Sedimentary structures of antidunes : An overview

Tadashi Araya* and Fujio Masuda*

There seem to be some misconceptions about the definition and the criteria of antidunes and their deposits. Antidune is one of the upper-flow-regime bedforms, whose definition was limited originally to upstream-migrating bedwaves but recently includes any bedwaves in-phase with surface gravity waves in the overlying flow. The term "antidune" represents a bedform, not a sedimentary structure or a deposit.

Thin lenticular laminaset and HCS-like structure ("HCS mimics") may be formed as antidunes as well as upstream-dipping, relatively low-angle stratification (backsets). HCS-like structure may be formed as three-dimensional antidunes in upper-flow-regime conditions, particularly in abundant suspension fallout. However, the paleocurrent direction or regional facies assemblage, for example, will be needed in practice for the recognition of antidune deposits, besides descriptions of their internal sedimentary structures and grain fabric.

Most studies were based on limited examples of diverse antidunes or only small portions of antidune deposits. The classification of antidune geometries is so insufficient that the processes, hydraulic conditions and mechanisms of the formation of sedimentary structures have been poorly understood. Detailed descriptions and analysis of the bedforms, resultant deposits and grain fabrics should be conducted based on a more sophisticated classification, from experimental or theoretical approaches.

Key words : antidune, bedform, HCS mimics, sedimentary structure, upper flow regime

INTRODUCTION

Antidune is one of the bedforms stable in upper-flow-regime conditions, and is characterized by upstream migration of the bedform and the resultant formation of backset cross stratification. Antidunes are supposed to be rarely preserved in ancient deposits (cf. Allen, 1982 ; Collinson and Thompson, 1982), because their deposits are destroyed by subsequent waning flows and only reworked lower-flow-regime sedimentary structures are likely to remain. However, there

have been many studies reporting sedimentary structures of antidune origin (or those inferred so) in modern and ancient deposits in various environments.

Although there have been a few studies dealing with antidunes and their deposits in detail, the definition and the criteria of antidune deposits seem to be confused. This study will review the definitions of antidunes and the characteristics of antidune deposits. Furthermore, some examples of antidune-induced sedimentary structures in modern and ancient deposits will be reported.

DEFINITION OF ANTIDUNE

Antidune was originally defined by Gilbert

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* Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, Kyoto 606-8502, Japan

(1914), which was based on the observations of bedforms in natural rivers and laboratory flumes. He defined antidune as a wavy, in-phase bedform migrating upstream in uni-directional flows.

On the other hand, the definitions by Langbein (1942), Simons and Richardson (1961, 1962), Kennedy (1961, 1963), Middleton (1965) and Reineck and Singh (1973, 1980) attached greater importance to in-phase nature of antidunes and included those migrating downstream or standing (stationary). Such broader definition is now more popular (e.g. Middleton, 1965 ; Allen, 1982 ; Barwis and Hayes, 1985) without some exceptions (e.g. Cheel, 1990). That is, most of them have been recognized to be antidunes without limitation to those migrating upstream as defined by Gilbert (1914).

MECHANISM OF UPSTREAM MIGRATION

Some hypotheses have been proposed about the mechanisms of upstream migration of antidunes (e.g. Gilbert, 1914 ; Kennedy, 1961, 1963 ; Middleton, 1965 ; Simons et al., 1965 ; Allen, 1982). Gilbert (1914), Kennedy (1961, 1963), Middleton (1965), Langford and Bracken (1987), Yagishita et al. (1988), Yagishita and Taira (1989) and Yagishita (1994) suggested that the upstream migration is caused by erosion on the lee side (where the water is accelerating) and deposition on the stoss side (where the water is decelerating) of antidunes, and Kennedy (1963, 1969) suggested that the greater angle between the slope and the center of gravity of the particles makes re-entrainment more difficult on the upstream limb. Recently, Kubo and Yokokawa (2001) explained upstream migration of antidunes with quasi-cyclic breaking of water surface wave as a result of intermittent hydraulic jumps moving upstream at the stoss side.

Breaking of water surface wave and partial destruction of the antidune may be due to two processes (Kennedy, 1963): (1) creation of adverse pressure gradients causing the onset of flow separation and subsequent flow instability

on the upstream side of the antidune ; and (2) instability of the surface waves as they increase in height.

HYDRAULIC CONDITIONS OF ANTIDUNE FORMATION

Laboratory experiments indicate that antidunes are stable in higher flow velocities (or Froude numbers) than those of upper-flow-regime plane bed conditions (e.g. Harms and Fahnstock, 1965 ; Simons et al., 1965 ; Reineck and Singh, 1973, 1980 ; Allen, 1982 ; Harms et al., 1982 ; Southard and Boguchwal, 1990). Cheel (1990) predicted based on flume experiments that with increasing flow strength the gradual sequence of bed phases in uni-directional flows is : 1) plane bed, 2) low-relief, downstream-migrating in-phase waves, 3) stationary in-phase waves and 4) upstream-migrating antidunes (note that he called only upstream-migrating bedforms “antidunes” and what he called “in-phase waves” corresponds to antidunes in a wide sense).

Simons and Richardson (1960) suggested that antidunes form at Froude numbers (F) greater than 1. Here F is given by :

$$F = \frac{U}{\sqrt{gd}}$$

where U is the mean velocity, g is the gravity acceleration and d is the flow depth. Antidunes can exist only for $0.844 \leq F \leq 1.77$ (cf. Allen, 1982). Kennedy (1963) reported that downstream-migrating antidunes form under lower Froude numbers than upstream-migrating ones. Barwis and Hayes (1985) suggested that standing antidunes occur at flow velocities intermediate between those for the two migrating forms. Some researchers (e.g. Shirasuna, 1972) suggest that antidunes are not formed in a closed (i.e., without free water surface) experimental flume.

Antidune bedforms, i.e., the wavelength (L) and the height (H) of antidunes reflect the hydraulic conditions. Kennedy (1963) showed experimentally and theoretically that the minimum wavelength of two-dimensional antidunes

formed in open channels may be given by :

$$L = \frac{2\pi U^2}{g}$$

whilst the maximum antidune steepness could be determined from :

$$\frac{2H}{L} \approx 0.142.$$

The dominant wavelengths of antidunes may be given by (Kennedy, 1963) :

$$F^2 = \frac{U^2}{gd} = \frac{2 + kd \tanh(kd)}{(kd)^2 + 3kd \tanh(kd)}$$

where k is $2\pi/L$. For antidunes produced by density currents, they occur not at the free water surface, but at a density interface within the fluid (Hand et al., 1972). Hand (1974) denoted experimentally that antidunes, breaking antidunes and chute-and-pools can be duplicated with density underflows (saline water flows). Hand et al. (1972) presented a modified equation relating density current velocity and antidune wavelength as following :

$$U^2 = \frac{gL}{2\pi} \frac{\Delta\rho}{2\rho + \Delta\rho}$$

where ρ is the density of the current and $\Delta\rho$ is the density difference between the density current and the ambient fluid. Furthermore, assuming the resistance coefficient (f), bed slope (S) may be estimated using the Darcy-Weisbach equation :

$$U = \sqrt{\frac{8gdS}{f}}.$$

RECOGNITION OF ANTIDUNE DEPOSITS

The criteria of antidune deposits seem rather confused or ambiguous. The term "antidune" means a bedform. Its definition contains the relation between the bedform and the formative current (e.g. in-phase or out-of-phase). Therefore, the definition of antidune described above is not applicable to ancient deposits or sedimentary structures.

tary structures.

Various sedimentary structures are supposed to be formed as antidunes (Fig. 1). "Upstream-dipping low-angle cross stratification", "lenticular or wavy stratification dipping both upstream and downstream" or "HCS-like structure" may be characteristic of antidune deposits (Table 1). For example, Alexander et al. (2001) closely observed bedforms and associated sedimentary structures formed under supercritical water flows over aggrading sand bed in a laboratory flume, and they described three-dimensional geometry of the sedimentary structures of antidunes and chutes-and-pools (Fig. 1f). They reported that the structures associated with antidunes are represented by : (1) lenticular laminae sets with concave-upward erosional bases in which laminae generally dip upstream or fill the troughs symmetrically, which are associated with growth and upstream migration of water-surface waves and antidunes, and with surface-wave breaking and filling of antidune troughs, respectively ; (2) sets of downstream-dipping laminae produced by rapid migration of asymmetrical bedwaves ; (3) rare convex-upward laminae defining the shape of antidunes that developed under stationary water-surface waves. Most studies identify antidunes in ancient deposits on the following grounds : 1) cross stratification dipping opposite (upstream) to the paleocurrent direction determined from lower-flow-regime sedimentary structures or regional facies assemblage ; and 2) parallel stratification adjacent laterally or vertically, suggesting deposition in upper-flow-regime conditions. Grain fabric may be also effective (see below).

Antidune cross laminae are vague and relatively low-angle, and thus hard to recognize in general (e.g. Middleton, 1965 ; Barwis and Hayes, 1985). The origin of individual laminae is supposed to be partly due to shear sorting (Barwis and Hayes, 1985) and partly due to low-relief (millimeter-high) bedwaves (Alexander et al., 2001). Some researchers attributed their faintness to the absence of grain sorting that accom-

panies avalanching (Leeder, 1982) or to the well-sorted nature of sands composing antidune deposits (Leeder, 1982; Barwis and Hayes, 1985) and regarded it as one of the reasons why antidunes have been scarcely discovered in ancient deposits.

"HCS MIMICS" AND ANTIDUNES

"HCS (hummocky cross stratification) mimics" is one of the sedimentary structures formed by antidunes. It is very similar in appearance to HCS (Harms et al., 1975) characteristic of storm-

dominated shallow marine deposits. The name "HCS mimics" (Rust and Gibling, 1990; Masuda et al., 1993) emphasizes that the sedimentary environment or process of formation is quite different from that of HCS.

Rust and Gibling (1990) found a HCS-like three-dimensional sedimentary structure in the braided-fluvial South Bar Formation (Pennsylvanian), Canada. The unit is near the top of a 4.7-m-thick abandoned channel sandstone. The wavelengths of the bedform were 50–110 cm, and the amplitudes ranged 5–10 cm. They called this structure

(h)

Fig. 1 Various sedimentary structures in antidune deposits. Data are shown in Table 1. (a) Fisher and Waters, 1970. Hammer for scale. (b) Prave and Duke, 1990. Height of the figure is about 30 cm. (c) Barwis and Hayes, 1985. (d) Langford and Bracken, 1987. (e) Cotter and Graham, 1991. Ruler is 15.2 cm long. (f) Massari, 1996. Hammer is 35 cm long. (g) Yokokawa et al., 1999. (h) Alexander et al., 2001. Flow-parallel vertical sections of antidune deposits produced under uni-directional supercritical flows in a flume experiment. Upstream dipping laminae (ud), downstream dipping laminae (dd), laminae filling trough symmetrically (sf), structureless part of trough fill (s), convex-upward laminae with trough-shaped base (cu) and small bedwaves on antidunes on bed surface (sbw) are identified.

“HCS mimics” because the original definition by Harms et al. (1975) restricted HCS to those formed by storm waves in shallow marine environments. They interpreted this structure as a trace of three-dimensional antidune bedforms under upper-flow-regime conditions, because they contained well-developed current lineations parallel to the unidirectional paleoflow and accompanied wavy parallel lamination.

Prave and Duke (1990) reported a “small-scale hummocky cross-stratification” in Upper Cretaceous turbidites in the western Basque Pyrenees

(Fig. 1b). This structure is characterized by wavy laminae continuous across crests and troughs with the wavelengths ranging between 20 and 70 cm (51 cm in average) and the amplitudes between 2 and 6 cm (3 cm in average). This occurs near the Bouma B-C boundary and grade laterally and vertically into flat, planar laminations suggesting the deposition in upper-flow-regime conditions. Thus, they interpreted this structure as a form of antidune stratification generated by standing waves along the interface of a denser underflow and an overlying low-

Table 1 Major previous studies on the sedimentary

Paper	Age	Kinds of deposits	Sedimentary structures or geometries	Amplitude, wavelength	Grain size
Timmermans, 1935*	Recent	Foreshore deposits		±1cm, ±40cm	
Van Straaten, 1953	Recent	Beach deposits			
Power, 1961	Pleistocene	Alluvial fan deposits	Upward-dipping cross-lamination ("backset bedding")		Pebble to coarse sand
Reineck, 1963	Recent	Beach deposits			
Middleton, 1965	—	Flume experiment	Faint lens-like units, inclined at low angles (<10 degrees) both upstream and downstream	5cm, 1-2m	Fine sand (mean=0.19mm)
Collinson, 1966	Namurian	Fluvial deposits	Massive, lenticular bedding		
Jopling and Richardson, 1966	—	Flume experiment	Backset bedding		Medium sand
Panin and Panin, 1967	Recent	Beach deposits (upper berm)	Regressive sand waves	2-6cm, 50-120cm	Fine sandy deposit (70-250μ)
Walker, 1967	Devonian	Turbidites	Broad, symmetrical undulations	2-4cm, 40-60cm	0.06mm (max.)
Hand et al., 1969	Triassic	Alluvial fan deposits (fanglomerates)	Cross laminae within the waves are parallel to the upstream wave fronts (maximum steepness about 22°)	6.5cm, 63.3cm (average)	Granule (median=2.1mm)
McCracken, 1969	Middle Tertiary	Fluvial deposits	Asymmetric dune-shaped wedges with backset lamination dipping upcurrent		Granular coarse sand
Fisher and Waters, 1970		Base surge deposits	Stoss-side layers tend to dip steeper, finer-grained and contain fewer laminae		Silt- to sand-size particles
Skipper, 1971**	Middle Ordovician	Turbidites	Sinusoid bed forms, internal laminations inclined upstream at <15°	48-approx. 100cm, 3-7cm	Very coarse to medium sand
Hand et al., 1972**	Ordovician	Turbidites			
Wunderlich, 1972	Recent	Foreshore deposits			
Schmincke et al., 1973	Pleistocene	Base surge deposits	Cross-bedded structures with steep stoss sides and very low-dipping lee sides		
Hayes and Kana, 1976	Recent	Foreshore deposits	Thin lenticular sets of low-angle lamination		
Shaw and Kellerhals, 1977	Recent	Alluvium	Essentially simple ridges, more or less evenly spaced in the direction of the flow	10cm, 2-3m (average)	Gravel
Skipper and Bhattacharjee, 1978**	Ordovician	Turbidites	Backset bedding	4cm, 30cm	Coarse to medium sand
Broome and Komar, 1979*	Recent	Beach face deposits	Regular patterns of ripples, heavier and darker minerals are left in the troughs and the lighter quartz and feldspar sand grains form the crests	?, 48-70cm (mean)	Mean grain size = 0.18mm
Augustinus, 1980*	Recent	Foreshore of the sandy chenier (in general)	Long-crested, asymmetrical wave ripples (cf. Barwis and Hayes, 1985)	3-5cm, up to 50cm	Fine sand
Reineck and Singh, 1980	—		Low-angle inclined bedding on the upstream face (common)		
Allen, 1982	Recent	Beach deposits	Backwash structures, long and generally sinuous crests, a symmetrical to weakly asymmetrical vertical streamwise profile	Several mm to a cm, 0.3-1.2m	Fine sand

structures or the bedform geometries of antidunes.

Collinson and Thompson, 1982	Pre-Cambrian	Fluvial deposits	Gentle 2D waves or 3D domes and hollows		
McCubbin, 1982	Recent	Beach deposits	Thin lenses with very gently dipping cross stratification		
Schwartz, 1982*	Recent	Washover fan deposits	Subhorizontal to very low angle (<5°), landward dipping, planar laminae (Fig. 4A) (cf. Barwis and Hayes, 1985)		
Barwis and Hayes, 1985	Ordovician-Pleistocene, Recent	Washover fan deposits	Nested, very thin lenses which are internally cross-laminated	2cm-0.5cm, 40-115cm or less	Fine sand
Langford and Bracken, 1987	Holocene	Alluvial fan deposits	Backset laminae in low-angle, cross-stratified, lenticular bedding	<1cm-4cm, 5cm-1.2m	Very well sorted fine sand (median=0.15mm)
Yagishita and Taira, 1989	—	Flume experiment	A symmetrical vertical streamwise profile with slope of 6°-8°	About 3.0cm, 30-34cm	Coarse- to medium-grained sand
Prave and Duke, 1990	Cretaceous	Turbidites	Gently curving wave-like forms (small-scale hummocky cross-stratification)	0.02-0.06m, 0.2-0.7m	Fine to very fine sand
Rust and Gibling, 1990	Pennsylvanian	Fluvial deposits	Gently dipping wavy hummock-like structures ("HCS mimics")	5-10cm, 50-110cm	Medium sand (approx. 0.3mm)
Cotter and Graham, 1991	Late Devonian	Fluvial deposits	Flat to inclined parallel laminated sets which meet the criteria for HCS	0.1-0.4m, 1-3m	Fine- and very fine-grained sand
Masuda et al., 1993	Pleistocene	Tidal deposits; flood deposits	Closely resemble to HCS ("HCS mimics")	<5cm, 10-40cm; <few cm, <tens of cm	Alternation of mud and fine sand; well-sorted fine sand
Yagishita, 1994	Cretaceous	Turbidites	Three-dimensional wavy bed forms (HCS-like bed forms)	0.15m, 0.4-0.7m	Medium to fine sand
Yagishita, 1995	Recent	Beach gorge deposits	Most of the bedforms consist of crestal sinuosity and sometimes display mound-like structures (3-D antidunes)	6.5cm (average), 15-60cm	Well-sorted medium- to fine-grained sand (mean=1.8phi)
Massari, 1996	Pleistocene	Gilbert-type progradational wedges	Lensing layers with broadly convex-up or wavy upper boundaries (with internal lamination ranging from planar or low-angle, boundary-unconformable, to curved, boundary-conformable), <10cm-45cm thick		Granule to pebble or pebbly sand
Alexander and Fielding, 1997	Recent	Fluvial deposits	Steeper stoss than lee faces and crest lines generally transverse to local flow	up to 1m, 8-19m	Gravelly sand to sandy gravel
Blair, 2000	Plio-Pleistocene	Alluvial fan deposits	Backsets in lenticular to wedge-planar sets, 10-40cm thick		Granule to pebble
Yokokawa et al., 1999	—	Flume experiment	Lens-like cross-lamination ("HCS mimics")	1-2cm, 40-100cm	Well-sorted fine sand (mean=0.18mm)
Alexander et al., 2001	—	Flume experiment	Lenticular laminasets with concave-upward erosional bases (troughs) in which laminae generally dip upstream or fill the troughs symmetrically; sets of downstream-dipping laminae; rare convex-upward laminae	66mm (symmetrical bedform, max.), 25-66mm (at breaking waves); 0.76-1.14m	Well-sorted sand (median=0.42mm, standard deviation =0.71mm)

* later recognized as antidunes

** re-interpreted as reflected turbidites (Pickering and Hiscott, 1985)

density layer in a turbidity current.

In Japan, Masuda et al. (1993) reported "HCS mimics" in the tidal deposits of the Pleistocene Shimosa Group and in the flood deposits of the Pleistocene Osaka Group. The former occurs in a sandy tidal deposit in a tidal flat or tidal creek with the wavelength of 10–40 cm and the amplitude less than 5 cm. The latter is in a braided-fluvial flood deposit (2 m thick) composed of well-sorted fine sand, and the wavelengths are less than several 10 cm and the amplitudes less than a few centimeters. Both these "HCS mimics" accompany climbing ripple cross-lamination, suggesting rapid deposition in a dense flow with high suspended load. They inferred that these structures were formed as three-dimensional antidunes under upper-flow-regime conditions based partly on the fact they laterally or vertically grade into parallel lamination.

"HCS mimics" indicate that HCS-like sedimentary structures may be formed by some currents other than storm-wave oscillatory or combined flows in shallow marine environments, suggesting that HCS is not indicative of a particular condition or depositional environment (Prave and Duke, 1990; Masuda et al., 1993; Masuda, 2000, 2001). In many cases, "HCS mimics" is inferred to be formed as three-dimensional antidunes in upper-flow-regime conditions, particularly in abundant suspension fallout (Masuda et al., 1993; Yokokawa, 1994; Yokokawa et al., 1999). This inference would be thought-provoking for those investigating the hydraulic conditions or the processes of formation of HCS or "HCS mimics".

HCS-like structure or "HCS mimics" might be explained by rapid aggradation of antidunes or chutes-and-pools. Fig. 2a is an observation of the bed profiles under a uni-directional density current (saline water underflow) during a flume experiment (Hand, 1974), representing the development of antidunes from an initially plane bed (profile 1), their conversion to chutes-and-pools and finally a return to simple antidunes migrating upstream. "HCS mimics" might be formed

Fig. 2 (a) Bed profiles showing evolution of bed profile during run involving breaking antidunes and chutes-and-pools (after fig. 6A of Hand, 1974). Current from right to left. Numbers indicate time sequence. (b) Resultant sedimentary structures of antidunes after removal of parts of profiles that were subsequently eroded (modified after fig. 6B of Hand, 1974). (c), (d) Results of deposition at a constant aggradation rate, supposing no modification of the bedforms. Imaginary "HCS mimics" may develop at a high net aggradation rate.

imaginarily under rapid net aggradational conditions (see Figs. 2c and 2d), if the bedforms suffer no modification in spite of high suspended-load fallout.

GRAIN FABRIC OF ANTIDUNE DEPOSITS

Grain fabric of antidune deposits has been studied by Johansson (1976), Taira (1976, 1989), Yagishita et al. (1988), Yagishita and Taira (1989), Yokokawa and Masuda (1990), Yagishita (1994) and other researchers. Upstream-dipping imbrication is supposed to be dominant in antidune deposits (e.g. Yagishita et al., 1988; Yagishita and Taira, 1989) as in upper-plane-bed parallel laminae, but probably the imbrication angle is somewhat steeper in antidune deposits (Johansson, 1976; Taira, 1976, 1989; Pickering and Hiscott, 1985). However, this would be the case only

in those formed by antidunes representing smooth aggradation and gradual, slow migration without breaking of surface waves.

Grain fabric in HCS is supposed to be characterized by quasi-cyclic vertical variations of imbrication angles reflecting the oscillatory component of the flow (e.g. Cheel, 1991). Yagishita et al. (1992) insisted that HCS and SCS formed by storm-generated combined flows are quite different from HCS-like antidune deposits in their internal imbrication tendencies. They reported that the grain fabric in HCS is characterized by the imbrication subparallel to the undulate lamination and in SCS by weak upcurrent imbrication relative to the lamination, whereas that in antidune deposits is characterized by high-angle upcurrent imbrication (up to 30° from the horizontal plane) (Yagishita et al., 1988; Yagishita and Taira, 1989). On the other hand, Yokokawa (1994) pointed out the periodic reversals of imbrication directions in "HCS mimics" formed in a laboratory flume, just as reported by Cheel (1991) in Cretaceous HCS sandstone. Masuda (2000, 2001) also reported similar imbrication patterns of the "HCS mimics" in the turbidites of the Cretaceous Uwajima Group, Ehime Prefecture, Japan. He suggested that such characteristics imply oscillatory currents generated by constructive waves or hydraulic jumps during three-dimensional antidunes develop.

As a result, "HCS mimics" and HCS seem to be difficult to distinct only from their grain fabrics at present. Only limited examples of diverse antidune deposits or only limited parts on the thin sections of antidune deposits have been investigated in grain fabric analysis. For example, antidune deposits with higher-angle backset bedding and those with HCS-like structure may represent different grain fabrics; foresets and backsets may differ in grain imbrication angles. The definition and classification of antidune bedforms and their deposits should be established and more examples are needed to be analyzed to clarify their sedimentation processes and hydraulic conditions.

GRAIN SIZES AND SEDIMENTARY ENVIRONMENTS OF ANTIDUNE DEPOSITS

Antidunes and antidune deposits have been reported in a wide range of grain sizes from gravel to very fine sand or silt (Table 1). At least in sand-sized sediments, antidunes may develop in any grain size of the bed surface.

Antidunes can be formed in various sedimentary environments from terrestrial to deep sea (Table 1). Antidunes are best known from beaches (e.g. Timmermans, 1935; Van Straaten, 1953; Reineck, 1963; Panin and Panin, 1967; Wunderlich, 1972; Hayes and Kana, 1976; Allen, 1982; McCubbin, 1982) where they are created by backwash in foreshore region and overwash in backshore (Reineck and Singh, 1973, 1980; Allen, 1982; McCubbin, 1982). In barrier-island systems, antidunes have been also reported on washover fans (Barwis and Tankard, 1983; Barwis and Hayes, 1985). There are also many studies describing antidunes in fluvial, alluvial fan or fan delta environments (e.g. Power, 1961; Collinson, 1966; Hand et al., 1969; Shaw and Kellerhals, 1977; Langford and Bracken, 1987; Rust and Gibling, 1990; Cotter and Graham, 1991; Massari, 1996; Alexander and Fielding, 1997; Blair, 2000; Suzuki, 2000). It may be partly because the current directions are estimated with ease and backset beddings are readily recognizable. Some researchers reported antidune deposits in turbidites (e.g. Walker, 1967; Prave and Duke, 1990; Yagishita, 1994), although what Skipper (1971) and Skipper and Bhattacharjee (1978) inferred to be antidune deposits were later re-interpreted as megaripple cross-stratification formed under reflected turbidity currents (Pickering and Hiscott, 1985).

EXAMPLES OF ANTIDUNE DEPOSITS

Case 1 : modern fluvial deposits This sedimentary structure (Fig. 3) was observed in July 1998 at the Otaki River (Otaki Village, Nagano Prefecture, Japan) and is interpreted to have been formed by antidunes, as previously reported by

Fig. 3 Three-dimensional antidune deposit in modern fluvial deposits at the Otaki River, Nagano Prefecture. Paleocurrent direction from left to right on the photograph, judging from the flow direction of the river.

Masuda (2000, 2001). The bedform geometry (Fig. 3a) is characterized by wavy mounds spaced evenly in the flow direction, whose wavelength is 0.5–2 m and the amplitude is about 30 cm in maximum. The antidune deposit is mainly composed of ill-sorted medium-grained sand to granule. In the vertical section parallel to the flow (Fig. 3), cross lamination dipping both upstream and downstream was observed, which is characteristic of antidune deposits. Some of the laminae were continuous from hummocks to swales laterally, as in hummocky cross stratifications. The antidunes were partly modified into dunes under the subsequent waning flow.

Case 2 : modern foreshore deposits Antidunes left on the beachface (Fig. 4a) were observed at the Kujukuri coast, Iioka Town, Chiba Prefecture, Japan on May 29, 2000. This is a two-dimensional, gently-inclined wavy bedform (the wavelength was about 30 cm and the amplitude was about 2 cm in maximum) with the crestlines subparallel to the shoreline. The antidune deposit was composed mainly of heavy-mineral rich, well-sorted fine sand. Bi-directional (dip-

ping both seaward and landward) low-angle cross lamination and thin lenses characteristic of antidune deposits were recognized on the vertical section normal to the shoreline (Fig. 4b).

Such antidunes in beach environments were formerly called “regressive sand waves” (Bucher, 1919 ; Van Straaten, 1953 ; Panin and Panin, 1967), “terugloop-zandgolven” (Timmermans, 1935), “Sandwellen” (Reineck, 1963) or “backwash ripples” (Komar, 1976 ; Broome and Komar, 1979). Antidunes are readily formed by swash and backwash in sandy foreshore, where limited water depths enlarge the Froude numbers. Kennedy (1963) reported that foreshore antidunes are easily formed when the steepness of the waves is 0.13–0.16.

Case 3 : ancient turbidites This structure (Fig. 5) occurs in the Upper Pliocene Katsuura Formation (Sawada, 1939 ; Tokuhashi, 1992), Kazusa Group in the Katsuura City, Chiba Prefecture, Japan. The lower part of the sandstone bed was “massive” or vaguely parallel-laminated (Bouma A–B divisions), which was overlain by the pebbly layer with low-angle cross lamination dip-

Fig. 4 (a) Two-dimensional foreshore antidunes at the Kujukuri coast, Iiooka Town, Chiba Prefecture. Crestlines are subparallel to the shore-line. Scale is about 30 cm long. (b) Vertical section of the antidune deposit normal to the shore-line.

ping both upstream and downstream, which graded upward into gently-undulated or subparallel lamination. This Formation is interpreted as lower fan to basin plain deposits *sensu* Walker (1978) (Katsura, 1984), so it is not plausible that this structure was formed by storm-induced oscillatory or combined currents.

This structure may be formed as antidunes in a turbidity current, by analogy with the examples in Prave and Duke (1990) and Cotter and Graham (1991). This is different from those regarded by Skipper (1971) and Skipper and Bhattacharjee (1978) as antidune backsets in turbidites and later re-interpreted by Pickering and Hiscott (1985) as megaripple cross-stratification in reflected turbidites, since cross lamination is

relatively low-angle and some laminae are continuous from the hummocks to the adjacent swales in this example.

CONCLUDING REMARKS

The term “antidune” represents a bedform, not a sedimentary structure or a deposit. The criteria of antidune deposits are rather confused. Antidunes are thought to form various sedimentary structures: thin lenticular structure and HCS-like structure (“HCS mimics”) are formed as antidunes as well as backsets/foresets. However, paleocurrent directions or regional facies assemblage, for example, will be needed for the recognition of antidune deposits as well as their sedimentary structures and grain fabrics.

The classification of antidune geometries is so insufficient that the processes and mechanisms of the formation of sedimentary structures have been poorly understood. Detailed descriptions and analysis of the bedforms and the resultant deposits should be conducted based on a more established classification from experimental or hydraulic approaches.

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Fig. 5 Antidune deposits in a turbidite in the Upper Pliocene Katsuura Formation at Katsuura City, Chiba Prefecture. Paleocurrent direction from right to left on the photograph, as recognized based on the directions of the sole marks, imbrication dips and the foreset direction of the current ripple cross laminae (Loc. 7 of Tokuhashi, 1992).

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* in Japanese with English abstract

** in Japanese

*** in Dutch

**** in German

アンティデューン堆積物の堆積構造

荒谷 忠・増田富士雄, 2001, 堆積学研究, No. 53, 1-15

Araya, T. and Masuda, F., 2001 : Sedimentary structures of antidunes : An overview.

Jour. Sed. Soc. Japan, No. 53, 1-15

アンティデューン（反砂堆, antidune）やその堆積物の定義や認定基準に関しては一般に誤解が見受けられる。そもそも、アンティデューンという用語は流れの高領域（upper flow regime）のベッドフォームの一種を示すものであって、特定の堆積構造あるいは堆積物を指すわけではない。上流側に比較的低角で傾斜した斜交葉理（層理）のみならず、薄いレンズ状のラミナセットやハンモック状斜交層理に似た構造（“HCS mimics”, HCS もどき）もアンティデューンで形成される。しかし、実際にアンティデューン堆積物を認定するには、その堆積構造や粒子配列だけではなく、古流向や堆積相の分布を調べる必要がある。