

Recent Studies on Some Sedimentary Structures Formed under Upper-flow-regime Conditions : Review and Discussion

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1. Introduction

In the past decades, many flume experiments and field surveys have been conducted towards the study of lower-flow-regime bedforms (*e.g.*, Kaneko and Honji, 1979 ; Hunter and Clifton, 1982).

However, a few reports on upper-flow-regime bed phases have also appeared over recent years (*e.g.*, Paola *et al.*, 1989 ; Cheel, 1990), and descriptions and discussions in these reports have led to a better understanding of hydraulic conditions for sedimentary structures formed under upper-flow-regime. Moreover, grain fabric studies of these sedimentary structures have received considerable attentions (*e.g.*, Yagishita & Taira, 1989 ; Cheel, 1991 ; Yokokawa & Masuda, 1991). However, there still exist some difficulties to understand and interpret the formational mechanisms of such bedforms. The purpose of this short review is to summarize the recent development of studies on upper-flow-regime bedforms, which includes grain fabric analyses of these sedimentary structures.

2. Bedforms produced under upper-flow-regime

a. Principles of formation of antidunes and backset beddings

Antidunes and backset beddings, which are typical products under upper-flow-regime (Fig. 1), have been increasingly reported from the geological rock records. However, unusual conditions of net sediment deposition are generally required to preserve these bedforms: either rapid deposition or sudden diversion of the upstream flow has to take place after formation of the structures. It is in general, however, that the bedforms are rapidly destroyed as the flow wanes. Both the antidune, which was originally coined by Gilbert (1914), and the backset bedding, which was first reported by Davis (1890), are of bed

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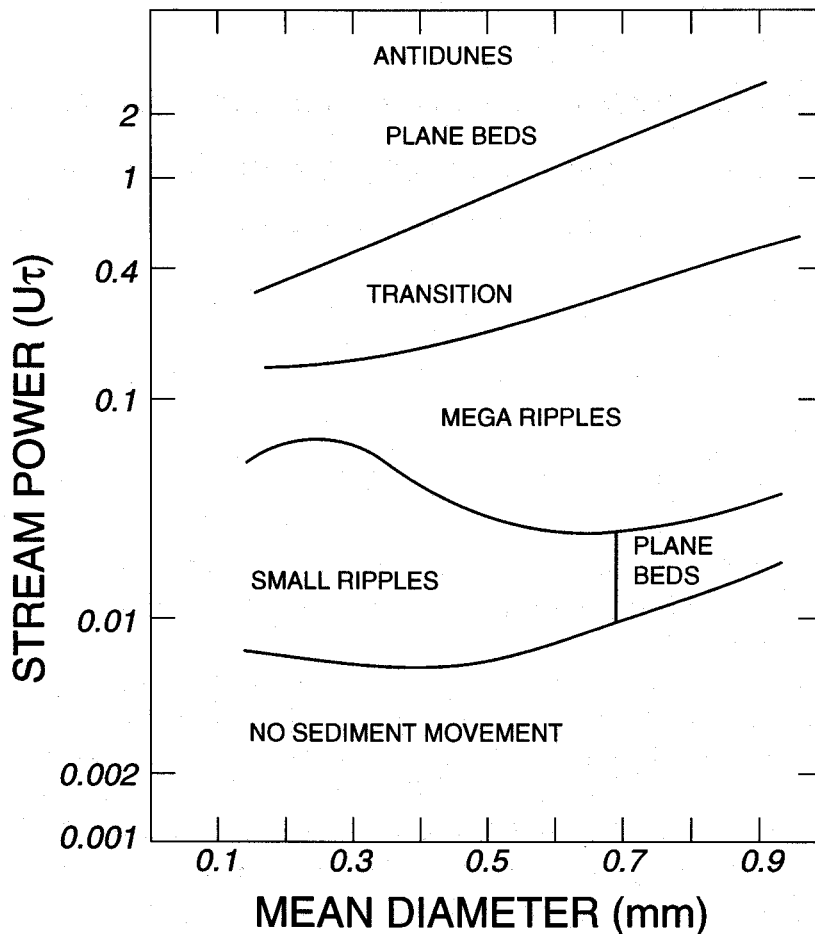


Fig. 1 Distribution of common sand bedforms plotted in the field of stream power ($U\tau$) and sediment grain size (mm). Note that plane beds are observed both in lower-flow-regime and in upper-flow-regime. Modified after Simon *et al.* (1965).

profiles *in phase* with surface waves of the overlying flow. Although antidunes observed by Gilbert (1914) tended to show upcurrent-migration owing to erosion on the lee side (downstream side) and deposition on the stoss side (upstream side), Kennedy (1961, 1963) revealed the existence of different types of antidunes that remain stationary or even move downstream. The backset beddings dip against the direction of current flow. The bedform was first reproduced by Jopling and Richardson (1966) in their experiment. Both antidunes and backset beddings are formed only at high regimes of flow, and the Froude Number, Fr is larger than unity (one):

$$Fr = u / (gh)^{1/2}$$

where u is the average velocity of the flow, h is the average water depth, and g is the

acceleration due to gravity.

Although these bedforms are generally considered to be preserved rarely in nature, a number of observations of such bedforms have been reported from various modern environments; antidunes from washover fans (*e.g.*, Schwartz, 1982; Barwis and Hayes, 1985), antidunes or backset beddings from foreshore zones (van Straaten, 1953; Augustinus 1980) and from backshores (Panin & Panin, 1967; Wunderlich 1972). Antidunes have also been reported in ancient rock records, including fluvial channels (Collinson 1966), alluvial fans (Power, 1961; Hand *et al.*, 1969; Rust and Gibling, 1990), and even turbidites (Prave and Duke, 1990). Indeed, as noted by Prave and Duke (1990), antidunes can be certainly recognized in some turbidite beds (Fig. 2). Because of the careless attention in the field, such high-flow-regime bedforms have been overlooked to date.

Kennedy (1961, 1963) carried out the first comprehensive experiments to observe the formational mechanism of antidunes. Through his experiments a straightforward relationship between current velocity and wavelength of antidunes was recognized:

$$L = 2\pi U^2/g$$

where U is the mean flow velocity, L is the minimum wave length of the antidunes, and g is the acceleration gravity. On the recognition of antidunes in ancient rocks together with

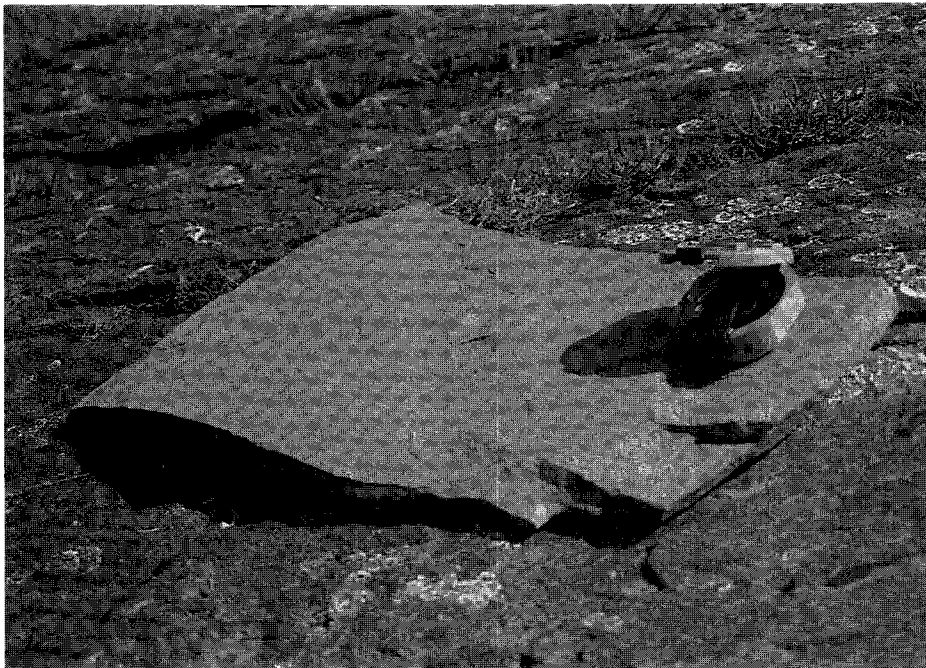


Fig. 2 A large slab of an antidune bedform from double graded turbidite beds. Note that parting lineations are observed on the surface of the antidune. The mid-Cretaceous Haida Formation, the Queen Charlotte Islands, British Columbia, Canada.

the information of wave lengths of the bedforms, we can roughly estimate the flow velocity from this formula.

Hand (1974) pointed out that the velocity/wavelength relationship defined by Kennedy can also be extended to density currents through use of the internal wave equation,

$$U^2 = (gL/2\pi)(\Delta\rho/(\rho + \rho'))$$

where ρ and ρ' are densities of the current and overlying fluids, and $\Delta\rho$ the density contrast. However, Hand (1974) revealed that the wavelength of turbidite antidunes are on the order of tens to hundreds of meters. In fact the lamina planes of these antidunes may be observed as "parallel laminae" in turbidite beds.

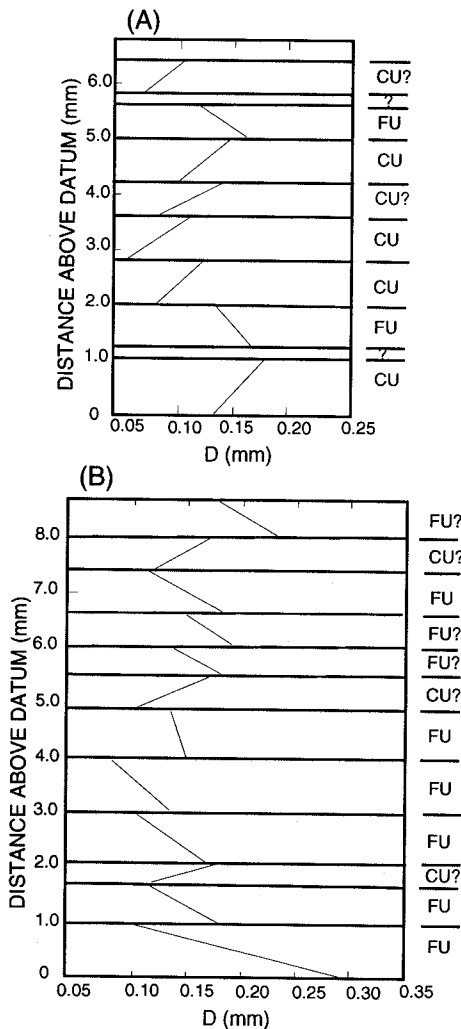


Fig. 3 Plots of average grain size versus distance above a fixed datum of flume sediments. Diagram (A) is from a normal (*i.e.*, without reliefs) plane bed, whereas (B) is from an in-phase wave bed. FU: fining-upward-sequence, CO: coarsening-upward-sequence. Modified after Cheel (1990).

b. plane bed and its parallel lamination

The plane bed is a term which refers to a bed that lacks any regular relief except current lineations, such as a parting lineation, on the top of the bed (Cheel, 1990). There are considerable debates as to exactly how the parallel lamination within a plane bed of upper-flow-regime is produced. Some workers prefer the process in which the migration of low-relief bedforms takes place (Smith, 1971; McBride *et al.*, 1975). In this case the shallow flow depth is the most important factor that controls the production of the laminae. Because of the common occurrence of parallel lamination in turbidites and fluvial deep channel deposits, however, Paola *et al.* (1989) have not considered such a process as plausible. Paola *et al.* suggested that the migration of extremely low-amplitude bedforms together with the lateral movement of the bedform troughs lead to continuous parallel lamination. The lower part of each trough is filled by coarse-grained sand, while the top of individual trough is closely packed with fine sand (grazed). Thus, all the laminae they observed show fining-upward grading.

Cheel (1990) has recognized two types of horizontal lamina in his experiments: one is made in "upper-flow-regime plane bed" that is produced without reliefs on the bed surface, and the other is formed in the presence of symmetrical bed waves (*i.e.*, low in-phase waves). Hydraulic conditions (such as the mean flow velocity and the Froude Number) for the latter (*i.e.*, in phase waves) are of higher flow strength than those for the former. He ascribed horizontal laminae produced by Paola *et al.* (1989) and by McBride *et al.* (1975) to the latter case, whereas his own previous experimental production of laminae (Cheel and Middleton, 1986) was assigned to the former case. Fining-upward grading is more common in beds of in-phase waves than in those of upper-flow-regime (Fig. 3). Heavy mineral concentrations are predominant in coarsening-upward grading in beds of upper-flow-regime, but they are not present in coarsening-upward grading in beds of in-phase waves.

3. Distinction from other bedforms by grain fabric analysis

In the rock record, recognition of antidunes or backset beddings and their distinction from other sedimentary structures, such as megaripples and hummocky cross-stratifications, is often difficult. We should also notice that while much work has been directed towards the study of upper-flow-regime, transitional bedforms, such as humpback (whaleback) dunes, have received less attention (Saunderson and Lockett, 1983; Bridge and Best, 1988). However, the following sections will be focused only on the subject of recognition for upper-flow-regime bedforms in terms of grain fabric analysis.

a. Antidunes and low-angle megaripples

In a thick turbidite bed of the Ordovician Cloridorme Formation, Skipper (1971) noticed the cross-laminae dipping gently in the opposite direction to the flute casts observed on the base of the turbidite. He maintained that the cross-stratification is a good example of well-preserved antidunes in the turbidite. However, Pickering and Hiscott

(1985) re-examined the same sedimentary structures and pointed out that the grain alignment in the cross-strata displays a smaller angle than the inclination of the cross-laminae. They suggested that the laminae in the turbidite bed of the Cloridorme Formation may not represent cross-sets of the upstream side of antidune or backset bedding, but these laminae may merely represent the downstream side of a megaripple. As a consequence of their re-examination study of the Cloridorme sandstone bed, Pickering and Hiscott (1985) suggested the reflected (contained) flows in a turbidity current. The evidence of paleoflow reversal as a result of reflection from confining basin slopes was also shown in a thick Miocene turbidite (RicciLucchi and Valmori, 1980).

Yagishita and Taira (1989) revealed a characteristic feature of grain fabric of a laboratory antidune. Their laboratory antidune is an upstream-migrating antidune with the Froude number, Fr , much larger than unity ($Fr \approx 1.6$). Upstream-dipping laminae that show a very gentle angle of inclination (2° - 3°) are also recognized. They observed high-angle upcurrent imbrication of detrital grains both on the upstream and downstream sides of the antidune. The high-angle imbrication pattern is thought to be produced by

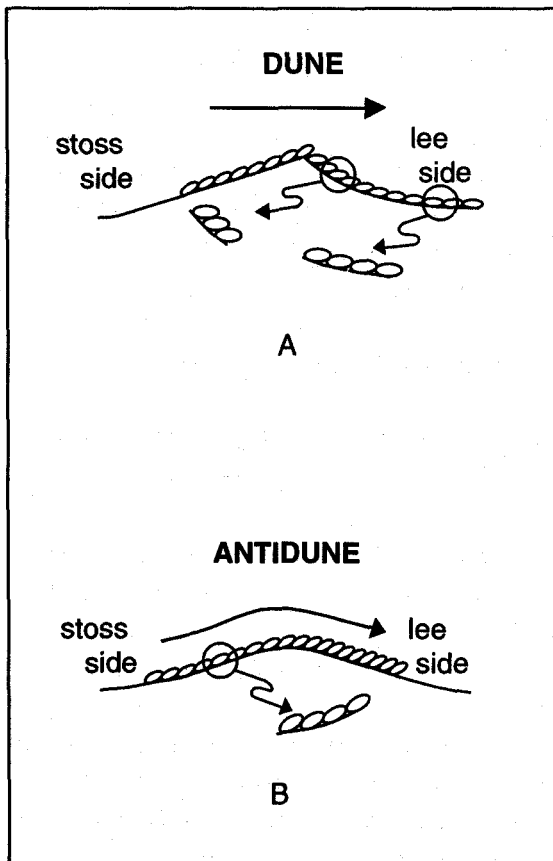


Fig. 4 Schematic models for grain deposition of a dune (A) and of an antidune (B). Note that horizontal grain placements due to avalanching is typical on the lee side of the dune (A). Modified after Yagishita and Taira (1989).

grain collisions between suspended sedimentary particles and by impinging such tilted (imbricated) grains onto the upcurrent face of the antidune mound. Owing to acceleration of the water current and to erosion of sediments, no deposition of grains may take place on the downstream side of the antidune (Middleton, 1965; Yagishita and Taira, 1989). Such a grain fabric totally differs from a normal dune or megaripple, in which grain alignment displays an upcurrent imbrication (horizontal placement) relative to the depositional slope in the foreset lamina (Fig. 4). Their results justify the fabric analysis and its interpretation made by Pickering and Hiscott (1985), and therefore "the antidune" in the turbidite bed of the Cloridorme Formation has been disclosed not to be convincing.

b. Antidunes and hummocky cross-stratification

Hummocky cross-stratification is formed by a combination of storm wave oscillation and unidirectional flow (Nøttvedt and Kreisa, 1987; Yagishita, 1991). Some workers differ, however, on the emphasis placed on the relative importance of oscillation (*e.g.*, Dott and Bourgeois, 1982; Hunter and Clifton, 1982) versus unidirectional flow (Allen and Underhill, 1989). Surlyk and Noe-Nygaard (1986) distinguished hummocky cross-stratification formed by orbital (oscillatory) currents from large-scale trough cross-bedding produced by less intense orbital flow (*i.e.*, unidirectional-dominant flow). A few flume experiments have been carried out to determine how the conditions of combined flow (Arnott and Southard, 1990) and pure oscillatory flow (Southard *et al.*, 1990) might affect the development of bed configurations, Nøttvedt and Kreisa (1987) showed a conceptual bedform phase diagram, in which a spectrum of oscillatory-unidirectional currents was proposed.

There is a superficial resemblance of hummocky and swaley cross-stratification to antidunes. Hummocky and swaley cross-stratification generally display the low angle of inclination ($<15^\circ$) (*e.g.*, Dott and Bourgeois, 1982; Hunter and Clifton, 1982), and this gently dipping and low-relief wavy structure is quite similar in shape to the profile of antidunes. Such a bedform resemblance has been pointed out by some workers. Rust and Gibling (1990) reported the three-dimensional bedforms that closely resemble hummocks and swales from the fluvial sediments of the Pennsylvanian age. Prave and Duke (1990) also described small-scale hummocky-like cross-stratification from the Cretaceous turbidite bed. Because of the sedimentological context, however, both the Pennsylvanian and Cretaceous hummocky-like bedforms are interpreted as antidunes: the Pennsylvanian bedforms occur with well-defined current lineations and they overlie the thick channel sandstone sequence, whereas the Cretaceous sedimentary structure shows no sharp grain size breaks or mud partings within a bed. The structure is thought to have been made by standing waves during a single flow (turbidity current) event.

Although these two structures were identified as antidunes by the stratigraphic and sedimentological context, grain fabric is another useful tool in helping to identify the origin of low-angle cross-stratification. Recently, Cheel (1991) has revealed a bimodal preferred grain orientation in the section normal to the lamina planes in his hummocky cross-

stratifications. He ascribed the fabric to oscillatory flow during deposition. In the hummocky and swaley cross-sets by the typhoon generated combined flow, however, Yagishita *et al.* (1992) did not observe the bimodalism so clearly as Cheel did. Yagishita *et al.* observed two-types of storm-made sedimentary structures: one is the classical hummocky cross-stratification formed by oscillatory-dominant flow, and the other is the swaley cross-bedding made by unidirectional-dominant flow. They recognized either an almost parallel grain alignment along lamina planes in the hummocky cross-strata or a weak upcurrent imbrication against the lamina planes in the swaley cross-bedding.

Both grain fabrics revealed by Cheel and by Yagishita *et al.*, however, obviously differ from those fabrics produced in antidunes and backset beddings. The very high-angle upcurrent imbrication (up to 30° from the horizontal plane) in antidunes is a key fabric pattern to distinguish antidunes from other structures that are made in rather lower flow energy conditions. As described earlier, the high angle imbrication is basically produced by grain encounter (Rees, 1968), while the sediments are in suspension. And these tilted grains are directly accreted on the upstream side of the antidune mound. It is noteworthy in this case that there is *no* grain avalanching to form antidunes. The avalanching is one of the most characteristic grain behaviours to produce cross-lamination of bedforms in lower-flow-regime (*e.g.*, Yagishita and Jopling, 1983).

4. Prospects of grain fabric analysis

As described above, it is hard in some cases to distinguish sedimentary structures formed in upper-flow-regime from bedforms made in lower-flow-regime. The best example of such difficulty is to distinguish antidunes from low-angle megaripples or from hummocky cross-strata. Another example is the distinction between plane beds produced in upper-flow-regime and those formed in lower-flow-regime (Fig. 1). In most cases, interpretations of formational mechanisms of such bedforms were set forth from the sedimentological context. However, some workers consider that the grain fabric analysis is a very useful tool to recognize the origin of these bedforms. A few cases have already been described in this report. Rust and Gibling (1990), and Prave and Duke (1990) have interpreted their hummocky-like bedforms as antidunes. However, the writer suggests that if we conduct grain fabric analysis in their bedforms, we may easily recognize the true formational mechanism for these bedforms.

A key fabric to distinguish plane beds made in lower-flow-regime from those formed in upper-flow-regime is probably the magnitude of imbrication angle of detrital grains. In the vertical section along the flow direction, the imbrication angle is expected to be large for the upper-flow-regime plane beds, whereas the angle may be very small or almost zero for those plane beds which are formed just above the threshold stream power.

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