

CHAPTER 6. FLOW, BEDFORMS AND STRATIFICATION UNDER OSCILLATORY AND COMBINED FLOWS

INTRODUCTION

Bedforms and stratification produced by unidirectional flows are well understood after almost a century of study in flumes and natural settings. However, in the geologic record of marine and lacustrine depositional environments other classes of fluid flow are important in producing structures that are preserved and form an interpretive basis for those deposits. Figure 6-1 summarizes a continuum of flow types, from purely unidirectional flows to purely oscillatory flows, between which are a range of mixed flows and their components are shown in the lower half of the figure. In this section we will begin by examining the nature of currents, bedforms and stratification produced by wind-generated waves on a free water surface (i.e., purely **oscillatory flow**). This will be followed by a very brief description of the bedforms and stratification that develop when unidirectional and oscillatory currents are superimposed to produce a general class of flow termed a **combined flow**. Note that figure 6-1 is a simplification of possible natural flows. To begin with, the classification shown in figure 6-1 does not consider the angular relationship between the oscillatory and unidirectional components: the resultant current produced by co-linear flows (i.e., both act in the same direction) will be much less complex than in the case where the oscillatory component acts at some angle to the unidirectional component. In addition, in natural flows several different oscillatory and unidirectional components may act simultaneously to result in a very complex flow pattern. In nature such patterns exist and experimental work, like that described in the section on bedforms, is limited to the relatively simplistic approach.

GENERAL CHARACTERISTICS OF GRAVITY WAVES

Waves generated by wind blowing over a water surface are prevalent in most marine and lacustrine settings. Such waves are commonly referred to as **gravity waves** because gravity is the most important force acting to dampen these waves (i.e., gravity acts to restore the water surface to a flat surface after a wave has been generated by wind).

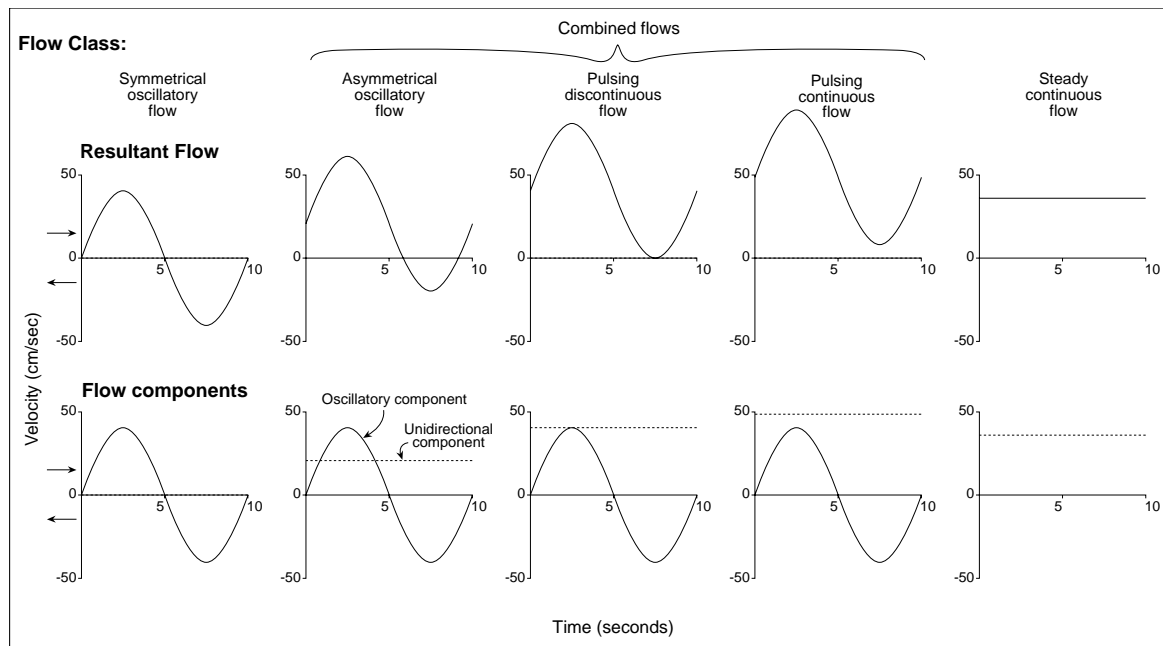


Figure 6-1. Flow classes defined in terms of the relative strength of their oscillatory and unidirectional components. Top graphs illustrate the pattern of variation of velocity over time of the net flow and the lower graphs show the oscillatory and unidirectional components of each flow separately. After Swift *et al.*, 1983.

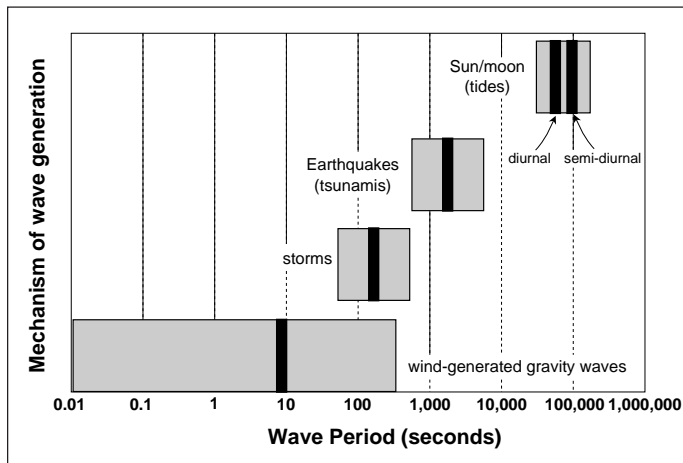


Figure 6-2. Wave classification by wave period and the mechanisms that generate waves on large water bodies such as oceans. Each shaded bar shows the range of wave periods generated by each mechanism and the solid black bars indicate the wave period that generates the maximum wave energy in the oceans due to each generating mechanism. The bar at approximately 10 seconds represents wind-generated waves by average wind conditions on the oceans; the bar representing a period of just over 100 seconds is associated with long period and wave length “swell” generated by storms. The bar associated with wave periods of approximately 2000 seconds (about half an hour) are waves generated by earthquakes (*Tsunamis*). The two bars on the far right represent, from left to right, tides with semidaily (or semidiurnal; two tidal cycles per day) and daily (or diurnal; one tidal cycle per day) periods.

Gravity waves are just one particular type of wave that acts in large water bodies such as oceans (Fig. 6-2) and they account for much of the total energy possessed by the worlds oceans.

The majority of gravity waves on a water surface are generated by wind moving over that surface. While the exact mechanisms of wave formation are not well understood the response of the water surface to wind is well known. Waves develop as sinusoidal oscillations of the water surface that propagate (i.e., travel) in the direction of the wind. The characteristics of wind-generated gravity waves (e.g., their size) depends on a number of factors that include wind speed, duration of wind and the distance over which the wind acts on the water surface (this distance is termed **fetch**). Waves will propagate beyond the region of wave generation and may travel thousands of kilometres and take days to dissipate. Waves that have left their region of generation are termed **swell**. Swell waves are typically very long, relatively low and straight-crested.

Any description of gravity waves must include wave length (L ; also referred to as wave spacing), wave height (H), wave celerity (C ; the speed at which the wave moves along the water surface, and wave period (T , where $T = L/C$; the time required for one full wave-length to pass a fixed point). All of these wave characteristics are determined by the intensity, duration and fetch (the distance over which the wind acts on a water surface) of the wind that generates them. To illustrate figure 6-3 shows the scales of waves produced by various wind speeds acting over seas with unlimited fetch.

Gravity waves are classified by the relationship between their wave length and the depth of water through which they are moving (this affects the form of the waves and waves in deep water undergo a number of changes as they move into shallow water; see below). **Deep water waves** are waves with lengths that are no more than two times the depth (h) of water over which they are moving (i.e., $h > L/2$; note that this depth is commonly called **wave base**). **Transitional waves** have longer wave lengths relative to water depth, between the limits $L/20 < h < L/2$. **Shallow water waves** are waves have lengths that are at least 20 times the water depth (i.e., $h < L/20$).

The geologically important result of gravity waves on the water surface is the fluid motion that they generate, motion that may result in sediment transport and the formation of primary sedimentary structures. The nature of fluid motion associated with waves is very complex and this section will only discuss this topic in a very superficial manner and in terms that will be particularly important to later discussion of the sedimentary structures generated by waves. The best general text that describes gravity waves and their products is that by Komar (1976).

To begin the discussion of fluid motion under waves we will consider so-called **deep water waves** that do not interact significantly with the bottom (i.e., the sediment substrate at some depth below the water surface is unaffected by the passage of such waves). Figure 6-4A shows the characteristics of a train of deep water waves. Fluid motion beneath such waves is complex and is shown in a simple but instructive manner in Fig. 6-4A. If we

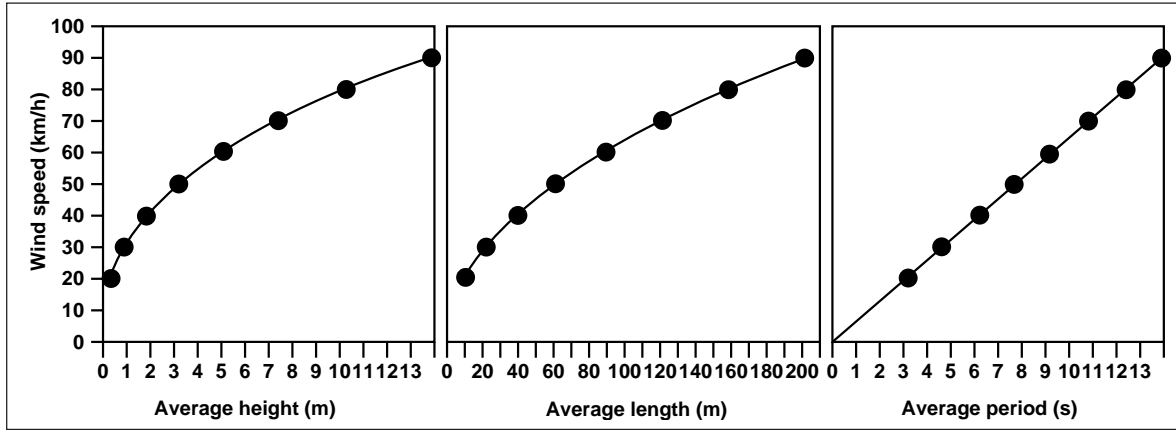


Figure 6-3. Wave conditions as a function of wind speed for a fully developed sea. Data from Thurman, 1988.

follow the path of a single water molecule as a wave passes one complete wave-length the path appears circular: motion is in the direction of propagation under the crest and in the opposing direction under the trough and at intermediate angles and directions, through 360°, at other positions beneath the passing wave (Fig. 6-4A). This circular path is referred to as the **wave orbital** and its diameter is termed the **orbital diameter** (d_o). Under deep water waves the orbital diameter becomes exponentially smaller with depth until it is of negligible size and the orbital diameter is related to depth by:

$$d_o = H e^{\frac{2\pi y}{L}}$$

Eq. 6-1

where y is a negative number indicating the distance below the water surface and L is the wave length. The wave orbitals persist but become negligible below the depth equal to $L/2$. The speed of fluid motion about the orbitals at any time during the passage of a single wave is termed the **orbital speed**. The orbital speed just as the crest and trough pass by is termed the **maximum orbital speed** (U_m); U_m is equal but acts in opposite directions beneath the crest and trough, as outlined above. The maximum orbital speed varies with depth by its relationship to the orbital diameter, given by:

$$U_m = \frac{\pi d_o}{T}$$

Eq. 6-2

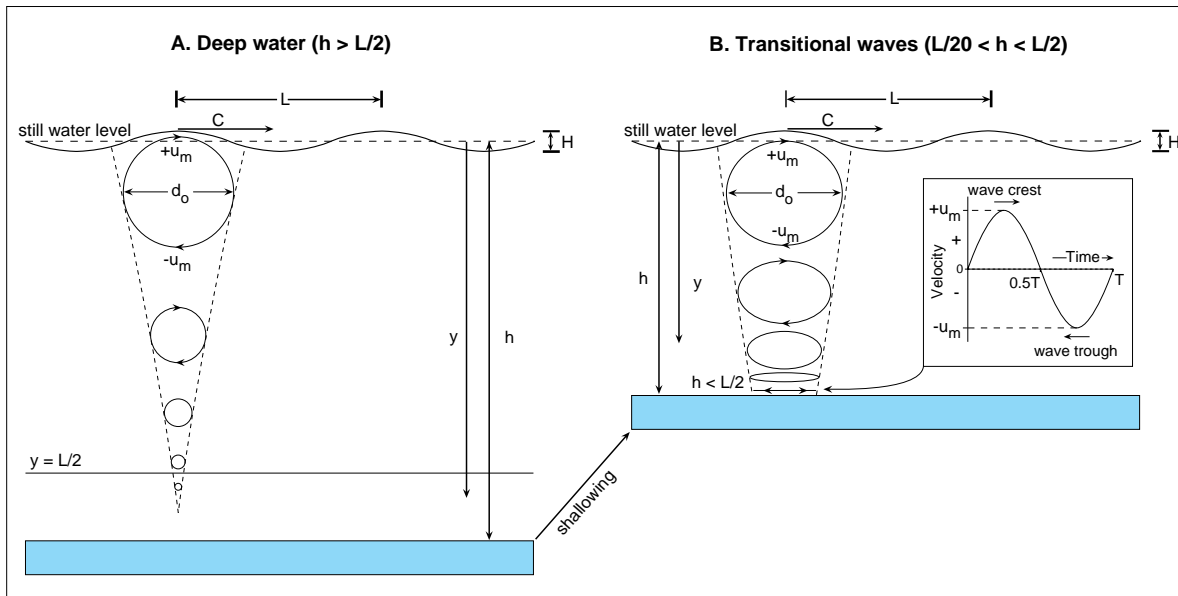


Figure 6-4. Characteristics of deep water and transitional waves. See text for discussion.

At the water surface the orbital diameter is equal to the wave height (i.e., $d_o = H$), such that:

$$U_m = \frac{\pi H}{T} \quad \text{Eq. 6-3}$$

As waves propagate into shallow water (at depths less than $L/2$) they begin to interact with the bottom and undergo several changes and the relationships given above no longer hold. A particularly important change involves the refraction of the wave crests to a position that parallels the isobaths of the bottom (isobaths are lines joining points of equal depth). Because isobaths approximately parallel the shoreline, refraction also aligns the waves parallel to the shoreline. In addition, waves become steeper due to an increase in H and the formulae given above no longer accurately describe the behaviour of the current that they generate. Steepening increases until the deep water wave height becomes 75% of the water depth (i.e., $h = 4H/3$); at this depth the wave will break. Concurrent with steepening of the wave the wave orbitals become elliptical, and increasingly flatter with depth until along the bottom (Fig. 6-4B) the motion of fluid molecules (and any sediment in transport) follows a line that is parallel to the bottom surface. Under transitional waves the rate of decrease in orbital diameter with depth is much less than the rate under deep water waves (Fig. 6-4B). Under transitional waves the orbital diameter is given by:

$$d_o = \frac{HT}{2\pi} \sqrt{\frac{g}{h}} \quad \text{Eq. 6-4}$$

where g is the acceleration due to gravity. Note that under shallow water waves the orbital diameter does not change with distance below the water surface but is constant. The maximum orbital speed under transitional waves is given by the general relationship for shallow water waves:

$$U_m = \frac{H}{2h} \sqrt{gh} \quad \text{Eq. 6-5}$$

(note that from here on we will assume that U_m is the maximum orbital speed acting on the bottom because that is where the sedimentologically important work is done).

BEDFORMS AND STRATIFICATION UNDER PURELY OSCILLATORY CURRENTS

As under unidirectional flows, bedforms begin to develop under oscillatory flows as soon as the flow conditions exceed some threshold for the initiation of movement of sediment. Also, the forms of bedforms, and their associated internal stratification, vary with the strength of the current. However, because of the very fundamental differences between unidirectional and oscillatory flows the properties of the flow that control when sediment will move and what bedform will be stable must also differ.

Initiation of sediment motion under waves

It is the to and fro fluid motion acting on the bottom that may produce bedforms and stratification if the strength of the oscillatory current exceeds some threshold condition required for the initiation of particle motion. Under unidirectional flows we saw that the critical flow condition for motion of a particle depends on the size and density of the particle, the density of the fluid, and the boundary shear stress (that was related to the flow velocity and depth). The condition for the initiation of motion of sediment under oscillatory currents may be similarly determined by the fluid and sediment properties but the flow strength is normally represented by the maximum orbital speed and the orbital diameter or wave period. Orbital diameter and wave period are important components of flow strength because they determine the spatial extent over which the maximum orbital speed acts and its duration. Komar and Miller (1973) determined that the critical condition for the movement of sediment under waves can be defined in a manner that is superficially similar to Shield's criterion for motion under unidirectional flows, by the general relationship:

$$\frac{\rho U_t^2}{(\rho_s - \rho)gD} = C \left(\frac{d_o}{D} \right)^n \quad \text{Eq. 6-6}$$

where U_t is the threshold maximum orbital speed required to move sediment; ρ is the fluid density, ρ_s is the density

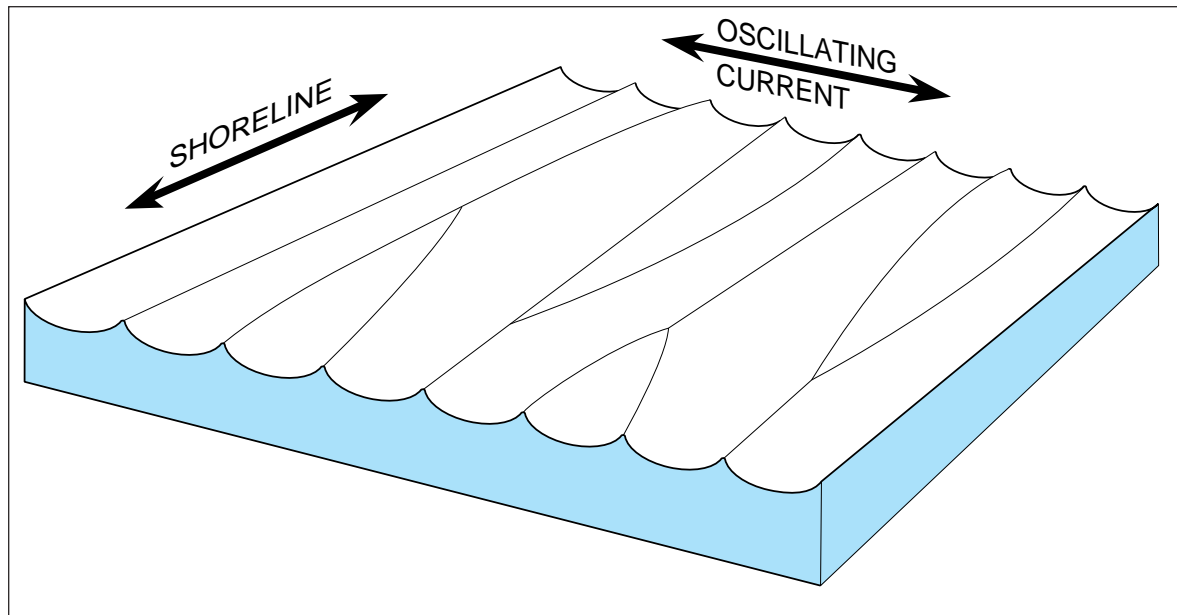


Figure 6-5. Schematic illustration of classical “wave ripples” or 2-D vortex ripples. Note the cross-sectional form and straight to gently bifurcating crestlines. The direction of oscillation and inferred shoreline orientation are shown for comparison. Note that no scale is shown but ripple spacing may range from centimetres to in excess of a metre, increasing with grain size. See text for discussion.

of the sediment, g is the acceleration due to gravity, and D is the size of the particles. C and n are constants that are determined by the size of the sediment. For grain sizes finer than 0.5 mm $C = 0.21$ and $n = 0.50$. For grain sizes coarser than 0.5 mm $C = 1.45$ and $n = 0.25$. Note in Eq. 6-6 that d_o varies with wave period (see Eq. 6-2 and 6-4) so that the threshold maximum orbital speed similarly varies with wave period: the longer the wave period the larger the threshold maximum orbital speed required to move the sediment.

Bedforms under waves

For many years one particular type of bedform has been considered diagnostic of the influence of waves on a sediment substrate: symmetrical ripples (commonly called wave ripples and the modern term is 2-D vortex ripples). Today we know that there are actually a variety of bedforms that develop under waves but before considering these in detail we will briefly focus on the common wave ripple.

So-called “wave ripples” are distinct from the “current ripples” produced by unidirectional flows by their symmetrical profile, relatively peaked crest and broad trough, and by their straight to bifurcating crestlines (Fig. 6-5). These are a very common bedform in shallow marine sediments and occur extensively on bedding plane exposures. The spacing of such ripples (λ) ranges from centimetres to in excess of a metre and they range in height from millimetres to about a decimetre. The overall size of wave ripples varies directly with grain size and small scale symmetrical ripples form in fine sand and large scale symmetrical ripples form in gravel. When such ripples form they are molded on the bed beneath the propagating gravity waves and their crests are aligned parallel to the crests of the water surface waves (but do not confuse these with in-phase waves of unidirectional flows). An important implication of the alignment of ripple crests is that, like the wave crests, such ripples will be aligned parallel to regional shoreline (a characteristic that was nicely demonstrated by Leckie and Krystinik, 1989). Some symmetrical ripples have two crests, aligned at approximately 90° to each other, and normally one crest is better-developed (the dominant crest) than the other. For many years such ripples were termed **interference ripples** and taken to represent the condition when symmetrical ripples form under two sets of gravity waves that propagate at right angles to each other. However, recent, as-yet unpublished, experimental studies have shown that interference patterns of ripple crests can develop under certain conditions when only one wave train is active. Thus, the standard interpretation

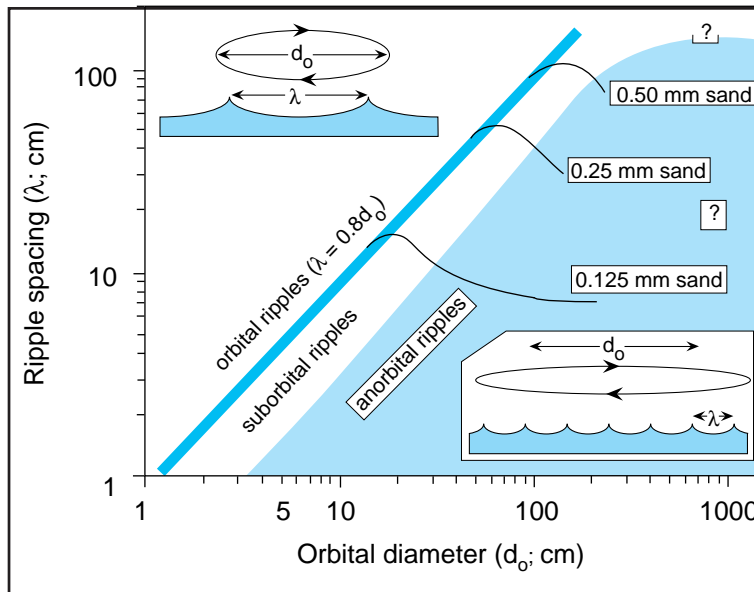


Figure 6-6. Schematic illustration showing the relationship between symmetrical ripple wave-length and the diameter of wave orbitals. Data are not shown. The dark, shaded line (labelled “orbital ripples”) is defined by ripples with lengths equal to 80% of their associated wave orbitals. Solid lines (labelled with grains sizes) indicate the limiting ripple wave-length for the grain size indicated. The shaded area represents the region of anorbital ripples. The drawings illustrate the relationship between symmetrical ripples and their wave orbital for orbital ripples (upper left) and anorbital ripples (lower right). See text for further discussion.

of this particular form of symmetrical ripple is now in doubt.

Many basic textbooks that discuss the humble wave ripple point out that the spacing of such ripples is determined by the diameter of the circular wave orbital that forms them. In general, the ripple spacing is slightly less than the orbital diameter acting on the sediment substrate (see Eq. 6-8). Considering the above discussion this idea makes sense for transitional waves under water depths just less than $L/2$ when a more-or-less circular orbital is present. However, it is difficult to conceive of shallow-water waves (as described above) producing such ripples. Figure 6-6 schematically illustrates observations of symmetrical ripple spacing (λ , the orthogonal distance between crests) from natural and experimental settings where the orbital diameters of the formative waves are known. When we plot ripple spacing against orbital diameter the data occur in two indistinct groups. Some ripples have spacings that are directly related to wave orbital diameter by the relationship:

$$\lambda = 0.8d_o \quad \text{Eq. 6-7}$$

Such wave ripples are termed **orbital ripples**. However, many wave ripples do not fall on the line defined by Eq. 6-7 but deviate from that line because their wave-lengths are much shorter than the orbital diameter and such ripples are termed **anorbital ripples**. Ripples with wave-lengths that fall between these two classes are termed **suborbital ripples**. Note that with increasing grain size the maximum ripple wave-length also increases (i.e., the coarser the sediment the larger the maximum possible ripple wave-length). This suggests that for any grain size there is an upper limit to the size of ripples that will form. Below the limit, a single orbital ripple will exist for every orbital diameter acting on the sediment surface and beyond that limit several individual anorbital ripples will be stable under a relatively long orbital diameter. The relationship between ripples and wave orbitals is shown schematically in figure 6-6.

The above discussion points to the fact that there are a variety of bedforms that develop under oscillatory flows. Over the past decade, experimental studies have helped describe these bedforms in terms of their morphology and behaviour and the hydraulic conditions that are necessary to form them. Harms et al. (1982), based largely on experimental work in John Southard’s labs at M.I.T., described bedforms under oscillatory flows in the manner that the unidirectional bedforms are described. In the remainder of this section we will consider the sequence of bedforms that develop under oscillatory flows much like we did the unidirectional flow bedforms in the previous chapter of these notes.

Consider an experiment where we induce oscillatory fluid motion (i.e., back and forth) over a sandy substrate in a closed tunnel. There is no free-water surface but the speed of the oscillatory current varies gradually in both

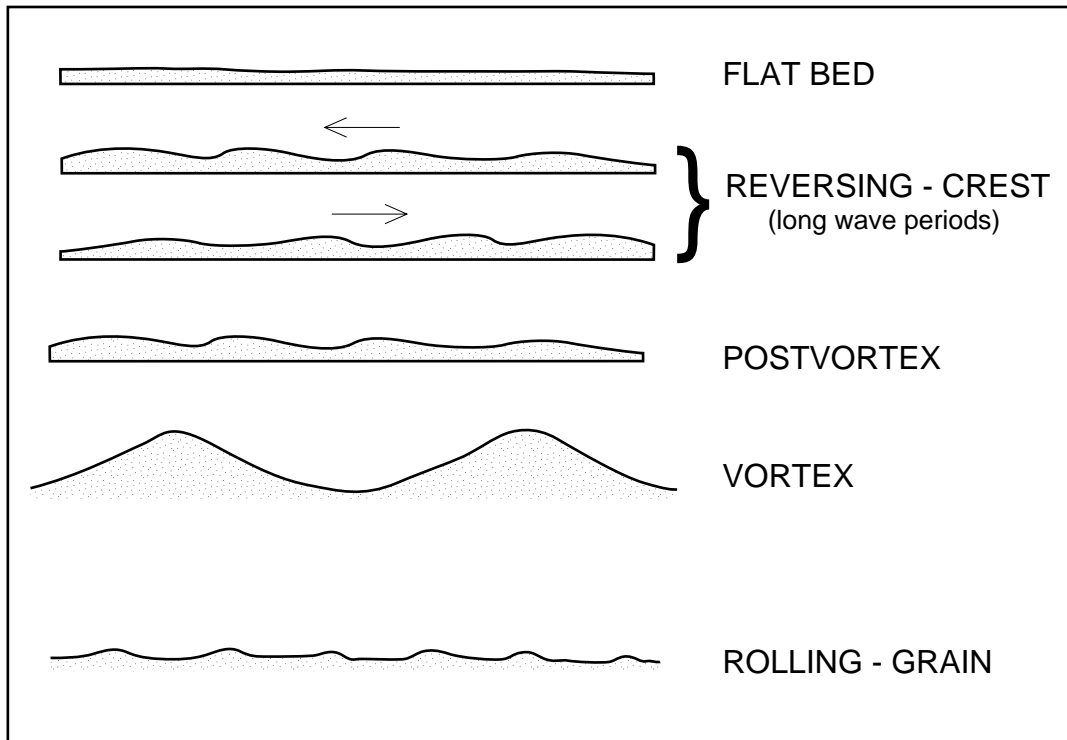


Figure 6-7. Schematic illustration of the bedforms that develop under oscillatory currents. From the bottom upwards the sequence of bedforms reflects the sequence that develops with increasing maximum orbital velocity (except for the reversing crest ripples). See text for further discussion. After Harms et al. (1982).

speed and direction (over 180°) and the maximum velocity, in either direction, is comparable to the maximum orbital velocity under waves. The duration of the current in either direction is related to the wave period and the distance over which the current moves during one oscillation is related to the wave orbital diameter. Like the mental experiment that we conducted to describe bedforms under unidirectional flows, in this case we will consider the sequence of bedforms that develops with increasing flow strength (maximum orbital speed) holding all other variables constant. Note that not all of the following bedforms will develop under a given wave period or bed grain size, as we shall see when we look at a bedform stability diagram for oscillatory flows.

The sequence of bedforms that develops under oscillatory flows is shown schematically in figure 6-7. Just as the current begins to move the sediment (i.e., the maximum orbital speed exceeds the threshold for motion) the first bedforms that develop are termed **rolling grain ripples**. These bedforms are small with lengths less than 10 cm and heights on the order of a few millimetres to approximately 1 centimetre. Rolling grain ripples are symmetrical in profile, have low slopes, and are straight-crested. Sediment movement over rolling grain ripples is as traction: grains roll back and forth under the oscillating current. This bedform is thought to be “metastable”, that is, over time they slowly grow in size (particularly height) and become **vortex ripples**. Under somewhat larger maximum orbital velocities vortex ripples develop quickly and are stable. Vortex ripples include the common form of wave ripple described above in the opening paragraphs of this section on bedforms. As noted above, they are symmetrical in cross-section and have slopes that are steeper than rolling grain ripples. Vortex ripple lengths vary from centimetres in fine sand to in excess of a metre in gravel and similarly vary in height from approximately a centimetre to a decimetre. Sediment transport over vortex ripples is both in traction and suspension. The first vortex ripples to develop are straight-crested (2-dimensional) as depicted in figure 6-5. However, as the orbital speed increases vortex ripples become increasingly 3-dimensional in plan view. The 3-D vortex ripples grow larger (with wavelengths in excess of 1 m) and form rounded bedforms with hummocks (areas of positive relief) and swales (areas of negative relief) on the bed (see top block diagram in Fig. 6-11). Such large, 3-D vortex ripples are sometimes referred to as “hummocky ripples”. Note that these large ripples may someday become thought of as dunes under oscillatory flows. With a further increase in maximum orbital speed the 3D-vortex ripples become flatter and somewhat shorter

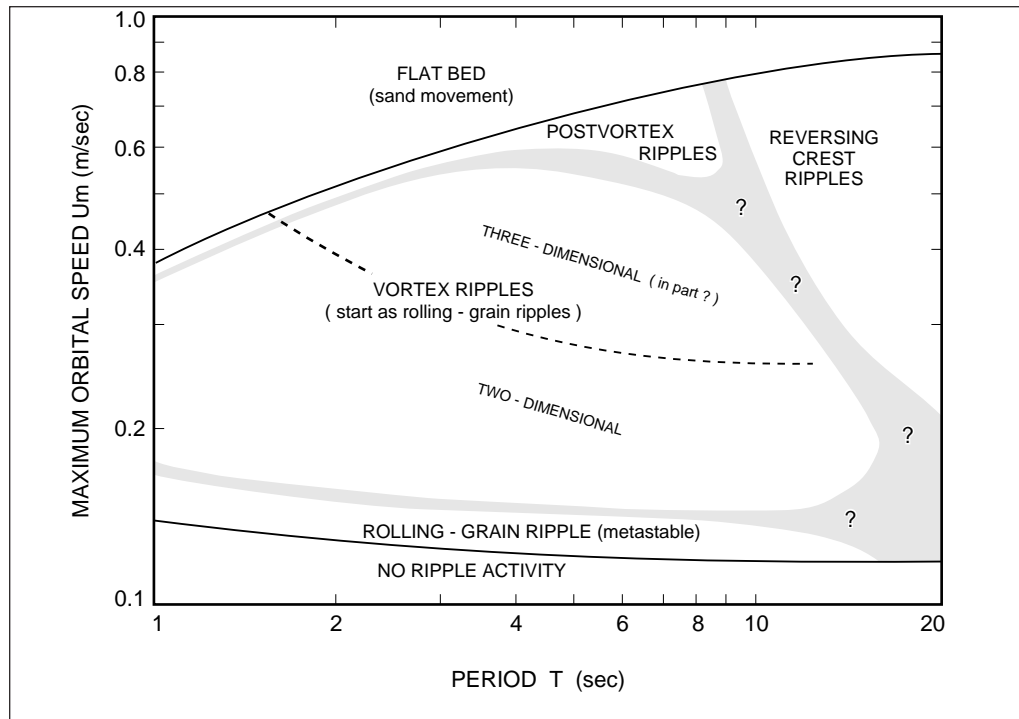


Figure 6-8. Diagram illustrating the fields of stability of wave-formed bedforms on beds of fine sand (0.15 to 0.21 mm). After Harms et al. (1982).

to form **post-vortex ripples**. These bedforms can be thought of as transitional forms with **flat bed**, an essentially flat, featureless bedform that develops under the highest orbital velocities and experiences intense sediment transport. The so-called flat bed of oscillatory flows is morphologically similar to upper plane bed of unidirectional flows (and many authors term the oscillatory bedform plane bed). Another bedform that develops under oscillatory currents, but only under waves with relatively long periods, is termed **reversing-crest ripples**. These bedforms are generally less than 10 cm long and rather low and are somewhat asymmetrical. They derive their name from the fact that they reverse in direction as the current reverses. This characteristic is possible because under waves with long periods the duration of flow in one direction is sufficiently long to generate a small, asymmetrical ripples (like ripples under unidirectional flows). Thus with each oscillation the current reverses and so does the direction of migration of the asymmetric ripples. These particular bedforms illustrate that bedforms under oscillatory flows are very similar to those under unidirectional flows but the current acting in one direction, under normally short period waves, does not persist long enough to generate bedforms like those under unidirectional flows.

Figure 6-8 shows a bedform stability diagram for fine, quartz sand (0.15 to 0.21 mm) in terms of orbital speed and wave period (we are ignoring the effects of temperature). Note that diagrams for other grain sizes will have similarly formed fields but at different positions (i.e., for coarse sand the fields shift upwards so that all transitions occur at higher maximum orbital velocities). Figure 6-8 shows that the sequence of bedforms with increasing maximum orbital speed are essentially as outlined above and reversing-crest ripples appear to replace other bedforms at significantly high wave periods. The range of conditions over which post-vortex ripples are stable extends to lower maximum orbital velocities with increasing period. Figure 6-8 is after Harms et al. (1982) but more recent experiments by Southard et al. (1990) have documented, in more detail, the development of vortex ripples with increasing orbital speed.

Stratification formed by oscillatory currents

Like bedforms that develop under unidirectional flows, bedforms under oscillatory currents result in a variety of forms of cross-stratification that differ in detail due to the geometry and behaviour of the generative bedforms.

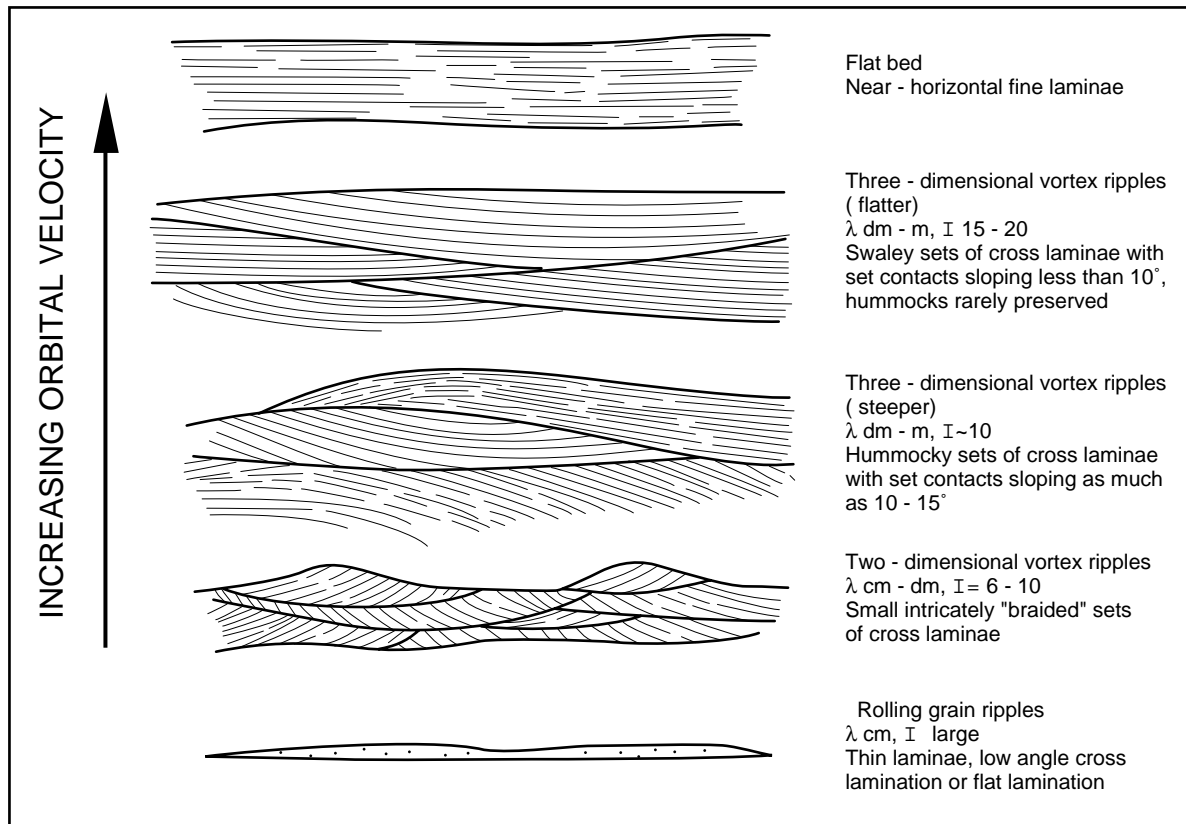


Figure 6-9. Forms of cross-stratification produced by wave-generated bedforms on slowly aggrading beds. Note that “ I ” is the ripple index (ratio of length to height). After Harms et al. (1982).

To make a broad generalization: the features of wave-formed cross-strata that distinguish them from those formed by unidirectional flows are (1) a wide variation in cross-strata dip directions (although this is not always the case; see below) and (2) the symmetrical, curved bounding surfaces that are sometimes preserved, reflecting the symmetrical form of the bedform. In addition, as we saw in the section on grain fabric, particle alignment in the deposits of wave-generated currents is distinctly different from that under unidirectional flows; under purely oscillatory flows the vector mean dip of particles may be horizontal.

Figure 6-9 depicts the forms of cross-stratification that develop under waves with increasing maximum orbital velocity (i.e., under the various bedforms described in the previous section) under conditions of vertical aggradation of a bed. Note that exact forms of stratification will vary, depending on the aggradation rate and the rate of ripple migration (if any; see below). This description follows that of Harms et al. (1982) and remains somewhat speculative although the discussion below includes some observations from recent experiments by Southard et al. (1990) and Arnott and Southard (1990).

Rolling grain ripples produce thin, sub-parallel laminae that may or may not display internal cross-lamination. As the bedforms grow to 2-D vortex ripples the internal cross-laminae become prevalent and the form of cross-stratification is complex. Under purely oscillating currents the internal cross-strata produced by 2-D vortex ripples form sets of alternately dipping laminae bounded by curved erosional surfaces. Such sets are sometimes said to be “braided” and form a particular type of cross-stratification that is termed **chevron cross-stratification**. The exact form of the cross-stratification produced by 2-D vortex ripples will depend on the behaviour of the bedform, which in turn depends on the symmetry of the oscillatory current. The thickness of cross-strata sets depends on the size of the ripples that form them; therefore, set thickness will be strongly influenced by the grain size of the sediment (larger bedforms and cross-strata sets are possible in sediment of coarse grain size). The form of cross-stratification

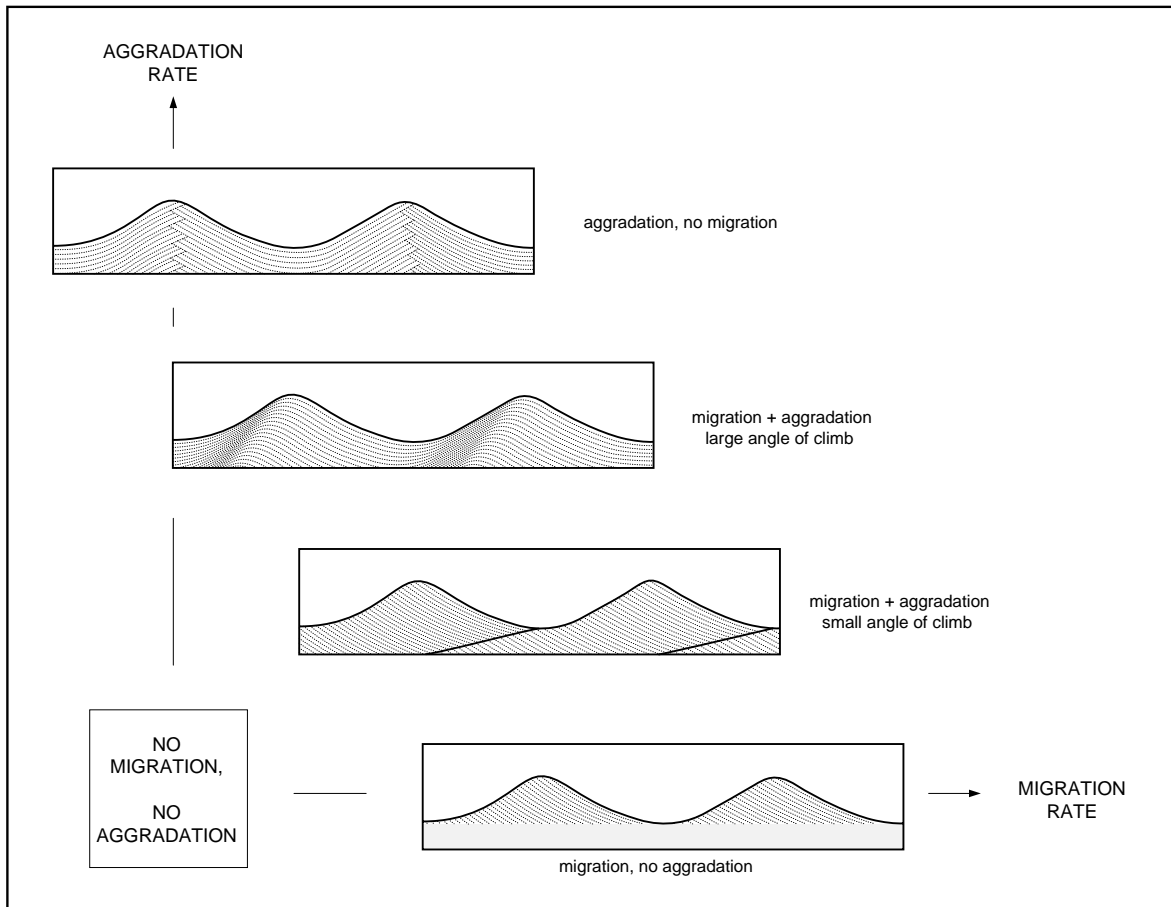


Figure 6-10. Schematic illustration showing the idealized forms of cross-stratification produced by 2-D vortex ripples as a function of their rate of migration and the rate of bed aggradation. After Harms et al. (1982).

shown in figure 6-9 is limited to purely oscillatory flows but in nature it is not unusual for even wave-generated currents in shallow water to have an asymmetry that induces a somewhat stronger current in one direction. Such asymmetrical currents may cause 2-D vortex ripples to migrate in the direction of the strongest component of the oscillatory current. Like current ripples, the form of cross-stratification that is preserved will vary with the rate aggradation of the bed. Thus, there are a variety of forms of cross-stratification produced by 2-D vortex ripples that depend on the combined effects of bed aggradation and the rate of ripple migration. Figure 6-10 shows the continuum of forms of cross-stratification that may be produced by 2-D vortex ripples as a function of bed aggradation and ripple migration rates. Note that with ripple migration and no bed aggradation the internal cross-strata dip only in one direction and might appear like cross-strata produced by current ripples under unidirectional flows. The similarities continue for the migrating ripples as increasing aggradation rates produce climbing forms of ripple cross-stratification. The preservation of symmetrical ripple forms is probably necessary to allow reliable distinction of cross-stratification produced by waves from current ripple cross-stratification formed under similar conditions of bed aggradation. In addition, even the migrating wave-generated bedforms may preserve local sets of cross-strata that dip in the direction opposing the average direction of ripple migration, the presence of such sets should suggest wave-generated currents. Only when the ripples do not migrate in a preferred direction will true chevron cross-stratification develop in which the proportion of cross-strata dipping in one direction or the other are approximately equal.

Returning to figure 6-9, with increasing maximum orbital velocity, as the bedforms grow and become more rounded and three-dimensional, the forms of cross-stratification change to mimic the morphology of the bedforms. As depicted in figure 6-9 there are two forms of stratification produced by 3-D vortex ripples. The first to develop,

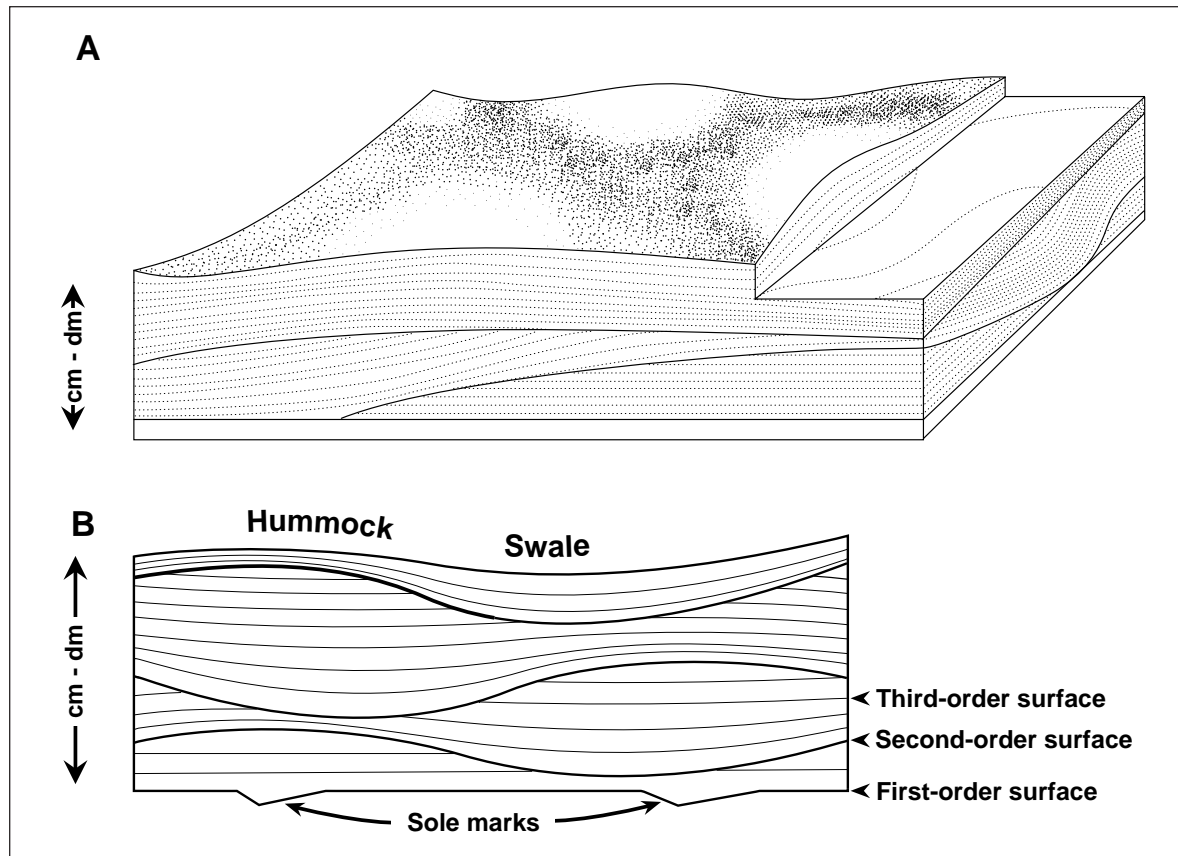


Figure 6-11. Schematic illustrations of hummocky cross-stratification. A. A block diagram showing the form of the three-dimensional bedform that is thought to produce HCS (3-D vortex ripples). B. The details of the internal structure of HCS. See text for details. From Cheell and Leckie (1992).

with increasing orbital velocity above that which 2-D vortex ripples are stable, is characterized by sets of both concave- and convex-up internal strata (termed swaley strata and hummocky strata, respectively) bounded by similarly shaped bounding surfaces. This form of cross-stratification is termed **hummocky cross-stratification (HCS)**, consistently one of the most enigmatic primary sedimentary structures over the past two decades (see the final section of this chapter for a closer look at this form of cross-stratification and the debate that it has generated). Figure 6-11 shows a large, hummocky, 3-D vortex rippled bed surface and the form of HCS that the bedform is thought to produce. Internal lamination in HCS dip at angles up to 15° and are isotropic (i.e., dip with equal frequency in all directions). Based on the descriptions of the bedforms that are believed to generate HCS, the spacing of hummocks should vary from approximately a decimetre to in excess of a metre. With increasing maximum orbital velocity figure 6-9 suggests that the next form of stratification is similar to HCS except for two distinctive characteristics: internal laminae dip at shallower angles (not exceeding 10°) and only swaley (concave) laminae are preserved. This form of cross-stratification is termed **swaley cross-stratification (SCS)**. The different form of SCS, compared to HCS, may be attributed to the lower relief of the bedforms and the greater scour of the bed (planing off hummocks) under the greater maximum orbital velocities. With increasing maximum orbital velocity, through the field of post-vortex ripple stability, the internal strata and their bounding surfaces must become increasingly flat and produce a form of horizontal lamination by deposition on a wave-generated flat bed. This form of horizontal lamination has not been extensively studied and descriptions of such lamination does not provide a basis for distinguishing it from upper plane bed horizontal lamination of unidirectional flows. Intuition suggests that internal fabric may provide a diagnostic criterion for the identification the formative processes responsible for this structure. Note that the internal structure of reversing crest-ripples is not well known. Presumably, with bed aggradation, they will form laterally and vertically alternating (or at least varying) sets of cross-strata that dip in opposing directions.

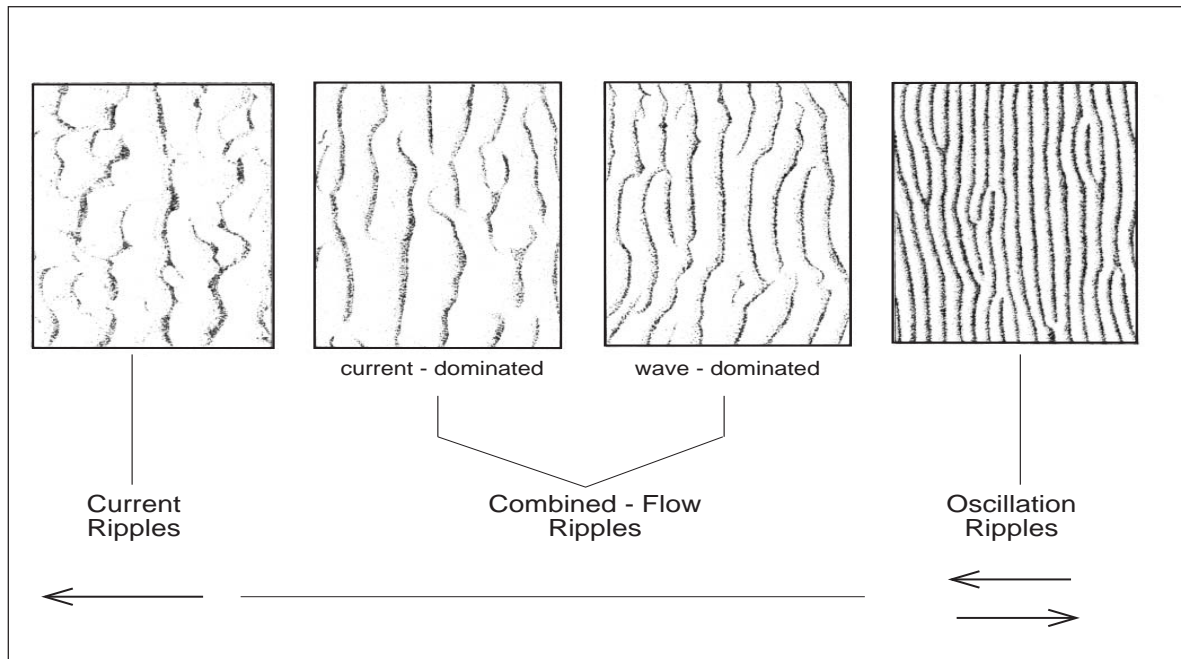


Figure 6-12. Plan view of ripples produced on beds of 0.28 mm sand by current, waves and combined flows. Note that net flow is from right to left and the boxes are 75 cm across. After Harms (1969).

The asymmetrical ripple form, if preserved, should distinguish this form of such cross-stratification from that produced by 2-D vortex ripples.

BEDFORMS AND STRATIFICATION UNDER COMBINED FLOWS

This brief section relies heavily on the results of recent work on the bedforms and stratification that develop under combined oscillatory and unidirectional flows. The flows considered are the result of the superposition of wave-generated currents (see above) on simple unidirectional currents to produce temporal variation in flow strength (e.g., velocity) as shown for combined flows in figure 6-1. Because this section is brief, the description of both bedforms and their stratification will be combined.

Figure 6-12 shows the differences in plan form of wave ripples (2-D vortex ripples; formed under purely oscillatory flows), current ripples (produced under purely unidirectional flows) and combined flow ripples. Note that the major differences are the smaller spacing, straighter crests of wave ripples, and symmetrical profile of wave ripples, compared to combined flow and current ripples, and the changes are gradual from one ripple type to the other. Internal stratification may reflect the differences in ripple behaviour: current ripples may have better developed unimodal dip directions of internal cross-strata. However, as noted above, true wave ripples may also migrate in one direction to produce similarly unimodal-dipping internal cross-strata.

Figure 6-13 is based on experimental work by Arnott and Southard (1989) who used a combined flow wave duct to simulate waves with an 8.5 second period acting on a bed of very fine sand. The apparatus was similar to that used to simulate purely oscillatory flows but included a recirculating pump to induce a unidirectional current within the duct. The graph shown in figure 6-13 is one of many such graphs that could be constructed for combined flow, each representing a narrow range of grain size and wave periods. The sequence of bedforms along the vertical axis is the sequence described for purely oscillatory flows (note that they did not go to high enough maximum orbital velocities to produce a wave-formed flat bed). Note also, that this figure suggests that there is a gradual transition from 2-D vortex ripples to 3-D vortex ripples and current ripples. The large 3-D vortex ripples have been termed hummocky ripples in an attempt to emphasize that these bedforms likely produce the hummocky cross-stratification that is common in the geologic record of shallow marine sediments. These hummocky ripples appear to be stable

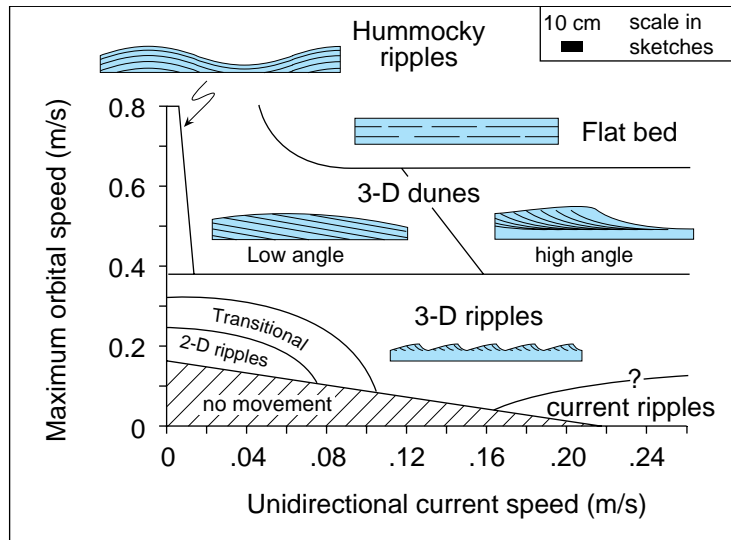


Figure 6-13. Very schematic illustration showing the bedforms and their internal stratification produced in a duct by combined flows with an oscillatory component with a period of 8.5 seconds acting on a bed of very fine sand. Note that structures along the vertical axis are formed under purely oscillatory flows and structures along the horizontal axis are formed under purely unidirectional flows. After Arnott and Southard (1989) and Duke, Arnott and Cheel (1991).

only under purely oscillatory flows or under combined flows with only a **very** weak unidirectional component. When the velocity of the unidirectional component of a combined flow is only a few percent of the oscillatory velocity the hummocky bedforms become asymmetric in profile and migrate in the direction of the unidirectional component, producing low angle inclined cross-strata that are isotropic (dip in one direction in contrast to the anisotropic dip of hummocky cross-strata). With a further increase in the strength of the unidirectional component the bedforms become steeper and more asymmetric and produce high angle cross-stratification. Note that these large bedforms, formed under combined flows are termed dunes in figure 6-13 (they were termed “large ripples” in the original paper by Arnott and Southard, 1989) and that they form under much lower unidirectional velocities than under purely unidirectional flows because of the superimposed oscillatory current. Indeed, combined flows appear to produce large, dune-like bedforms that would **not** develop under purely unidirectional flows over fine sand. In addition, the superposition of an oscillatory component reduces the threshold unidirectional flow strength required to produce upper plane bed (or flat bed).

Figure 6-14 is similar to figure 6-13 but includes a wider range of orbital and unidirectional flow velocities and figure 6-15 schematically shows the forms of cross-stratification produced by the various bedforms. Figure 6-15 indicates that there is a more-or-less gradual change in the styles of cross-stratification produced by oscillatory and combined flows but that the overall geometry of the stratification should provide a basis for distinction of the generating flow types. However, this work is currently in its infancy and will require further experimentation and observations from the ancient record before we have a good foundation for interpreting the formative processes that produce these primary structures.

THE ENIGMA OF HUMMOCKY CROSS-STRATIFICATION

Note: Earlier in this chapter we introduced a form of cross-stratification termed hummocky cross-stratification (HCS) and attributed its formation to the presence of 3-D vortex ripples on an aggrading bed. This view of HCS is one of several that appear in the literature and the debate on the origin of this primary sedimentary structure is ongoing. This section aims to focus on HCS and to show that its interpretation is not so straight-forward.

Hummocky cross-stratification became popular during the late 1970's and early 1980's as its widespread recognition followed description by Harms *et al.* (1975), although it had been earlier reported under different names (e.g., truncated wave-ripple laminae, Campbell, 1966; crazy bedding, Howard, 1971; truncated megaripples, Howard, 1972). The presence of HCS has since become a prime criterion for the recognition of ancient shallow-marine storm deposits; however, its reliability as an unequivocal criterion for this environment is now less certain. Despite the fact that HCS is widely accepted to be the product of waves, the structure continues to be the focus of ongoing debate regarding its mode of formation and, by implication, its specific paleohydraulic interpretation. HCS in marine deposits has been variously attributed to formation by oscillatory flows produced by waves, combined oscillatory and unidirectional flows, and purely unidirectional flows. This diversity of hypotheses for HCS formation is justified

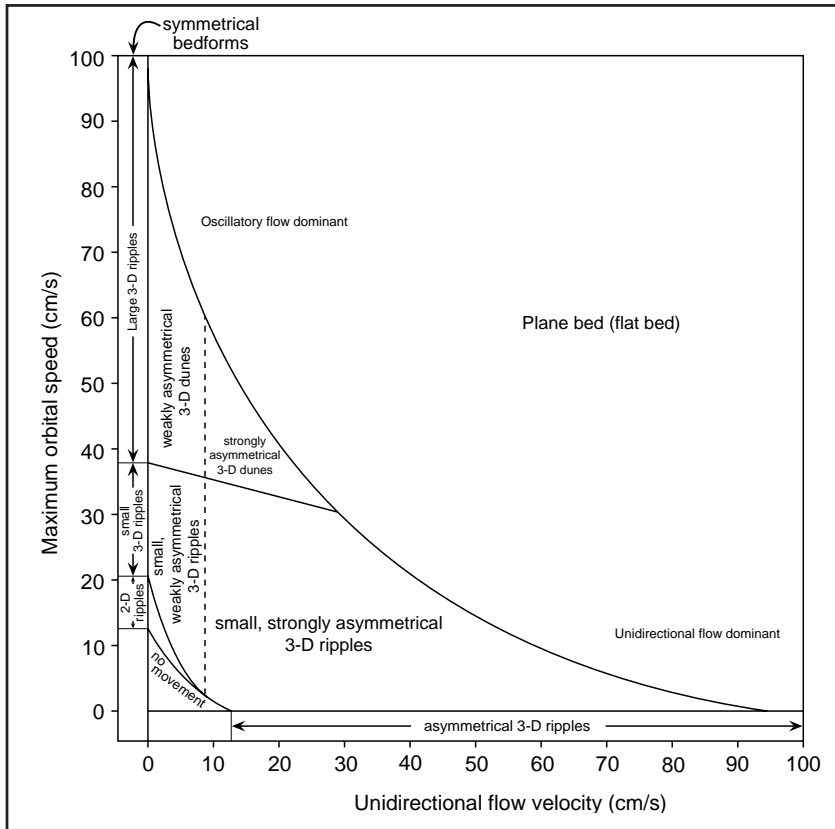


Figure 6-14. Extended bedform stability diagram for combined flows with an 8.5 second period oscillatory component acting on a bed of fine sand. Compare with figure 6-15 for the forms of cross-stratification produced under the conditions shown. After Myrow and Southard (1991).

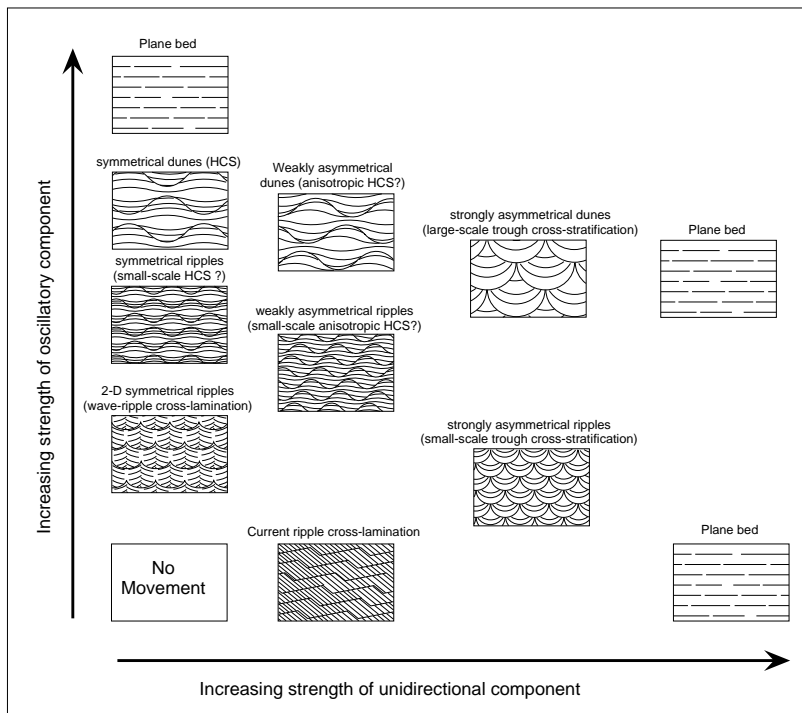


Figure 6-15. Highly schematic illustration showing the forms of cross-stratification produced by combined flows with an 8.5 second period oscillatory component acting on a bed of fine sand. Compare with figure 6-15. Based on Myrow and Southard (1991).

because the basis for its interpretation is not as sound as that for many other sedimentary structures that are readily visible in modern settings or produced in laboratories. For example, our knowledge of the relationship between paleohydraulics and stratification formed under unidirectional flows is quite advanced because we can easily dissect recognizable bedforms developed under known hydraulic conditions in rivers, intertidal areas and flumes, to precisely document the geometry of their internal structure. In contrast, HCS is found largely in ancient sediments and sedimentary rocks where paleohydraulic conditions must be inferred from associated deposits and structures. Thus, HCS has been largely interpreted on the basis of inference rather than direct observation of the relationship between hydraulic processes and the form of the structure. The argument over the origin of HCS has been further complicated by the recognition of similar forms of stratification in settings in which wind-generated water surface waves were an unlikely mechanism in its formation. The growing range of physical settings in which HCS-like stratification may have formed may justify the suggestion (Allen and Pound, 1985) that HCS has become just a “bucket term” that embodies similar stratification styles that may be generated by a variety of processes or combinations of processes.

This section of these notes aims to describe HCS, in detail, and indicate that there is no consensus at this time as to the exact origin of this form of cross-stratification although recent data points to an origin of HCS under purely or strongly oscillatory dominant flows.

HCS—description and associations

Because of the paucity of modern and experimental examples of HCS, its paleohydraulic interpretation has largely been based on its preserved characteristics in the geological record. The following description will review the basis for the recognition of HCS, including its common stratigraphic and sedimentologic associations, and stress characteristics that have led to the various ideas on HCS formation.

Characteristics of HCS

Grain Size

The grain size of sediment in which HCS occurs varies from coarse silt to fine sand (Dott and Bourgeois, 1982; Brenchley, 1985; Swift *et al.*, 1987). HCS in coarser sediment is relatively rare but has been reported. Brenchley and Newall (1982) described HCS in sandstones with mean grain sizes ranging from 0.7 - 1.1 mm (i.e., up to coarse sand). Walker *et al.* (1983) noted that gravel may comprise beds displaying HCS. However, in cases where gravel-size sediment is present in HCS, the gravel normally makes up a small proportion of the total grain size distribution and is found largely as lag-deposits on surfaces within or at the base of beds displaying HCS. Therefore, the consensus seems to be that HCS is most common in very fine to fine-grained sand with the frequency of its occurrence decreasing dramatically with increasing grain size.

Morphology and geometry

Harms *et al.* (1975, p. 87) provided an early description of HCS (Fig. 6-11A) that has remained fundamental over the years (*cf.* Harms *et al.*, 1982). They pointed to four essential characteristics of individual cross-strata sets as being: (1) low-angle (generally less than 10° but up to 15°), erosional bounding surfaces; (2) internal laminae that are approximately parallel to the lower bounding surface; (3) individual internal laminae that vary systematically in thickness laterally and their angle of dip diminishes regularly; (4) dip directions of internal laminae and scoured surfaces are scattered (i.e., dipping with equal frequency in all directions). They also postulated that the stratification was due to deposition on a scoured bed surface characterized by low hummocks (bed highs) and swales (bed lows) with a spacing of one to a few metres and with a total relief of between 10 and 50 cm. Hence, the form of the internal stratification was one of convex-upward hummocky laminae and concave-upward swaley laminae, essentially draped over the hummock and swale topography of the basal scoured surface (Fig. 6-11B).

Following Campbell (1966), Dott and Bourgeois (1982) employed a hierarchy of surfaces (Fig. 6-11B) to provide a careful description of HCS based on their observations. Here we employ their descriptive terms but details also come from other sources (Bourgeois, 1980; Hunter and Clifton, 1982; Brenchley, 1985).

First-order surfaces are surfaces of lithic change in discrete HCS beds (discussed below) and may bound HCS cosets or beds containing a sequence of various structures. The basal surface is commonly nearly flat and erosional, although local relief, up to several tens of centimetres may occur due to the presence of tool marks (scratches, grooves, prod-marks), gutter casts and/or rare flutes. This surface may be mantled with a lag of coarse debris of inorganic (intraclasts and/or extraclasts) or biogenic origin (e.g., shell or bone material). In some instances, the upper surface is deeply-scoured with a hummocky appearance whereas in many other cases this surface is rippled. Cosets of HCS range from decimetres to several metres in thickness, although the thickest cosets may actually consist of several amalgamated beds.

Second-order surfaces are erosional surfaces within HCS cosets and are normally responsible for the form of the stratification. They cut third-order surfaces but are contained by the first-order surfaces and therefore bound HCS sets (Fig. 6-11B). These surfaces commonly form the distinctly “hummocky” surfaces in HCS that are characterized by laterally alternating synforms (swales) and antiforms (hummocks), although the antiforms are generally less common than the synforms. The relief on second-order surfaces ranges from several centimetres to approximately 50 cm (the same relief reported for hummocks and swales) with rare, extreme dip angles of up to 35°. HCS sets range from several centimetres up to two metres in thickness although the latter extremes are probably the result of the amalgamation of beds. The erosional character of these surfaces may be obvious where relatively sharp, angular discordances occur between second and third-order surfaces or may be subtle where third-order surfaces are nearly tangential with second-order surfaces. The angular relationship commonly varies laterally, giving second-order surfaces the appearance of changing from discordant to concordant surfaces along an individual bed. The visibility of second-order surfaces is due largely to their angular relationship with underlying strata. A change in grain size is typically not evident across second-order surfaces although they may be mantled by dispersed shale and/or siderite rip-up clasts, pebbles and shell debris. Such surfaces, exhumed in outcrop, typically display the hummock and swale topography described above. Most commonly, the plan form of hummocks and swales is circular, although elongate forms have also been reported (e.g., Handford, 1986). Exhumed second-order surfaces may display forms of parting lineation including parting-step lineation (McBride and Yeakle, 1963) and current lineation (Allen, 1964).

Third-order surfaces bound individual laminae within HCS sets and account for many of the diagnostic characteristics of this structure although their visibility may depend on such fortuitous factors such as the degree of weathering of the outcrop and cementation. Third-order surfaces are nearly concordant with underlying second-order surfaces which normally determine their overall geometry of internal laminae. Angles of dip are typically highest directly above erosional second-order surfaces but decrease upwards. Third-order surfaces are commonly mantled by mica, clay or comminuted plant debris (in many post-Silurian examples). Laminae defined by third-order surfaces tend to pinch and swell laterally and are most commonly thickest within swales, thinning upwards over hummocks. Individual laminae may or may not display internal grading, depending largely on the sorting of sand-size particles; well-sorted sand may not have a sufficiently wide range of grain sizes available to develop visible grading. For example, Bourgeois’ (1980) observations of the Upper Cretaceous Cape Sebastian Sandstone of southwest Oregon reported centimetre-scale internal laminae in which grading was not detectable. However, Hunter and Clifton (1982), also working on the Cape Sebastian Sandstone, noted that under certain conditions, light/dark couplets that comprise the internal laminae bore characteristics that suggested that they were normally graded. Like second-order surfaces, exhumed third-order surfaces may display various forms of parting lineation.

The scour and drape form of HCS is the most common variety of this structure although other forms have also been recognized, including vertical accretionary forms and migrating forms (Fig. 6-16). Several workers (e.g., Hunter and Clifton, 1982; Bourgeois, 1983; Brenchley, 1985; Allen and Underhill, 1989) described vertical accretionary HCS in which internal laminae thickened over hummocks rather than swales. As such, the hummocks appeared to have grown by accretion rather than formed by erosion of second-order surfaces. However, this “accretionary” HCS was thought to be relatively rare. A variant of this form of HCS displays internal laminae that parallel the hummock and swale morphology of second order surfaces (e.g., Allen and Underhill, 1989). Another type of HCS, described by Nöttvedt and Kreisa (1987) and Arnott and Southard (1990), is characterized by low-angle cross-strata sets (generally >5 cm thick) filling shallow scours (swales) and which have a preferred, unimodal dip direction; hummocks are generally rare to absent. This latter structure has been termed “low angle trough cross-

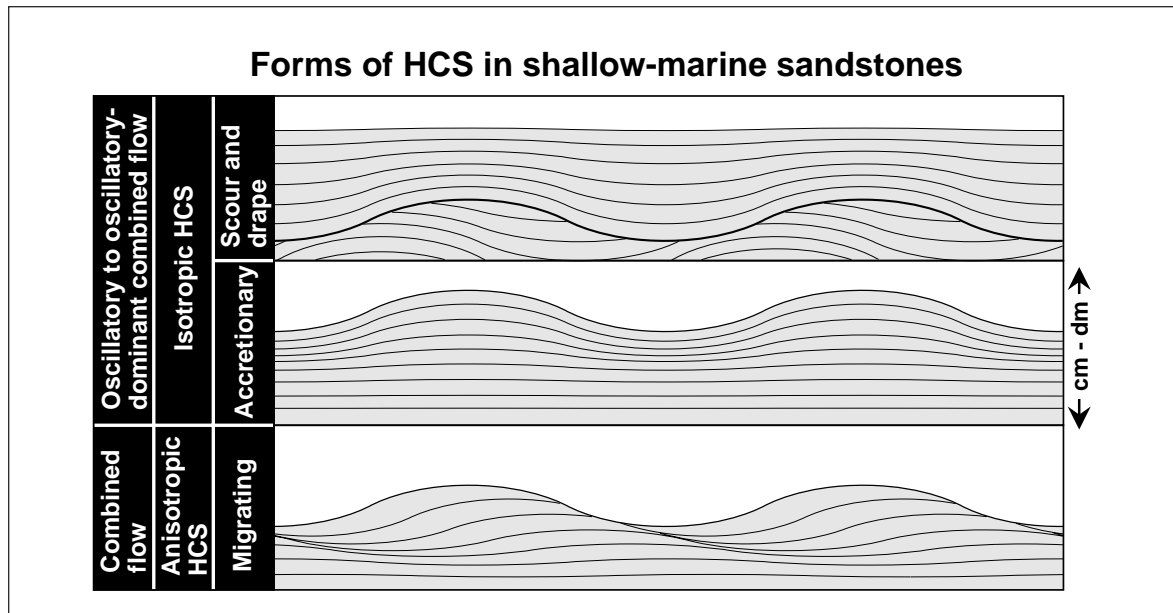


Figure 6-16. Schematic illustration showing the various forms of hummocky cross-stratification. Note that the unidirectional component of the flow forming anisotropic HCS is from right to left. See text for discussion.

stratification” by Nöttvedt and Kreisa (1989) and “anisotropic” HCS by Arnott and Southard (1990) in contrast to the more common *isotropic* HCS.

The adherence by later workers to the essentials of the definition of HCS given by Harms *et al.*, (1975) above has been a matter for some debate. For example, Brenchley (1985) reported slopes on hummocky surfaces up to 35° and spacings as small as the spacing of wave ripples (i.e., centimetres). These deviations from the original definition have led some to suggest that these smaller forms (commonly termed micro-HCS) are not true HCS as Harms *et al.* (1975) had defined it. For example, Duke (1987, p. 345) argued that HCS-like stratification with hummock spacings below the “1 m lower limit assigned to HCS by Harms *et al.* (1975)” is not true HCS. However, the first experimentally-produced analogs of HCS identified by Harms *et al.* (1982) had spacings on the order of a couple of decimetres (and Harms *et al.*, 1982, point out the discrepancy with HCS observed in the field). The scale of HCS may or may not be a limiting factor in defining HCS but may represent a natural variation in scale that reflects the breadth of conditions over which this structure may form. Sherman and Greenwood (1989; p. 985) emphatically state that “there is no apparent physical rationale for the 1 m lower limit on hummocky cross-stratification wavelength” and Campbell (1966) suggested that hummocks may occur with wavelengths of 0.1 to 10 m. Alternatively, many of the examples of HCS that differ significantly from the form defined above may represent similar stratification styles that formed by different processes. The breadth of variation in form of HCS that has grown in the literature may be partly responsible for the similar proliferation of ideas regarding its mode of formation that is discussed below.

HCS associations

With the onset of widespread recognition of HCS, several studies reported its occurrence in particular associations with other structures (e.g., Hamblin and Walker, 1979; Dott and Bourgeois, 1982; Brenchley, 1985). The most common occurrences of HCS in the ancient record can be classified into two such associations: (1) discrete sandstone beds interbedded with mudstones (commonly termed HCS storm beds), and (2) amalgamated sandstones; however, specific associations vary widely in nature (cf. Dott and Bourgeois, 1983).

Discrete HCS sandstones

Dott and Bourgeois (1982) were the first to propose an “ideal sequence” or model showing structures that

are preferentially associated in outcrop within sandstone beds containing HCS; an ideal sequence that began a lineage of such sequences for HCS sandstones. This sequence consisted of sharp-based sandstone interbedded with bioturbated mudstone; the basal-scour surface includes sole marks and is mantled by a lag of coarse debris overlain by an interval of hummocky cross-stratification passing upward into flat lamination and ultimately to cross-laminae associated with symmetrical ripple forms that cap the sandstones. A similar sequence of associations was proposed by Walker *et al.* (1983) which differed in detail from that proposed by Dott and Bourgeois (1982; 1983) by the occurrence of a basal parallel (horizontal to sub-horizontal) laminated interval directly overlying the basal erosional surface. The evolution of the model continued as more observations were made and data collected. For example, figure 6-17 (Leckie and Krystinik, 1989) shows a recent version of the early ideal sequences and contains considerably more information and more variability than the earlier sequences; the new information includes the occurrence of parting lineation on surfaces within HCS, paleocurrent relationships and a range of ripple types capping the beds, from purely wave-formed ripples through to purely current ripples. The trend of the parting lineation is generally orthogonal to wave-ripple crests and sub-parallel to sole marks at the bases of hummocky beds (e.g., Brenchley, 1985; Leckie and Krystinik, 1989). Rarely, a polymodal trend of parting lineation has been observed on second or third-order surfaces (D.A. Leckie and L.F. Krystinik, unpublished observations). Capping wave-ripples are typically straight crested with bifurcating patterns, although irregular forms are not uncommon, including: polygonal, ladderback and box patterns (all forms of interference ripples). In addition, Leckie and Krystinik (1989) include directional relationships between structures in the HCS beds with regional shoreline and paleoslope (Fig. 6-17). Specifically, they showed that directional structures such as sole marks and parting lineation indicate paleoflows directed offshore, orthogonal to regional shoreline-trend indicators. Similarly, capping ripples have crests aligned approximately parallel to regional shoreline and the internal cross-laminae, when present, indicate migration offshore. Such relationships had been suggested earlier on the basis of local studies (e.g., Hamblin and Walker, 1979; Brenchley 1985, Rosenthal and Walker, 1987) but data provided by Leckie and Krystinik (1989) suggested that the directional associations may be the norm for discrete HCS sandstones.

Amalgamated HCS Sandstones.

This association of HCS is characterized by thick (up to several tens of metres) sandstones and differs from the other association by the lack of mudstones (except as local lenses) and the absence of a preferred sequence of structures. Amalgamated HCS commonly occur above the discrete HCS beds in regressive shoreline successions (e.g., Hamblin and Walker, 1979; Leckie and Walker, 1982) and is representative of sedimentation in the lower shoreface. First-order surfaces may be recognized within amalgamated sandstone beds by the presence of a lag or where they overlie intensely bioturbated horizons, discontinuous mudstone beds or concentrations of mica and fine plant debris.

Swaley cross-stratification, as originally defined by Leckie and Walker (1982), is not the amalgamated HCS as described here, although there is a growing tendency amongst some authors to state this. For example, Dott and Bourgeois (1983), McCrory and Walker (1986) and Plint and Walker (1987) suggest that the swaley cross-stratification is typical of amalgamated sandstone beds. Duke (1985, p. 171), however, specifically stated that swaley cross-stratified sandstones do not show evidence of amalgamation. In a vertical, progradational succession discrete HCS is overlain by amalgamated HCS which, in turn, is overlain by SCS.

The HCS Debate

When Harms *et al.* (1975) first introduced HCS they suggested that the structure was the product of the interaction of waves with a sandy substrate during powerful storms (i.e., the waves that produced HCS were particularly large and powerful). Emplacement of sand by storms is widely accepted because discrete HCS bed, encased in shale, must represent extreme sediment transport events that introduced sand into a marine setting that received only deposition of mud during periods of "normal sedimentation"; storms are known to provide such a mechanism of sand emplacement. The specific depositional setting of the HCS storm beds is thought to be at depths above 200 m (the approximate maximum depth of the continental shelf) but below the depth where normal, fairweather waves will affect a sediment substrate (i.e., below effective fairweather wave base). This setting is suggested by the normal mud deposition and by the trace fossils and body fossils associated with HCS storm beds. In support of a storm origin are estimates of the recurrence intervals of emplacement of the sands forming discrete storm beds.

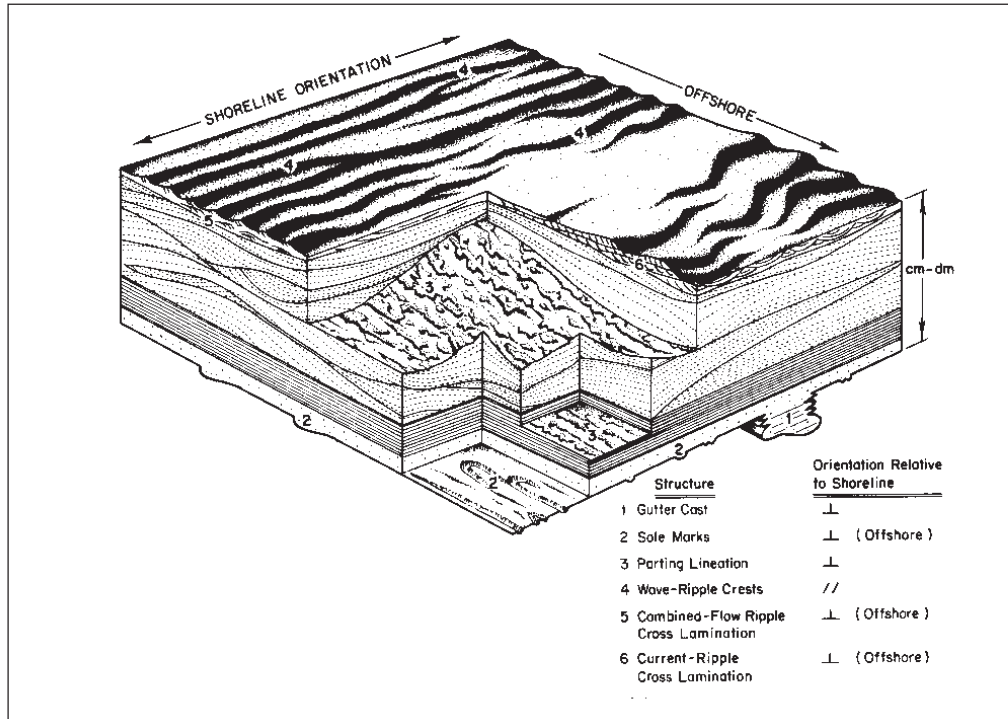


Figure 6-17. Ideal sequence of structures found in HCS storm beds. See text for discussion. From Leckie and Krystinik (1989).

Table 6-2 shows that independent estimates suggest that HCS storm beds are emplaced only every few thousand years. Hence the intensity of storms that transported the sand out onto the shelf and formed the sequence of structures within the deposits were likely of an intensity not yet recorded. However, as more became known about HCS the role of waves in its formation became less certain. Particularly, the presence of unidirectional paleocurrent indicators (such as sole marks on the bases of HCS storm beds), along with the recognition of anisotropic HCS, suggested that unidirectional currents may play a role in forming this structure. The importance of unidirectional currents in the emplacement of HCS storm beds in settings that normally received mud is obvious: the sand is transported offshore, from beach and near-shore environments where it dominates during fairweather conditions, and such transport requires a directed current (i.e., a unidirectional current). Furthermore, such unidirectional currents are well known to modern oceanographers who have measured their intensity during historically moderate to large storms.

In light of the recognition of the importance of unidirectional currents in emplacing HCS storm beds several new mechanisms of HCS formation were proposed, stressing the importance of unidirectional currents. Swift *et al.* (1983) reported HCS on modern shelves in 15 to 40 m water depth. Their examples of HCS collected from wave-modified dunes that formed under combined flows, with a powerful unidirectional component, generated by storms. Box cores taken from the bedforms displayed wedge-shaped sets of heavy mineral-rich laminae in fine to very fine-grained sands. Swift *et al.* (1983) explained the wedge-shaped sets as curved lamina intersections and likened the structure to HCS. Hence, the HCS was attributed to combined flows, and specifically to wave modification of what would have otherwise been dunes under unidirectional flows. Elsewhere, Greenwood and Sherman (1986) suggested that, in a lacustrine setting, a unidirectional flow (in their case, a longshore current) was crucial to the formation of HCS. They argued that without the combined-flow component, purely oscillatory waves would only produce flat-bed conditions. Similarly, Allen (1985) argued convincingly on theoretical grounds that oscillatory currents alone could not form hummocky bedforms of metre-scale wavelength, the development of which required a unidirectional current.

The above debate progressed on the basis of inference from the ancient record and from observations in

Table 6-2. Estimates of recurrence intervals between events (storms?) that emplaced HCS storm beds.

Age	Recurrence Interval	Author
Kimmeridgian	3,200 - 4,000 years	Hamblin and Walker (1979) Walker (1985)
Devonian	400 - 2,000 years	Goldring and Langenstrassen (1979)
Ordovician	10,000 - 15,000 years	Brenchley <i>et al.</i> (1979)
Triassic	2,500 - 5,000 years or 5,000 - 10,000 years	Aigner, 1982
Ordovician	1,200 - 3,100 years	Kreisa, 1981

the modern, shallow-marine environments where no unequivocal HCS could be identified. Over 1990-91 the results of two different approaches to the study of HCS were reported that added more factual knowledge of HCS that pointed to a return to the original ideas on HCS formation under waves. The new data included experimental studies and studies of grain fabric in HCS sandstones.

Experimental Evidence

Southard *et al.* (1990) conducted experiments in a wave duct that produced three-dimensional bedforms (large, 3-D vortex ripples) that behaved in such a way under the purely oscillatory currents that they would produce a form of stratification that very closely resembled HCS observed in the ancient record (Fig. 6-18). This experimental evidence showed that purely oscillatory flows could form HCS but did not rule out the possibility that combined flows could also produce this structure. However, the combined-flow experiments of Arnott and Southard (1990) appeared to eliminate combined flows as having an important role in forming HCS. In their experiments, symmetrical bedforms could only be produced under purely oscillatory flows or combined flows with a negligible unidirectional component (Fig. 6-13). As soon as the velocity of the unidirectional component exceeded a few percent of the maximum orbital velocity the bedforms became asymmetrical and the stratification that they produced would appear as anisotropic HCS. These experiments suggested that combined flows with strong unidirectional currents **could not** form HCS, in contrast to the result of Allen's theoretical analysis and the suggestions of oceanographers.

Evidence based on grain fabric

A detailed study of grain fabric (Fig. 6-19) was reported by Cheel (1991) based on samples oriented with respect to sole marks on the base of discrete HCS sandstone beds interbedded with shale. This study showed that particle a-axes, measured in plan view (Fig. 6-19A) varied widely but displayed modes oriented approximately normal to sole marks and parallel to the associated ripple crest. This suggests that a-axis alignment of grains in HCS develops by rolling (a-axes transverse to the oscillatory current) and the wide variation in a-axes orientation points to deposition under a complex array of surface gravity waves with a mode aligned parallel to the shoreline. In vertical section through HCS sandstones imbrication of grains varied about a mean of 0°, parallel to visible lamination (Fig. 6-19B). In some cases, this variation in imbrication was markedly cyclic about the 0° mean. This pattern of imbrication was interpreted in terms of the action of symmetrically oscillating currents during the

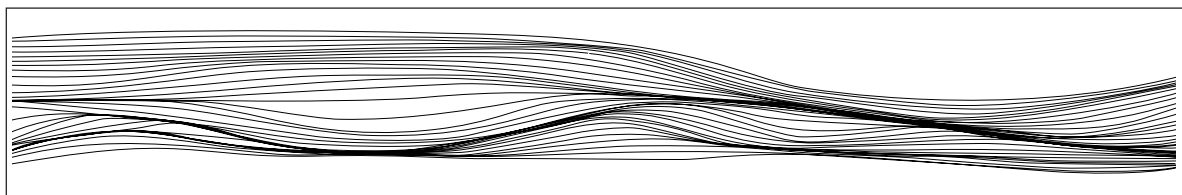


Figure 6-18. HCS simulated from large 3-D vortex ripples. Total length of bed shown in 2.15 m. From Southard *et al.* (1990).

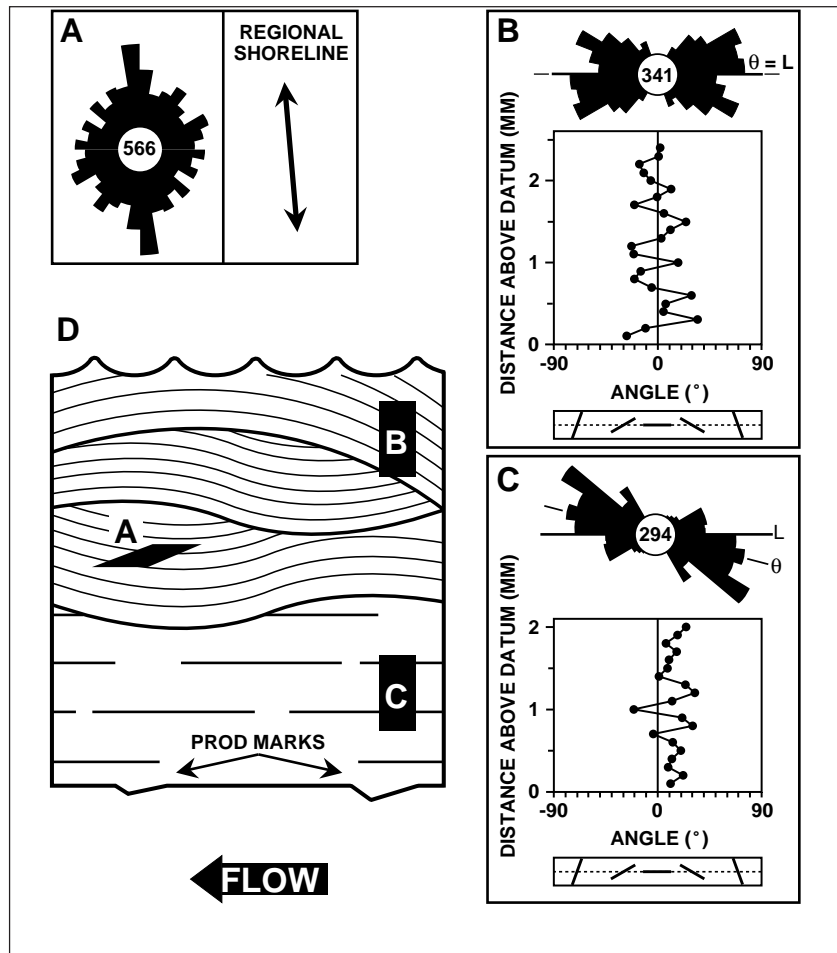


Figure 6-19. Grain fabric in a hummocky cross-stratified sandstone. A. Apparent grain long axes as seen in plan view on surfaces cut parallel to bedding. B and C. Apparent grain long axes seen in vertical section on surfaces cut perpendicular to bedding and parallel from inferred flow direction. Note that the relative positions of A and B are shown in the block diagram.

formation of isotropic HCS. In contrast, in the basal parallel-laminated interval of an HCS bed, the mean particle imbrication was approximately 13° into the flow direction (based on the sole marks) and varied quasi-cyclically about that mean (Fig. 6-19C). The interpretation of this pattern of variation in fabric suggested that an offshore-directed unidirectional current was active during deposition of the horizontally-laminated portion of HCS storm beds (producing the onshore imbrication). However, when the HCS formed this unidirectional component had either stopped or had become too weak to influence grain fabric. Thus, in the HCS storm beds it appeared that HCS forms in response to oscillatory flows, the same conclusion that arose from the experimental evidence.

Origin of HCS?

Given the above interpretation of HCS storm beds we must explain the different forms of HCS that have been observed (Fig. 6-20). The HCS storm beds displaying isotropic HCS form as sediment is delivered onto the shelf by offshore-directed combined flows generated by storms; combined flows with powerful oscillatory components due to large gravity waves and offshore (or offshore-oblique) unidirectional components. Such currents are well-known to modern oceanographers, although their directional relationship to the shoreline is more complex than described here (see Duke 1990 for a full discussion). While the unidirectional component of the current is active not only is the sediment transported offshore but erosion of the substrate occurs, forming the basal solemarks oriented onshore-offshore and any directional solemarks (such as flutes and prod marks) are directed offshore.

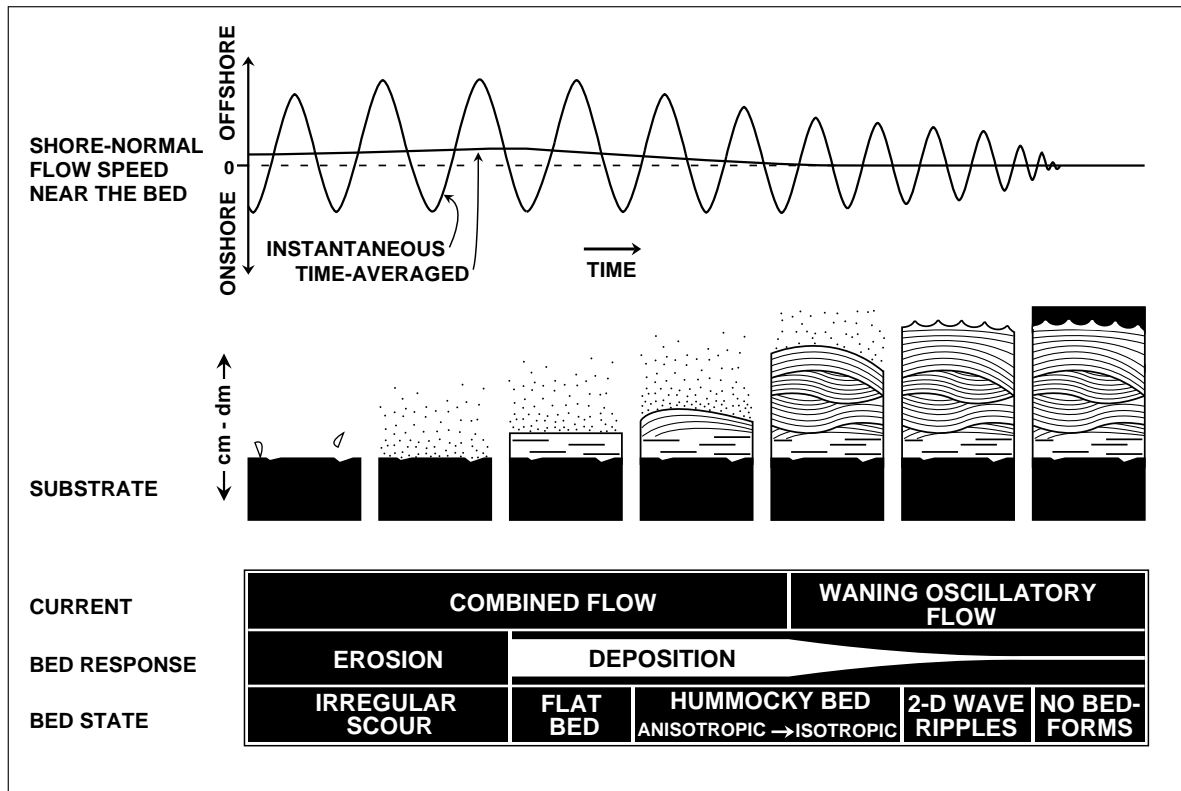


Figure 6-20. Schematic illustration of the temporal variation in currents involved in the formation of HCS storm beds. See text for discussion. After Cheel (1991), Duke, Arnott and Cheel (1991) and Cheel and Leckie (1992).

With the onset of sand deposition conditions are initially on a flat bed (which has a wide stability field under combined flows; see Fig. 6-14) but this bed state is replaced by large, 3-D vortex ripples as the unidirectional current wanes and only a powerful oscillatory current continues. Deposition under this oscillatory flow forms isotropic HCS. As the oscillatory flow wanes small, 2-D vortex ripples are formed, capping the sandstone. Under fairweather conditions, following the storm, muds are deposited, encasing the storm-deposited sandstone bed.

The above scenario accounts for much HCS associated with HCS storm beds but it does not explain the variety of forms of HCS shown in figure 6-16. Certainly, the isotropic forms are likely formed by oscillatory currents. However, the interaction of these currents with a sandy substrate must differ in detail to produce scour and drape versus vertical accretionary HCS. In the case of the scour and drape form of HCS the fact that internal laminae drape and diminish the hummocky relief suggests that a hummocky bedform is not stable under conditions that form the structure but are only stable during periods of intense flow that causes erosion of the hummocky surface. Such erosion during a storm might occur due to the temporary development of constructive waves on the water surface. Swift *et al.* (1983) described the generation of thick clouds of sediment that rose off the bottom during a storm with the passage of groups of exceptionally high waves formed by constructive interference. The formation of these clouds must involve the local addition of sediment into suspension by erosion that might form hummocky second-order surfaces. Between periods of wave construction the “normal storm waves” would act as sediment continued to deposit, causing the temporal variation in flow strength that results in the formation of internal laminae. In this scenario the hummocky surface is not due to the generation of a stable bedform but is inherited from the form of an erosional surface, a surface that might mimic the morphology of the stable bedform under the same conditions but with net deposition on the bed. Subsequent deposition of sediment onto the hummocky erosional surface acts to bring the topography into equilibrium with the normal storm-wave conditions (and this equilibrium bed appears to be more-or-less flat). Hence, the currents that produce the hummocky form are associated with erosion, during the most intense conditions on the bed.

Vertical accretion forms (Fig. 6-16), characterized by thickest laminae within hummocks, appears to involve the growth of a *depositional* hummocky topography. This type of HCS might represent the product of currents, possibly produced by sustained constructional waves that are less transient than the case of scour and drape. Under conditions of rapid deposition, such sustained currents, capable of building a stationary hummocky bedform that is in equilibrium with the prolonged, oscillatory currents generated by the constructional waves, would form vertical accretionary sets. Hummocky bedforms that would produce such stratification were produced under purely oscillatory flows and strongly oscillatory combined flows by Arnott and Southard (1990). In this case, a true bedform is constructed under conditions of net aggradation.

The low angle migratory forms (Fig. 6-16) may represent similar bedforms that form accretionary HCS but which migrate over the substrate, preferentially preserving internal laminae that dip in the direction of migration (Nöttvedt and Kreisa, 1982). Arnott and Southard (1990) produced stationary and migrating bedforms experimentally in a wave duct. The stationary forms were stable under oscillatory flows and strongly oscillatory-dominant combined flows. However, migrating forms developed when the velocity of the unidirectional component exceeded a few percent of the orbital velocity of the oscillatory component. Hence, anisotropic HCS may be interpreted to indicate the influence of a unidirectional component of a combined flow under conditions that would otherwise form isotropic HCS.

Conclusion

The debate over the origin of HCS continues and has become more perplexing over the same period that new evidence for a wave-induced origin. Work by Rust and Gibling (1989) and Prave and Duke (1990) provided examples of cross-stratification that appears like HCS but was produced by three-dimensional in-phase waves. Now we have an HCS-look-alike. The paleoenvironmental interpretation of each structure is radically different; HCS formed by in-phase waves is definitely indicative of unidirectional flows whereas the shallow marine forms of HCS appear to have been largely influenced by waves. The most promising approach to distinguishing the two forms is through detailed studies of grain fabric and this research is on-going and the general debate continues.