Challenge the Paradigm Part 1: HCS - Storm Wave Bedform or Deep Water Antidune?

Dennis Meloche
Devon Canada Corporation, Calgary, Alberta, Canada

Abstract:

Sequence stratigraphic, depositional, and ichnological models for many if not most marine siliciclastic units within the Western Canada Sedimentary Basin (WCSB) espouse a paradigm of a shallow depositional shelf subjected to high frequency fluctuations in relative base level. This is particularly true for the Upper Cretaceous Cardium and Viking formations comprising relatively thin sandy regressive successions that span virtually the entire width of the basin (lateral distributions > 65,000 km^2). Depositional models for both have vacillated through time between deep water offshore and storm-influenced, shallow shelf interpretations. The currently popular forced regressive lowstand, shallow shelf depositional models for virtually all shoreface-detached sand bodies in the WCSB appear to be based largely upon the presence of sandy, hummocky (HCS) and swaley (SCS) bedforms within upward cleaning regressive successions.

Hummocky cross-stratification (HCS), as formally defined by Harms et al. (1975) comprises low-angle (2° to 15°), curved to undulating laminae which are broadly concave upward (swales) and/or broadly convex upward (hummocks). The swales commonly erode hummocks and cut into underlying swales, producing low-angle, curved intersections of laminae. Above the scours, laminae are broadly sub-parallel over hummocks and swales, forming sets up to 20 cm thick.

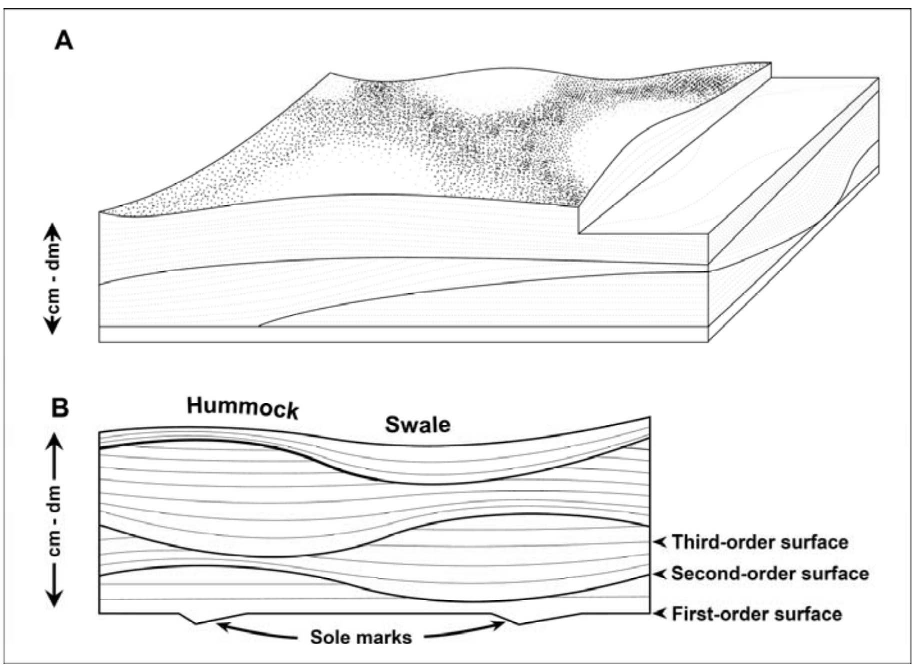

Figure 1. Schematic illustrations of hummocky cross-stratification. A. Form of the three-dimensional 3-D vortex ripple bedform thought to produce HCS. B. Details of the internal structure comprising HCS. (from Cheel (2005) after Cheel and Leckie (1992))

HCS in marine sandstone is typically restricted to lower fine and finer grain sizes, and occurs in both thin (few to tens of cm's), sharp-based beds interbedded with shale and thick (up to several meters) amalgamated bedsets. Wavelengths range from ~ 1 to 5 m, and heights range from about 10 to 40 cm. Erosive scours and oriented sole marks at the base of the thinner beds commonly demarcate regional paleoslope. Shale interbeds are commonly bioturbated, while the HCS sandstone beds are generally not.

Harms et al. (ibid.) where among the first to recognized HCS as a recurring bedform and suggest a storm-event origin by means of “strong wave action with surges of greater displacement and velocity than those required to form wave ripples”. Shortly thereafter Hamblin and Walker (1979) described in detail the close association between HCS and gravity flow deposits (turbidites) in Jurassic strata of the Fernie Group in Alberta, and placed the HCS/SCS within a vertical shoreface depositional context.

The storm-wave origin for HCS proposed by Harms et al. (ibid.) appears to have formed the basis for all subsequent shallow water depositional interpretations of the Cardium and Viking formation published between 1985 and 2003. In turn, these shallow water depositional interpretations spawned the forced regressive and ‘lowstand’ depositional models proposed by Walker, Plint and others that were needed to rationalize the extremely high lateral distribution of HCS-bearing facies. Sequence stratigraphic models for the Cardium and Viking formations involving shallow shelf deposition and high frequency oscillations in relative base level have been employed as analogs for interpretation of similar HCS sandstone-bearing successions in multi-age basins worldwide.

To date, there are most likely several hundred examples of strata containing HCS bedforms interpreted as shallow shelf marine deposits. However, HCS bedforms have also been described from fluvial deposits (Cotter and Graham (1991)), beach swash zones and intertidal flats (Bartsch-Winkler and Schmoll (1984), Dott and Bourgeois (1982), turbidites (Higgs (2009), Monaco (1992)), spiculitic chert (Gatesa et al. (2004)) and organic-rich, transgressive black shale (Schieber (1994), Wignall and Newton (2001)). Duke (1985) summarized the numerous agents that had been proposed to date for HCS and the controversy surrounding its formation. The agents fall into two categories: The first involves density underflows (gravity flows) generated by progressive gravity waves (i.e. storm-generated waves). Although there are several variations described by Duke to the gravity wave theme, it forms the principle means to redistribute sediment within the storm-origin paradigm for HCS. The second group of generative agents describe by Duke include Helmholtz waves and ‘stratified-underflow’ antidunes, both which involve an element of shear between unidirectional density underflows and the bounding media. In the end, Duke chose to reinforce the storm-event origin.

Duke (ibid.) was the first to note that geomorphologists working in modern environments and geologists working in ancient deposits have generated seemingly contradictory data sets concerning the origin of HCS bedforms. Virtually all that is known of the depositional setting, structure and origin of HCS bedforms has been <u>inferred</u> by geologists from studies of ancient sedimentary strata, as there are no modern storm-generated analogs. HCS bedforms of the types described in outcrop and core have never been formed experimentally. HCS bedforms have never been observed in the process of formation in natural environments nor have storm-generated HCS bedforms been recognized unequivocally from any recent sediment. There is no direct evidence to indicate that gravitational acceleration of suspended sediment during storms can produce large-scale gravity flows, since the depositional gradients over relatively flat shelves are too low to achieve auto suspension. Furthermore, the distance that sediment can be transported basinward of the shoreline by storms is severely limited by the depth-averaged steady flow component directed approximately parallel to bathymetric contours and the local shoreline. Opponents of the storm-origin paradigm for HCS point out that on uniformitarian grounds storm-generated flows in ancient shallow marine systems must have been qualitatively similar to the flows observed in modern settings, and powerful storm-generated turbidity currents are absent in modern shallow seas.

In spite of this, by 1990 HCS appears to have been adopted by most as an ‘a priori’ proxy for shallow water depositional conditions (i.e. < 200 m). The shallow water HCS interpretation culminated in development of the generic geomorphic ‘shoreface’ models of Walker and Plint (1992), Galloway and Hobday (1996) and Reading and Collinson (1996) based upon relative depths of fair weather and storm wave-bases. The storm wave interpretation for HCS and its corollary for shallow-water deposition have also imposed strong biases on WCSB ichnofacies models based largely upon observations of recurring trace fossil suites within the Cardium and Viking formations (Pemberton and Frey (1984), Vossler and Pemberton (1988 & 1989), MacEachern et al. (1991), MacEachern et al. (1992), Pemberton et al. (1992a), Pemberton, et al. (1992b), MacEachern and Pemberton (1992)). More recently, the generic geomorphic 'shoreface' models were integrated with the ichnofacies models to refine existing deltaic depositional models to better differentiate river- from wave-dominated successions in the subsurface (Bhattacharya and Giosan (2003), MacEachern et al. (2005)), again relying upon the presence of HCS as a key criterion.

Walker et al. (1983) summarized their field observations for HCS beds into a conceptual model (figure 2), modifying the idealized HCS sequence first published by Dott and Bourgeois (1982). Stratification within their 'idealized' model grades systematically from a sharp basal scour surface upward through massive, graded and/or planar-laminated sand through hummocky cross-laminated sand into flat- (planar-) laminated sand capped by unidirectional 'combined-flow' current ripples. The vertical sequence (unidirectional upper flat bed➡oscillatory flow upper flat bed➡oscillatory flow HCS) is interpreted by most workers to reflect decreasing rate of deposition and increasing importance of wave reworking in a waning underflow.

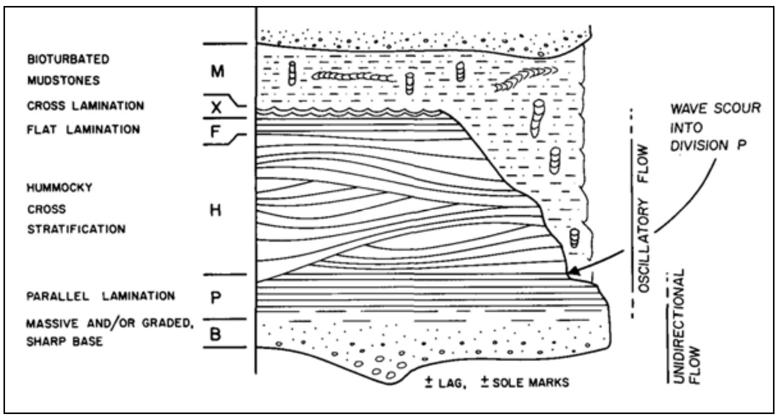

Figure 2. Conceptual model of a sandstone-mudstone couplet containing HCS from Walker et al, (1983). The full sequence is not always preserved and some divisions may be absent. In some beds, the upper part of division P may be scoured to form a hummocky surface with only a thin veneer of laminae as shown by the erosion surface in the diagram. Two types of transition from planar to hummocks are shown: on the left, hummocks scour into planar laminae; on the right hummocks evolve vertically from planar lamination.

The lateral and vertical distributions, thickness and more significantly, the internal architecture of HCS sequences are inconsistent with generation by storm-generated oscillatory (gravity) waves. Bedform stability diagrams for both unidirectional and oscillatory flow preclude the development of lower plane bed lamination in sands finer than medium grain size (figure 3). 3-D vortex ripples that can produce HCS form under intermediate flow conditions. Flat or planar lamination within HCS successions must represent higher (i.e. upper-) flow regime flow conditions regardless of whether the flow is unidirectional or oscillatory. To account for the nearly ubiquitous upper set of 'flat lamination' (F) below the topset ripples (X) in vertical HCS sequences, the storm-generated oscillatory wave model requires two separate waxing-waning cycles within each succession (figure 3).

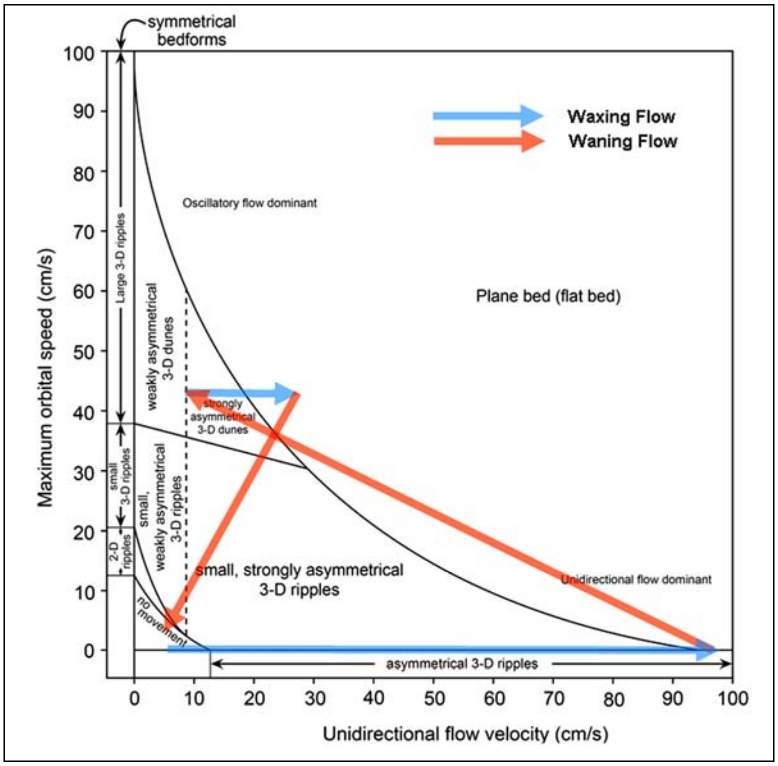

Figure 3. Extended bedform stability diagram for combined flows with an 8.5 second period oscillatory component acting on a bed of *fine* sand, from Cheel (2005) after Myrow and Southard (1991). Arrows depict the flow path represented by the vertical arrangement of bedform divisions within the conceptual model of Walker et al. (1983). The color and direction of the arrows indicate whether the flow must wax (accelerate) or wane (decelerate) to account for the change in bedform type.

Upper flow regime standing wave antidunes offer a more viable alternative interpretation for much, if not most, of what has been described as HCS. Antidunes are in-phase, low relief bedforms that form on a sandy substrate beneath unidirectional super-critical flows commonly associated with fast, shallow water. They represent the highest 'flow velocity' bedform that evolves out of upper plane-bed stratification with increasing Froude number (by either increasing velocity or decreasing depth) (figure 4). During formation, they rapidly amplify and deform the overlying flow until the surface of the flow becomes unstable and collapses, partially or completely eroding the underlying antidune. The resulting bedform in rapidly aggrading settings is an intricate pattern of stratification consisting of laminae that can dip at low angles both upstream and downstream.

In many respects, antidunes resemble the HCS bedforms described from shallow shelf settings, and much effort has been spent to identify criteria to distinguish the two (e.g., Rust and Gibling (1990), Prave and Duke (1991)). Antidunes are common features in alluvial fans (Wataru et al. (2009)), fluvial channels (Hand et al. (1969), Fielding (2006)), beaches, tidal flats, wash-over fans (Barwis and Hayes (1985)), submarine channels and canyons (Ito (2010), Yagashita (1994)), and basin floor fans (Walker (1967), Skipper (1971), Skipper and Bhattacharjee (1978), Prave and Duke (1990), Mulder et al. (2009). Antidune preservation is generally thought to be rare in the rock record because it requires conditions of net sediment deposition (i.e. aggradation) to preserve the bed forms. Aggradation of antidune bedforms is generally attributed to either a rapid rate of deposition and/or a rapid loss in flow strength after dune formation. The only depositional setting where antidunes appear to have not been described is from the depositional shelf where a single HCS event bed can aggrade to a thickness in excess of one metre.

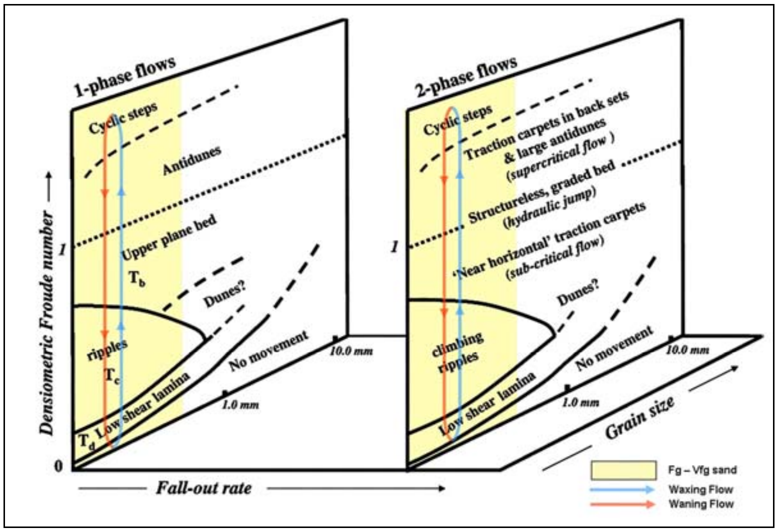

Figure 4. Three dimensional bed-form stability diagram for 1 and 2-phase suspension flows depicting the approximate stability fields of the various bed forms relative to critical flow conditions (Froude number =1) from Postma et al. (2009). The 1-phase flow diagram is based on compiled data from unidirectional free-surface flows and on experimental data from particulate saline underflows. The 2-phase flow diagram is also based on experimental data, but incorporates field data to illustrate the difference in large-scale architecture of super critical and sub-critical traction carpet deposits. The finer grained domain occupied by HCS bedforms is highlighted in yellow. The path for waxing and waning density underflows are depicted. Under waxing flow conditions, lower flow condition bedforms would have little chance for preservation.

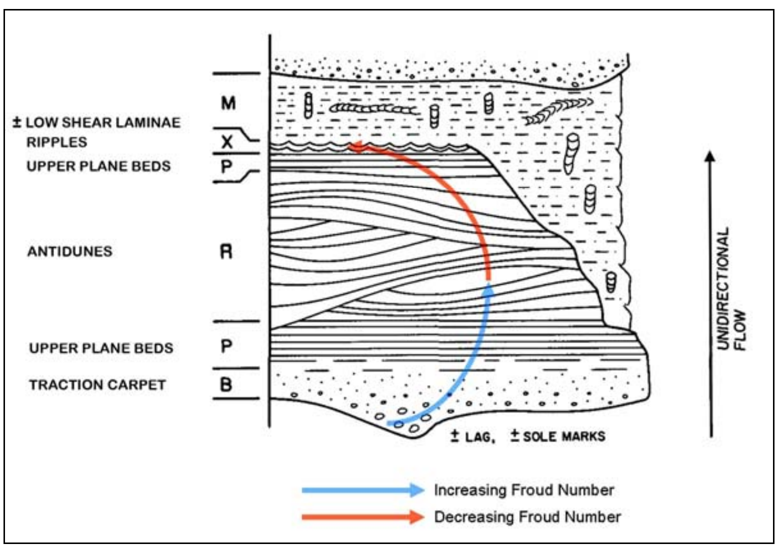

Figure 5. Conceptual model of a sandstone-mudstone couplet containing antidunes and upper plane-bed stratification, modified from Walker et al, 1983. The model depicts a single waxing (blue)-waning (red) cycle of a unidirectional underflow possibly related to a single fluvial flood cycle. As with the HCS model, all divisions need not be preserved due to erosion and re-suspension.

'Stratified-underflow' antidunes offer a more viable explanation for the vertical succession depicted in 'idealized' HCS sequences (figure 5). The vertical change from swales through planar lamination to ripple cross lamination represents a simple waning flow signature related to the passing of a high density gravity underflow. Development of ripple-scale cross-laminae (Tc) is dependant on the residence time of the flow within the ripple stability field (Sumner et. al. (2008)). Residence time needed to develop ripples increases with decreasing grain size. Consequently, Tc divisions in HCS successions, if present, are restricted to a single layer of ripples. Below the HCS division, massive, graded and even planar laminated bottomset beds can be attributed to either waxing of the initial flow or damping of antidune development by high sediment fallout rates.

Re-interpretation of HCS bedforms as 'stratified underflow' antidunes has profound implications for the stratigraphy and sedimentology of clastic successions within the WCSB. Cores exhibiting HCS from the Cardium and Viking formations will be used to explore some of these implications.

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