A NOTE ON SAND GRAIN ORIENTATION IN CROSS-BEDDING

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Abstract Sand-size grains in the undeformed planar cross-bedding observed in the Miocene Ogawa Formation, central Japan, display a remarkable current-normal preferred orientation. These grains also show an upcurrent imbrication relative to the surface of deposition. The sediments are rather coarse-grained and poorly sorted. Such current-normal orientation and imbrication of the grains are probably produced by bed-load rolling of the detrital grains under the condition of gravity avalanching down foreset laminae.

Introduction

In the history of sedimentology, more attention has been paid to cross-bedding than to any other depositional structures. Apart from obtaining paleocurrent data, studies of this primary sedimentary structure are indispensable for gaining information of the hydrodynamic condition during sedimentation. A comprehensive list of papers about cross-bedding is given by POTTER & PETTIJOHN (1963), and the actual processes involved in the development of this structure are summarized by ALLEN (1968) and REINECK & SINGH (1975).

Although a little is known about grain fabrics in cross-bedding, a better knowledge of the fabric pattern will help clarify the process of cross-stratified sedimentation. The purpose of this short paper is therefore to demonstrate a previously undocumented sand-size grain alignment in cross-bedding and discuss its relationship to the mechanism of cross-bedding formation.

Occurrence and fabric pattern

Cross-bedding is very common both in time and space but the literature suggests that the cross-bedding in fluvial and eolian deposits has been more studied than that in marine

sediments (POTTER & PETTIJOHN, 1963, pp. 63–66; ALLEN & BANKS, 1972). The cross-bedding described in this paper occurs in the Upper Miocene Ogawa Formation, in northern Fossa Magna, central Japan. It is well exposed along Sanseiji–Sakakita route,

Fig. 1. Distribution of the Upper Miocene Ogawa Formation, in northern Fossa Magna, central Japan. A cross mark denotes the location of sample studied.
Sj : Sanseiji, Sk : Sakakita.

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the right side cliff of the Omi River (Fig. 1). The Ogawa Formation is distributed along both the western and eastern flanks of the Saikawa anticline. The western facies of the formation, named the "Minochi facies", contains abundant marine fossils, whereas the eastern or "Tochiku facies" is characterized by coarse-grained lignite bearing sandstone intercalated with the beds including *Ostrea* (MORISHITA *et al.*, 1957). The eastern facies is conspicuously cross-bedded with the foresets dipping mainly to the north or to the north-west (SUZUKI, 1977).

As is illustrated in the columnar section (Fig. 2), the cross-stratified bed studied underlies a massive fine to very fine sandstone bed (23 cm) and overlies a granule grade subangular conglomerate bed (4–5 cm). The planar cross-stratification occurs in sets of up to 22–24 cm in thickness, but laterally the bed passes into a structureless sandstone which thins out within a few meters in the down current direction. The strike and dip of the bedding is about N10°E, 60°W. The foresets have a steep inclination (29°) but become tangential forwards their base (Plate IA). The average strike and dip of the cross-bedding is N35°E, and 38°W, respectively. Some foresets rest with erosional contact upon

Fig. 2. Columnar section of the outcrop. The cross-bedding unit occurs between a fine to very fine-grained sandstone and a sandy granule conglomerate. The foresets have slightly tangential basal contacts and scours with the conglomerate.

the underlying granule conglomerates.

To prepare the thin section, a rock specimen was cut from an upper part of a foreset (Plate IB and Fig. 3) and impregnated. The procedure for optical measurement of grain orientation has been outlined previously (YAGISHITA, 1971; YAGISHITA & MORRIS,

Table 1. Compositional and textural analysis of the thin-sections from the undeformed cross-bedding in the Ogawa Formation.

Thin-section No.	Composition												Texture*			
	Qm	Qp	Flp	Flo	Rfss	Rfsh	Rfch	Rfsc	Rfqtz	Mx	Cly	Misc	Md ϕ	M ϕ	$\sigma\phi$	$\alpha_2\phi$
1 a-c	35.5	8.7	1.4	5.4	6.0	6.3	12.5	8.5	8.3	2.6	4.8	0.4	1.2	1.3	0.9	0.4
2 a-c	34.2	9.7	1.7	4.5	4.8	3.3	13.4	8.0	8.2	5.6	4.1	2.6	1.5	1.3	1.2	1.4
3 a-b	30.0	10.5	2.1	3.5	8.5	5.0	13.3	9.3	8.3	4.6	3.1	1.9	1.1	1.2	0.8	0.7
4 a-b	33.0	8.2	0.9	4.1	6.0	3.7	13.7	7.7	13.1	4.3	3.6	1.5	1.0	1.1	0.9	0.3

Qm : monocrystalline quartz. Qp : polycrystalline quartz. Flp : plagioclase. Flo : orthoclase. Rfss : sandstone rock fragment. Rfsh : shale rock fragment. Rfch : chert rock fragment. Rfsc : schist rock fragment. Rfqtz : quartzite rock fragment. Mx : matrix. Cly : clay (including hematite). Misc : miscellaneous (chlorite etc).

*Texture analysis is based on the INMAN's formula (1952). Md ϕ : median diameter. M ϕ : mean diameter. $\sigma\phi$: sorting. $\alpha_2\phi$: skewness.

These compositional and textural analysis were made by counting more than 500 points and 200 points, respectively.

1979). However in this study only grains whose length exceeds 0.5 mm and whose dimensional elongation is greater than 2.0 were selected. The results are displayed by circular histograms drawn at 10° intervals, and to express the grain orientation, the three dimensional coordinate system figured by POTTER & PETTIJOHN (1963, pp. 70) is used (Fig. 3).

Since the matrices in all the thin sections studied are minor amount, the sandstones are classified as lithic-arenites (subclass A or B) of OKADA (1971). Sedimentary rock fragments, such as chert, quartzite and sandstone, are predominant (Table 1). Probably these rock fragments were derived from the Paleozoic terrain exposed south of the Tertiary sedimentary basin. Textural analysis shows the sandstones are medium-grained (mean diameter $M\phi=1.1-1.3$) and only submature (sorting $\sigma\phi=0.8-1.2$). As will be discussed later, such results of textural analysis are intimately related with the fabric pattern of studied cross-bedding.

The measurements in the a-b plane reveal a current-normal preferred orientation for long-axes of the sand grains (Fig. 3). Such a finding is quite contrary to those of many previous investigations in which the grains are aligned parallel to the flow direction (e.g. POTTER & MAST, 1963; HAMILTON *et al.*, 1968; YAGISHITA & MORRIS, 1979). Although there are some exceptions to the flow-normal grain orientation, by far the majority of the grains are *not* oriented parallel to the flow direction (see Fig. 3, sections No. 3 and 4, and also Table 2). To the author's knowledge this is the first description

of such a situation, except in an eolian foreset bed reported by SCHWARZACHER (1951). Grain alignment in the a-c plane shows a well developed upcurrent imbrication relative to the surface of deposition (Fig. 3, sections No. 1 and 2).

Fig. 3. Preferred orientation of long-axes of grains in the dip direction of cross-lamina (the a-c plane) and the strike direction (the a-b plane). Despite some divergences, current-normal preference is outstanding in the a-b plane. Dotted line segments in the a-c plane denote the orientation of the cross-lamina. Maximum percentage of orientation is marked in each circular histogram. Number in parentheses shows counted grains for orientation measurement.

Table 2. Data analysis of grain fabrics in Fig. 3.

Section No.	Fabric mean to reference direction*	Standard deviation	χ^2 (f=3)
No. 1	-7.2° (a-axis= 0°)	42.7°	1.18
No. 2	-3.3° (a-axis= 0°)	44.4°	3.77
No. 3	-12.0° (b-axis= 0°)	44.3°	8.68
No. 4	-5.4° (b-axis= 0°)	44.3°	5.99

*In all cases, clockwise from reference direction is taken as minus.

Discussion

Grain orientation and flow direction: The relationship between current direction and the orientation of long-axes of sedimentary particles is somewhat controversial. Two conflicting observations, one in which the long-axes are parallel to the current direction (e.g. SCHLEE, 1957), and the other in which they are normal to the flow (e.g. SEDIMENTARY PETROLOGY SEMINAR, 1965; RUST, 1972), have been appeared in reports describing the pebble orientation in fluvial deposits.

The relation between pebble orientation and the current direction is chiefly influenced by flow velocity and pebble size (RUST, 1972). Namely, the long-axes of elongate pebbles parallel the flow direction either in conditions of high fluid velocity or where the pebble size is small; whereas they are transverse to the flow where the fluid velocity is low or the pebble size is large. The sedimentary particle orientation determined by such factors is closely related with the mechanism acting on individual sedimentary clasts (WALKER, 1975, 1977). The clasts rolling along a bed tend to have an orientation with the long-axes transverse to the flow direction and with the intermediate-axes dipping upstream (a(t), b(i) type of WALKER, 1975, pp. 136—137). Particles that are dispersed (suspended) in transport above the bed assume an orientation with the long-axes parallel to the flow and imbricate upstream (a(p), a(i) type of WALKER).

Emplacement of cross-laminated detritus: In an attempt to clarify the mechanism of formation of cross-stratified set, JOPLING (1965) investigated the effects and interrelations of flow velocity (bed shear stress), water depth and grain size. He demonstrated that cross-lamina planes are planar, steep (close to the angle of rest) and have an angular contact with the basin floor under condition of low flow velocity, or considerable water depth. Conversely, the cross-lamina become concave of gentle inclination and have a tangential basal contact where the fluid velocity is high or the water depth is shallow. In terms of

grain size, fine sediments were found to be more likely to form low slope and tangential contact cross-sets than coarse grained sediments because a higher proportion of the fine fractions are carried in suspension. He concluded that gentle and tangential type cross-bedding was formed by the pulsatory deposition of suspended sediments, whereas steep and angular type cross-set was formed by the periodical downslope transfer of bed-load sediments moving *en masse*.

Although the cross-bedding in the Ogawa Formation has a slightly tangential contact and erosional scours at the base, the cross-lamina planes are tabular and the slope of foreset is steep (29°). Moreover the grain size of sediments is rather coarse ($M\phi = 1.1—1.3$) and the preferred orientation of grain fabric is evidently normal to the flow direction. Judging from all of these facts, the cross-set studied is thought to have been emplaced mainly by downward sliding of the poorly sorted detrital grains toward the toe. The grains were coarse enough to be transported as bed-load and possessed substantial inertia when sheared in water.

Compared with this, the cross-set of flow-parallel grain fabric and small angle of inclination may be mainly formed by the deposition of fine-grade detrital grains settling from suspension onto the lee slope. For example, the planar cross-set in the Upper Carboniferous (Pennsylvanian) Caseyville Formation, where slope is 20° and $M\phi$ ranges from 1.4 to 2.0, does show the preferred grain orientation parallel to the flow direction (see Fig. 4 of YAGISHITA & MORRIS, 1979). In this case, parallelism of detritus long-axes and current direction may be ascribed to the intergranular encounters in a transporting fluid of negligible viscosity and inertia (REES, 1968). Perhaps the current (flow velocity) for this cross-set was high and strong enough to cause the drag force which resulted in overturning the cross-set *below* and forming a recumbent fold.

Although the described current-normal grain arrangement in the fluvial cross-set has not been reported so far, similar grain fabrics

were already produced in the laboratory experiments (NAKAJIMA, 1977). Therefore, it is likely that we will find the same situation in the other cross-sets of coarse-grained sediments with steep slope, elsewhere.

Imbrication of cross-laminated detritus: As is well known in fluvial gravels, pebbles accumulate with the plane of maximum projection dipping or imbricate upstream. Similarly in cross-bedded sandstones, detrital grains lying in the foresets show the upcurrent imbrication mode relative to the depositional surface (e.g. POTTER & MAST, 1963; HAMILTON *et al.*, 1968).

The process acting to form the foreset lamina is a combination of grain deposition from suspension onto the lee face and avalanching from the lee crest downwards the toe (ALLEN, 1965). Needless to say, the combination is controlled by the variables such as flow velocity and grain size. During the accumulation of grains from avalanching, only the gravity effect will be such that it orients the longest axes of grains in the horizontal plane. Probably, the overall process of deposition from avalanching is similar to the model proposed by ALLEN (1972, see Fig. 4). Grains initially settled at the base of slope constitute a relatively loosely packed column or "shadow" whose depositional surface remains parallel to the basin floor. Thus further accumulation from avalanching always takes place onto the horizontal depositional surface of "shadow". It seems this preponderance of avalanching that accounts for the upstream imbrication fabric developed on the foreset plane.

Fig. 4. Column of the loosely packed sediments called "shadow". Note that the depositional surface of this inclined column remains horizontal during sedimentation (modified after ALLEN, 1972).

By contrast in the case of deposition from suspensions it is the grain collisions that are mainly responsible for forming the imbrication alignment relative to the depositional surface. Although there is also the gravity effect on suspending grains when they are coming to rest (HAMILTON *et al.*, 1968), tilting of long-axes of grains (i.e. imbrication) is caused largely through the medium of intergranular encounters while the grains are in suspension (REES, 1968). Thus the mechanism of imbrication in both cases seems to be different.

Conclusion

In the fluvial cross-bedding of the Ogawa Formation, the sand-size grains are aligned normal to the flow direction and display imbrication relative to the surface of deposition. The sediments showing this fabric are rather coarse-grained and poorly sorted. Such current normal grain orientation and imbrication appear to have been produced by bed-load rolling of sedimentary detritus downwards the toe under the influence of gravity.

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*in Japanese with English abstract.

斜交層理における粒子配列

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(要 旨)

変形されていない斜交層理の水平面、あるいは斜交層理面における detrital grain の配列方向は、斜交層理面を形成した際の水流の方向に平行である、という報告が従来では圧倒的に多い。しかし、これまでに行われた幾つかの実験結果によれば、水流の方向に対して粒子配列が直交するものを天然の斜交層理には多数見られるはず

である。この小論ではそのような（直交配列の）一つの実例を示した。

平行な配列は主に suspension, 直交する配列は bed-load による運搬・堆積の機構に基づくと考えられるが、これらの粒子配列の違いはまた堆積物の粒径、淘汰度などとも関係しているであろう。

Explanation of Plates

- A.....Outcrop of the cross-bedding studied.
A sample was taken from the area enclosed with a broken line.
- B.....The sample before making thin sections.
Four thin sections were made from the upper part of this specimen. Line segments coincide with that of Fig. 3.