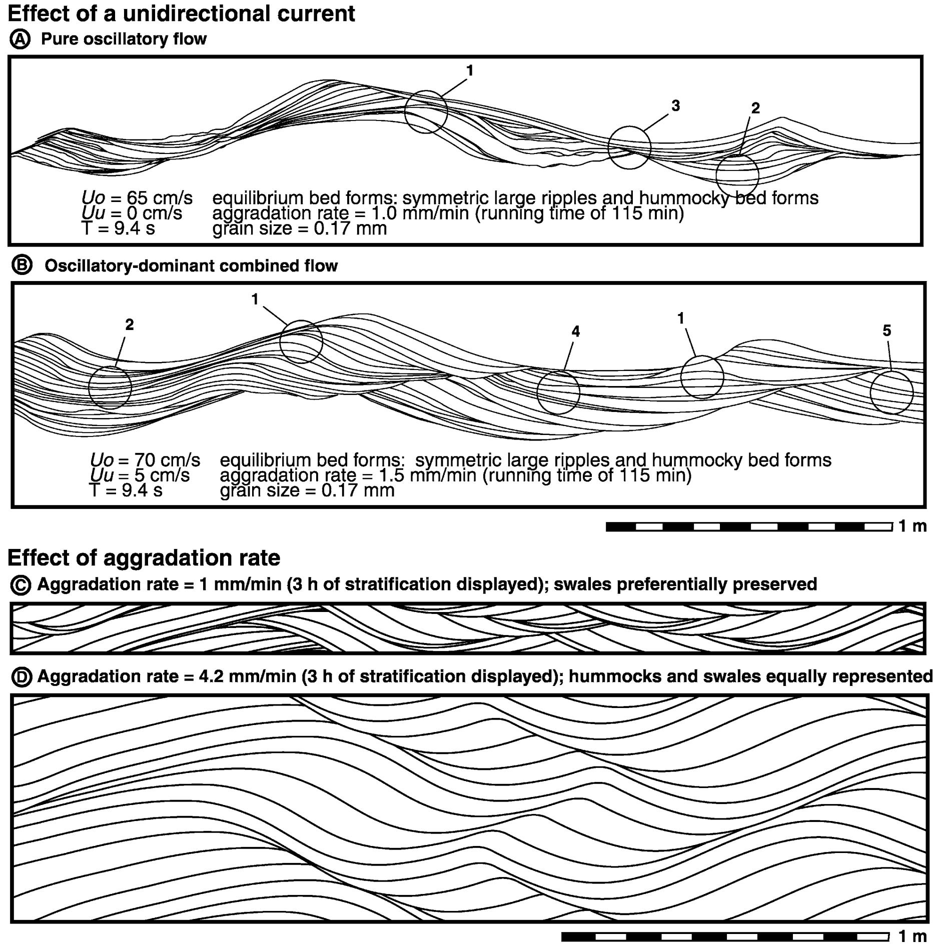

Figure 3. Synthetic stratification. Effect of a unidirectional current: Time series of 24 bed profiles taken at 5 min intervals for a total running time of 115 min. Vertical and horizontal scales are equal. Current is from left to right. The resulting stratification displays many of the diagnostic features of hummocky cross-stratification (HCS) as listed by Harms et al. (1975), including (1) hummocks, (2) swales, (3) truncation surface, which becomes conformable when traced laterally, (4) thickening and thinning of laminae, which result in fan-like stratification and fluctuating dip, and (5) low dip angles of laminae (<15°). A: Pure oscillatory-flow run; note isotropic stratification. B: Oscillatory-dominant combined-flow run; note anisotropic stratification. Effect of aggradation rate: Close-up view of one static bed profile (stacked 32 times). Profile was taken from experimental run where oscillatory velocity (U_o) was 65 cm/s and unidirectional velocity (U_u) was 0 cm/s (Dumas et al., 2005). Vertical and horizontal scales are equal. Dominant equilibrium bed forms during this run were meter-scale hummocky bed forms (biconvex flanks, round crests). C: Aggradation rate = 1 mm/min; note characteristic broad, low-angle swales, and uncommon convex-up laminae (hummocks). D: Aggradation rate = 4.2 mm/min; note better preservation of hummocks and consequential increase in average dip of cross-laminae.

METHODS

Experiments were conducted in a 15-m-long, 1.20-m-wide, and 0.65-m-deep combined-flow tunnel capable of generating long period (T) (7 and 9.4 s), high-velocity (U_o) (up to 125 cm/s) oscillatory flows to which a colinear unidirectional current could then be added (U_u) (0–25 cm/s) (see Dumas et al., 2005). Flow conditions were chosen to be representative of common shallow-marine storm conditions (Cheel and Leckie, 1993; Duke et al., 1991; Héquette and Hill, 1993; Wright et al., 1994). Runs were performed with two different sediment sizes (0.11 and 0.17 mm), which were chosen to be consistent with grain size commonly reported in the field. The data set consisted of 18 sets of experiments, each of which was composed of several runs (totaling 76).

Because of the enclosed nature of the wave tunnel, no new sediment could be added during a run. As such, in order to generate stratification, the bed was aggraded ''synthetically'' by sequentially stacking sidewall bed profiles (e.g., Southard et al., 1990).

EFFECT OF A UNIDIRECTIONAL CURRENT ON CROSS-STRATIFICATION

Figures 3A and 3B illustrate the effects of synthetically aggrading a hummocky bed under purely oscillatory flow (Fig. 3A) and under the same conditions but with a 5 cm/s unidirectional current added (Fig. 3B). Stratification in both profiles displays many of the diagnostic characteristics of hummocky cross-stratification outlined by Harms et al. (1975) (refer to Figs. 3A and 3B). The anisotropy observed in the combined-flow run resulted from preferential deposition on the bed form's lee side, and caused the bed form to migrate with the unidirectional current. This finding supports earlier work that suggested that the addition of only a small unidirectional current (a few cm/s) to an intermediate oscillatory flow (~50–90 cm/s) causes hummocks and their stratification to become anisotropic (Arnott and Southard, 1990). For a unidirectional current greater than ~10 cm/s, bed forms become sharp-crested and distinctly asymmetric, fore-

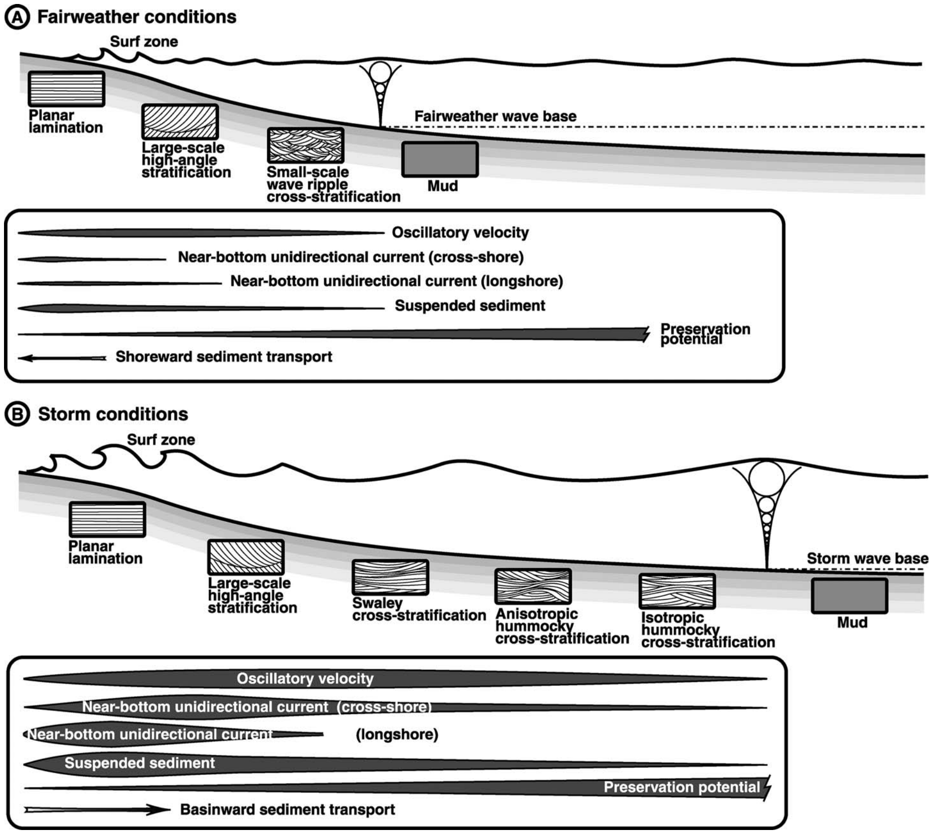

Figure 4. Onshore-offshore shallow-marine depositional profile. A: Fair-weather conditions. Sediment transport is shoreward with short-period, low oscillatory velocity affecting bottom from shoreline to fair-weather wave base. Both cross-shore and longshore near-bottom currents are very weak. Suspended sediment concentrations are low and peak in area of breaking waves. B: Storm conditions. Sediment transport is basinward with long-period, high oscillatory velocity waves affecting bottom from shoreline to storm wave base. Unidirectional currents are significantly stronger, with geostrophically balanced flow, assuming a shore-parallel direction for most of flow depth but becoming shore-oblique (offshore direction) near bottom. Suspended sediment concentrations are high and peak under breaking waves but remain high toward offshore. (See text for discussion on stratification style.)

sets become straight (rather than sigmoidal), lee-face dip angles increase to angle-of-repose, and bed forms migrate down current, producing unidirectional-dune-like cross-stratification (Dumas, 2004).

EFFECT OF AGGRADATION RATE ON CROSS-STRATIFICATION

Figures 3C and 3D illustrate the effects of varying the rate of synthetic aggradation of a hummocky bed. At the lower aggradation rate of 1 mm/min (Fig. 3C), swales are preferentially preserved and hummocks selectively eroded. The stratification style is similar to swaley cross-stratification. When aggradation rate is increased to 4.2 mm/min (Fig. 3D), the resulting stratification bears a striking resemblance to hummocky cross-stratification.

DEPOSITIONAL MODEL

Based on these results, we propose the conceptual model for the generation of swaley cross-stratification and hummocky cross-stratification on storm-dominated shorefaces shown in Figure 4. During fair-weather periods on most storm-dominated shelves, waves tend to be small, and near-bottom unidirectional currents are weak to absent. Bottom shear stress remains below the threshold for fine sand movement across most of the shelf, and as a consequence, sand movement is limited to the shoreface, commonly in depths of about ~10 m or less (Snedden et al., 1988). Near fair-weather wave base, small, symmetric wave-ripples may form under the action of small, symmetric wave orbitals (Clifton, 1976), producing thin, high-angle (>15°), scoop-based wave-ripple cross-sets with both onshore and offshore dipping laminae (e.g., De Raaf et al., 1977). As waves move progressively landward, wave orbitals increase in diameter, and wave orbital motions become increasingly asymmetric as bed friction preferentially slows wave troughs, generating shorter but stronger shoreward-directed orbital motions, longer and weaker basinward direction orbital motions, and net shoreward bedload transport (Swift et al., 1991). Bed forms formed under these conditions will tend to be asymmetric (Clifton, 1976), migrate onshore, and generate onshore-dipping high-angle (>15°) cross-stratification. At the shoreward limit of wave influence, in the swash and breaker zones, high shear stresses associated with breaking waves create sheet-flow conditions, forming planar lamination (Clifton, 1976).

By contrast, during storms, large waves and strong unidirectional currents are generated that, in combination, commonly strip sand from the upper shoreface and transport it offshore into deeper water (Vincent et al., 1982; Grant and Madsen, 1979; Snedden et al., 1988; Swift and Figueiredo, 1983). Variables considered important in the generation of hummocky bed forms, for example, the size, symmetry, and velocity of wave orbitals, the unidirectional current velocity, and the availability of sand, will likely vary across the shelf and shoreface during a storm (Fig. 4). Considering this, and taking into account our results, hummocky bed forms should develop optimally where net sedimentation rates are sufficiently high to preserve hummocks, in water that is shallow enough for wave orbitals to become large (>1 m) and fast (>50 cm/s), but deep enough for waves to remain symmetric and unidirectional currents slow (<10 cm/s). Near the shallow-water limit of the hummocky cross-stratification window, isotropic hummocky cross-stratification should be succeeded by anisotropic hummocky cross-stratification due to higher unidirectional current speed closer to shore. As an example of the possible depth range of hummocky cross-stratification, an extreme 5 d storm on the U.S. Atlantic Coast generated near-bed unidirectional currents just in excess of 10 cm/s in 13 m of water (Wright et al., 1994), and near-bed wave-orbital velocity (calculated from the method of Komar [1976], with wave period and height of 14 s and 3.5 m, respectively) fell below 50 cm/s in water just over 50 m deep. From this example, hummocky cross-stratification could be expected to form in water depths ranging from 13 to 50 m. Further up the shoreface, swaley cross-stratification is assumed to form under similar hydraulic conditions as hummocky cross-stratification but at lower net aggradation rates, which result from higher sediment transport rates. This landward position of swaley cross-stratification versus hummocky cross-stratification is supported by observations from the rock record, where swaley cross-stratification generally occurs above hummocky cross-stratification in upward-coarsening (progradational) shallow-marine successions (e.g., Arnott, 1992; Duke, 1985; Leckie and Walker, 1982; Tillman, 1986; Walker, 1982). In addition, an implication of the proposed depositional setting for swaley cross-stratification is the expected presence of non-negligible near-bottom offshore unidirectional currents, which, given the effect of even a weak unidirectional current on cross-stratification dip direction and migration, also implies that storm-generated swaley cross-stratification on a natural shelf setting should be slightly to moderately anisotropic. Further shoreward, the higher near-bottom offshore unidirectional current (>10 cm/s) would generate large-scale bed forms, that, if aggraded, would deposit large-scale, angle-of-repose cross-stratification that resembles unidirectional dune cross-stratification (Dumas et al., 2005). Finally, at the most shoreward position of wave influence, breaking wave conditions in the surf and swash zones would generate planar lamination.

In summary, these experimental results suggest that some (if not most) of the hummocky cross-stratification observed in the rock record was generated by actively aggrading and migrating hummocky bed forms under long period (8–10 s), high oscillatory velocity (U_o > 50 cm/s), and oscillatory-dominant combined flow ($U_u \leq 10$ cm/s). However, combined flow conditions would be more likely, because the unidirectional component of the flow provides a mechanism to advect sediment offshore and into the area of deposition.

Furthermore, hummocky cross-stratification and swaley cross-stratification are believed to be genetically linked, where swaley cross-stratification could be described as truncated anisotropic hummocky cross-stratification. The depositional setting of swaley cross-stratification is proposed to be likely of intermediate anisotropy and bathymetry between anisotropic hummocky cross-stratification and large-scale high-angle cross-stratification. And since, to the best of our knowledge, anisotropic swaley cross-stratification has yet to be reported from the geological record, a good validation of the proposed genetic and depositional models would be to see if, upon closer inspection, swaley cross-stratification deposits might reveal the predicted anisotropy.

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