Grain Fabric in Cross Laminated Deposits Conformably Superimposed on Parallel Laminae: Flume Experiments and Application to Geologic Records

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Abstract

Small-scale bed waves under unidirectional currents can be classified into two types: Type I: well-developed bed waves formed under a flow with a certain velocity, and sand grains move by avalanche on the lee slope; Type II: immature bed waves with short wavelength and low height formed at the early stage after the flow velocity decreases from the upper-plane-bed-regime, and grains on the bed move as a sheet flow. Experiments demonstrated that Type II bed waves could be preserved in the presence of ambient sedimentation and resulted in small-scale cross-stratifications similar to Type I formed under a relatively slow flow. Grain fabric analyses showed that the dominant direction of long axes of grains in the deposit of Type II bed waves dipped upstream against the lee slope, unlike Type I deposits. It is possible to identify the type of small-scale cross-stratifications by its grain fabric. We found an ancient example of ripples categorized into Type II in a turbidite sequence of the Plio-Pleistocene Kakegawa Group, in Japan.

Key words: cross-lamination, grain fabric, immature bed wave, ripple, turbidite

Introduction

Bedforms under equilibrium flow conditions have been studied experimentally by many researchers. In the natural environment, however, it is common that flow conditions change even in small time-scale in which only a few centimeter deposition occurs. Allen and Friend (1976) observed the response of bedforms to unsteadiness of flow conditions in the intertidal area of Norfolk, UK. They suggested that it took some time (a relaxation time) to transform one bedform into another, which means that the bedform does not always respond to the flow condition at a given time. Crowley (1983) observed the same phenomena on bars of the Platte River, USA. Ashley et al. (1982) studied patterns of climbing ripples formed under the transitional flow by accumulating sediments in a flume. Endo and Masuda (1997) studied the aspect of transition of bedforms from upper plane beds to dunes until a system reached the equilibrium, i.e., during its relaxation time. The time lag for the bedform transformation in response to the change of the flow velocity is an important factor especially for the sedimentary process under the flow quickly damped like a turbidity current. Walker (1965) supposed that the scarcity of large- or medium-scale cross-bedding in turbidites is related to the lack of time to develop bedforms.

Experiments in Endo and Masuda (1997) indicated hysteretic behavior in development of bedforms (Fig. 1). It is known that low-relief bed waves (Bridge and Best, 1988, 1997; Baas and Koning, 1995) with low wave heights and relatively long wavelengths are formed during the transition from dunes to upper plane beds. Low-relief bed waves occur rather stably if the flow condition is constant. On the other hand, when the flow condition changes from the upper-plane-bed regime to the lower flow regime, the bed waves that are with short wavelength and low height are formed until well-developed bed waves are established. These small nascent bed waves migrate at a faster rate than bed waves formed under the steady state with the same flow velocity. It is known that a migration rate of bed waves becomes slower with growth of bed waves (Ashley et al., 1982; Endo et al., 1997). From geometrical consideration, the migration rate is inversely proportional to the bed wave height, when a transport rate of sand grains is constant (Fredslø and Deigaard, 1992).

Bed waves (ripples or dunes) can be classified into
two types. Type I is well-developed bed wave under a certain flow condition and sand grains on the lee slope move by avalanche (Endo, 2000). A vortex recognizable with the naked eye occurs in the trough. Type II is immature bedforms before changing to well-developed ones. In Type II, grains on the bed surface move as a sheet flow because the flow can transport grains even on troughs at faster rate than that by avalanche (Endo, 2000). Type II ripples are called “upper ripples” (Endo, 2000). Type II ripples under a faster flow are similar in size to Type I ripples formed under a slower flow, in some cases. Although Type II ripples have more symmetrical profiles compared to type I, their difference is subtle (Endo and Masuda, 1997; Endo, 2000).

The aims of this study are:

1) to investigate the sedimentary structures and the grain fabric of Type II ripples experimentally formed, by experiments in the system of net-sedimentation

2) to find a method to identify Type II ripples in natural deposits.

**Methods**

A recirculating flume at Osaka University (10 m long, 10 cm wide and 50 cm deep) was used to investigate bedform transition in waning flows with ambient sedimentation. Sand feeders were installed above the flume. Sediment was supplied through feeders as sediment rain, to reproduce ambient sedimentation (e.g. Arnott and Hand, 1989).

Well-sorted quartz sand of 0.2 mm in mean diameter was used. Experimental hydraulic condition (E.H.C.) was set to the flow rate at 47 cm/s and 13 cm in water depth by decreasing the flow velocity after an upper plane bed was developed. The flow was decelerate as quickly as possible, and then kept constant (E.H.C.) until the end of the run. The flow velocity was measured at a height of 5 cm above the bed using an ultrasonic current meter (ADV, SonTek Co. Ltd.). The average bed wavelength under E.H.C. is about 20 cm when the bed is fully developed. We focused on the bed waves with length of about 5 cm under E.H.C., which are Type II (Endo, 2000). The sand supply rate was almost constant at 1.3 ml/cm²/s over the flume. Sedimentary structures were observed directly through the glass wall of the flume.

We examined the grain fabric of cross laminae in vertical sections parallel to the flow direction in the experimental and the natural sediments, to distinguish Types I and II. The grain fabric in deposits was analyzed after hardening the samples (Yokokawa and Masuda, 1988). To avoid disturbing the bed deposit, low viscosity epoxy resin (E 205, Konishi Co. Ltd.) was used to fix sand grains. The hardened sample was sliced into thin sections. The grain fabric was analyzed on the digital images of the microscopic photographs of these sections. Grains with no distinct long axis (the longest axis is shorter than twice of the axis normal to the longest axis) were neglected in the statistics analysis. To compare the experimental deposits and natural ones, we sampled turbidite deposits from the Plio-Pleistocene Kakegawa Group.

**Results**

1. **Sedimentary structure of Type II bed waves**

The bedform started to develop with Type II bed waves (short in wavelength and low in wave height, different from low-relief bed waves) in the presence of ambient sedimentation under E.H.C. The ambient sedimentation resulted in climbing ripples, which develop from plane beds, through Type II bed waves, to Type I bed waves.

The sedimentary structures of the experimental deposit are shown in Figure 2. Bed waves that appear first are ripples with low in height and short in length, not ones with low wave height and long wavelength. This shows that medium-scale cross-stratifications do not lie conformably on parallel lamination, while small-scale cross-stratifications do so as seen around the B-C boundary of a Bouma sequence (Bouma, 1962). The inclination of set boundaries becomes steeper upward. The angles of climbing are gentle (3.5°-5.0°) in the lower part of the deposit and steep (11°) in the upper part, although the flow velocity (E.H.C.) and the deposition rate (1.8 cm/minute) were nearly constant throughout the entire run.

The horizontal distance between two coadjacent set boundaries increases upward, as well as the length of intervening cross laminae. The angles of laminae also become steeper upward. The average angles of laminae in Type II bed waves and large Type I bed waves were 18° and 25.3°, respectively.

Some set boundaries join their neighbors. The coalescence of bed waves forms wedge shape structures more commonly in the lower part than in the upper part (Fig. 2a). Preservation of laminae on the stoss sides is also common in the lower part (Fig. 2a).
2. Grain fabric of experimental deposits

The grain fabric of experimental deposits of Types I and II were analyzed (see Fig. 2b for the sampling points). The grain fabric of Type II ripples is shown in a rose diagram (Fig. 3a). The predominant direction of long axes of grains intersects across the average direction of laminae at an angle of about 30°, which is so called "imbrication type". Type I, on the other hand, has the dominant direction nearly parallel to the average direction of the cross laminae (Fig. 3b). This is the typical fabric on the foreset of fully developed ripples on dunes (Yokokawa and Masuda, 1990).

3. Grain fabric in the natural deposit

Natural turbidites of the Plio-Pleistocene Kakegawa
Fig. 4. Turbidite bed in the Plio-Pleistocene Kakegawa Group at Hamaoka Town, Shizuoka Prefecture, Japan.

This geological record includes a parallel lamination part and a climbing cross-lamination part conformably overlying it without large cross lamination between these two parts. The thickness of the bed is about 10 cm. CL: cross lamination part and PL: parallel lamination part. Two areas in the cross stratification were sampled; the lower part (a) and the upper part (b).

Group include small-scale cross-stratifications conformably superimposed on parallel laminae, generally corresponding to C- on B-divisions of Bouma Sequence (Fig. 4). The angles of cross laminae increase from the lower part (less than 20°) to the upper part (about 30°). The inclination of set boundaries also becomes steeper upward. The sediment particles from parallel laminae to cross laminae are nearly uniform in size; very fine sand.

The grain fabric of the cross lamination was analyzed at two points in the sequence; one is at the lower part close to the parallel laminae, and the other was 2 cm higher in the deposit (Fig. 4). The results are shown in Fig. 5. In the lower part (Fig. 5a), the predominant direction of long axes of grains differs from the average direction of the laminae at an angle greater than 20°. In the upper part (Fig. 5b), there are two dominant directions; one intersects the average direction of the laminae at an angle less than 20° and the other does at an angle greater than 30°.

Discussion

1. Sedimentary structure including Type II bed waves

Climbing-ripple-deposits developed from plane beds, through Type II bed waves, to Type I bed waves have steepening-upward set boundaries. The inclination of set boundaries is determined by both the sedimentation and migration rates (Allen, 1982). In the present study, the sedimentation rate and the flow velocity were constant after the flow condition was set at E.H.C. Steepening-upward set boundaries were due to retardation of ripple migration with ripple growth. If a flow wanes continuously to a slower velocity than E.H.C., Type I ripples would be formed with the size similar to the underlying Type II ripples formerly formed while the flow velocity is still fast. In this case, the deposit will have steepening-upward set boundaries as well, because ripples migrate slower due to the slow flow velocity.

Although the mode of grain movement on Type I bed waves is different from that on Type II, it is difficult to distinguish them by their shape. Both

Fig. 5. Rose diagrams of grain fabric, in the vertical section parallel to the flow, of the cross lamination in the turbidite of the Plio-Pleistocene Kakegawa Group at Hamaoka, Shizuoka Prefecture.

The mode is adjusted to the radius of the diagram. N is the number of grains measured. (a) A part close to the parallel laminae (a) in Fig. 4). The mode is 22%. The tendency of this fabric is similar to Type II (Fig. 3a). (b) A part 2 cm above (a) (b) in Fig. 4. The mode is 16%.
types show cross laminae. The difference is subtle and the upper part of a cross-lamina is not preserved in many cases (a part of the lee slope over a set boundary has been eroded). The inclination of set boundaries is not useful for estimation of the flow velocity because the inclination is determined by sedimentation rate as well as the migration rate of bed waves. Therefore, the sedimentary structure does not provide a useful basis for identifying the bedform type (I or II).

2. Grain fabric as an indicator of type of bed waves

The grain fabric can be a clue for discriminating the bedform type (I or II) and estimating the flow regime in which the small-scale cross stratifications were formed. Results of this study show that the grain fabric in deposits of Type II ripples is the "imbrication type" (Fig. 3.a) similar to that of the upper-plane-bed (Schwarzer, 1951; Parkash and Middleton, 1970; Yokokawa and Masuda, 1990). This is consistent with the observation that sand grains on Type II bed waves move as a sheet flow (Endo, 2000). On the other hand, the fabric of Type I is known as such that the dominant direction of long axes of grains is parallel to laminae (Yokokawa and Masuda, 1990), because when Type I bed waves are formed the mode of the grain movement is avalanche (Gates, 1987 in Ritter et al., 1995). The present study also shows the same pattern for Type I bed waves developed sufficiently after the condition was set to E.H.C. (Fig. 3.b).

3. Grain fabric of natural turbidites

The fabric pattern of the lower part of the small-scale cross-stratifications close to the parallel laminae of natural deposits from the Kakegawa group (a a in Fig. 4) has a tendency similar to that of Type II bed waves formed by the present experiment (Figs. 3.a and 5.a). The predominant direction intersects the direction of laminae at an angle of greater than 20°, i.e., the fabric is "imbrication type". Grains on the bed surface should have moved as a sheet flow. Consequently this part is considered to be composed of Type II formed under a relatively fast flow, not Type I formed under a slow flow. Thus, the experimental results suggest that small-scale cross-stratifications just on the parallel laminae without an erosional surface are generally formed by Type II bed waves, because it is formed immediately after waning from the upper plane bed regime even in the presence of ambient sedimentation. This is true for deposits by other types of waning flow, for example, fluvial flood flows. Here, in the case of sufficiently gradual fall in flow velocity, a well-developed ripple (or dune) bed can form above small Type II bed waves (e.g. Miall and Smith, 1989).

The grain fabric of the cross laminae around 2 cm above the parallel laminae ((b) in Fig. 4) indicates the compound of Type I and II ripples (Fig. 5.b); one predominant direction for type I, the other for Type II. This part is considered to be formed when the lee slope reached the critical angle for the mode of grain movement, at which sheet flows and avalanches occurred alternately. We can see the transition from Type II to Type I by means of grain fabric.

Summary

Bed waves (ripples or dunes) can be classified into two types, I and II. Type I bed waves are well-developed under a certain flow condition. Sand grains avalanche down the lee slope, by which bed forms migrate. Type II bed waves are relatively small (both in length and height), immature bedforms formed at the early stage after the flow wanes from the upper-plane-bed-regime. Grains on the bed surface move as a sheet flow. According to the observation in flume experiments, it is found that Type II bed waves can be formed in the presence of ambient sedimentation as well as the case of no sedimentation.

It is generally impossible to judge whether cross-laminations are formed by Type I or Type II bed waves by their sedimentary structures. On the other hand, the grain fabric analyses showed that the dominant direction of long axes of grains in the Type II deposit dips upstream against the laminae, while the direction in the Type I is parallel to the laminae. Therefore it is possible to identify the type of cross-stratifications by its grain fabric. We found the deposits of Type II bed waves in the Bouma C division of natural turbidites of the Plio-Pleistocene Kakegawa Group in Japan.

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