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Article

Grain fabric of Bouma A and B divisions deposited from surge-like turbidity currents: an example from the Plio-Pleistocene Kakegawa Group, Japan

Tetsuya Sakai*

Abstract

The grain fabric of the massive Bouma A division of a turbidite bed from the Plio-Pleistocene Kakegawa Group, Shizuoka, Japan is analyzed in detail. The bed is interpreted as having been deposited on the levee of a small submarine channel, and consists of a T_{a-d} Bouma sequence thinning in the down-current direction in a ~ 15 m-wide outcrop. This feature indicates that the flow waned rapidly away from the channel.

The grain fabric of the A and B divisions analyzed in horizontal intervals of 0.4 mm and 0.2 mm, respectively, can be characterized as follows: (1) The lower part of the A division is dominated by down-current imbricated intervals, and the corresponding rose diagrams have large circular variance. (2) The upper part of the A division is characterized by both down-current and up-current imbricated intervals, although the latter is dominant, and highly inclined grains tend to be less common. (3) The B division is represented only by up-current imbricated intervals. These results are similar to those derived from fabric analysis of experimental gravity flow deposits, except for the dominance of down-current imbricated intervals in the lower part of division A. The down-current imbricated intervals are interpreted as having being formed by shear oscillation in the basal high-density flow layer (i.e., a quick bed), as observed in flume experiments. The prominence of the down-current imbricated intervals in the natural turbidite beds compared to those seen in experiments is probably due to the larger flow scale. These results also suggest that paleoflow analysis based on the grain fabric of division A may give incorrect flow directions in some turbidites. For improved reliability of paleoflow analysis, flow directions should be determined from a combination of paleoflow indicators.

Key words: Bouma A- and B-divisions, grain fabric, Kakegawa Group, turbidite

Introduction

Since the introduction of the concept of turbidites, the grain fabric of turbidites has been studied extensively (e.g., Bouma, 1962; McBride, 1962; Spotts, 1964; Sestini and Prazini, 1965; Colburn, 1968, Onions and Middleton, 1970; Parkash and Middleton, 1970; Taira and Scholle, 1979; Hiscott and Middleton, 1980; Taira and Niitsuma, 1986). Numerous studies have revealed that the grain fabric of turbidite beds, particularly in the massive division (Bouma's division A) is characterized by a flow-parallel orientation and up-current imbrication (Taira and Scholle, 1979). However, several studies have also revealed different types of fabrics, such as current-normal orientation in the base of the bed or down-current imbrication (e.g., Bouma, 1962; Sestini and Prazini, 1965; Onions and Middleton, 1969; Parkash and Middleton, 1970; Hiscott and Middleton, 1980). Although several explanations have been offered for the appearance of such grain fabrics (Ballance, 1964; Hamilton et al., 1968; Rees, 1968, 1983), no systematic theory has been put forward for fabric formation. It is also possible that such complicated grain fabrics may arise due to flow complexities and topographic effects (cf. Sakai et al., 2002). To understand the successive change in the grain fabric of turbidite beds in the absence of strong topographic control, Sakai et al. (2002) made detailed measurements of the grain fabric of complete turbidite beds deposited in an experimental flume from a surge-type high-density turbidity current. They reported grain imbrication patterns in the massive part, with larger circular variance near the base of the bed, and down- and up-current imbrication grading upward into the interval consisting of up-current imbrication.

Such grain fabrics have not been reported for natural turbidite beds because detailed grain fabrics are rarely analyzed successively in a single bed. In the present study, the grain fabrics of the A and B divisions of a natural turbidite were analyzed in detail to test the findings of laboratory experiments. The bed selected for analysis is interpreted to have been deposited from a surge-like turbidity current (*sensu* Mulder and Alexander, 2001) as an overflow from a submarine channel found in the Plio-Pleistocene Kakegawa Group, Shizuoka, Japan.

Geological setting and characteristics of the analyzed turbidite bed

The Plio-Pleistocene Kakegawa Group (4-1 Ma) crops out in the western part of Shizuoka Prefecture, central Japan (Fig. 1). The Kakegawa Group has a total thickness of up to 3500 m and fills a small fore-arc basin (Ishibashi, 1989; Sakai and Masuda, 1996). Early phase sediments are

*Department of Geoscience, Shimane University, Matsue 690-8504, Japan

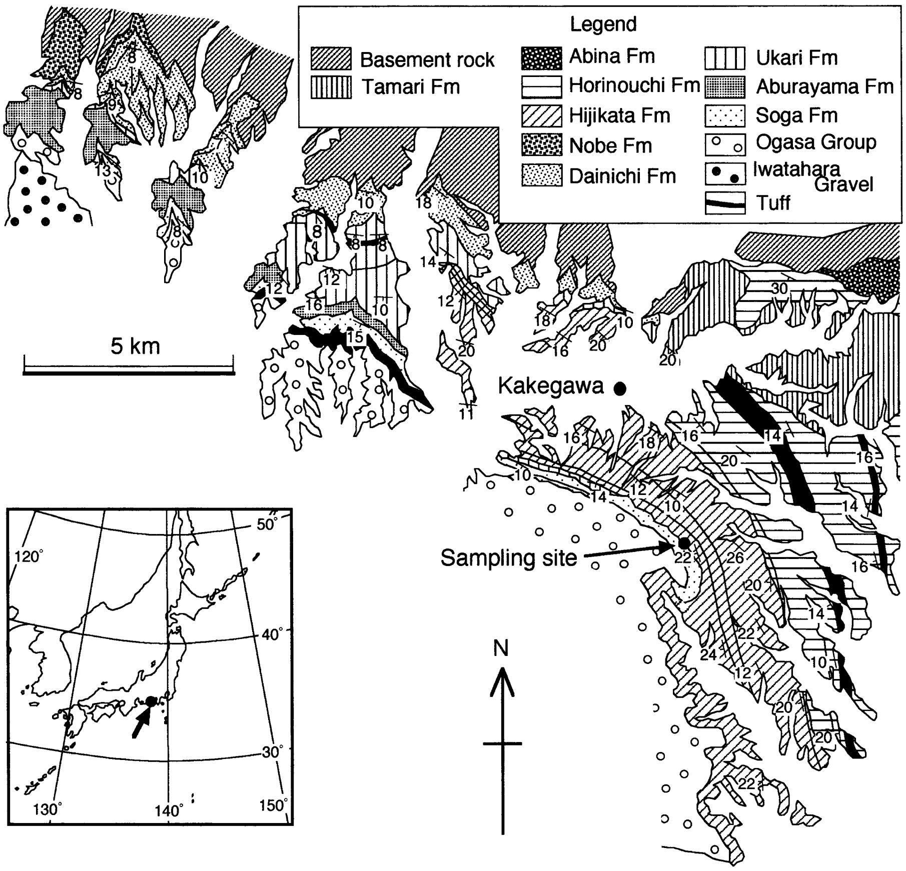

Fig. 1. Location and simplified geologic maps of the upper part of the Kakegawa Group.

characterized by turbidites and hemipelagic silt beds that fill a small depression (Ishibashi, 1989; Masuda and Ishibashi, 1991, Sakai and Masuda, 1996). Turbidite beds in this interval exhibit features of reflected turbidites (Sakai, 2000). The upper part of the Kakegawa Group is characterized by a transgressive and regressive succession in the western part where shallow marine sediments are distributed, and by slope deposits in the east. Near the top of the group, a short period of alluvial fan progradation is apparent in the west, while the basinward equivalent is characterized by submarine channel fill and natural levee deposits (Soga Formation) developed on the outer shelf to upper slope (Sakai and Masuda, 1996).

The outcrop studied is located in Ganshoji, Kakegawa City (Fig. 1), and consists of 6 m of amalgamated massive sand beds with basal gravel beds (channel fill deposits) with overlying amalgamated sand beds or alternations of sand and silt beds (levee deposits) of the Soga Formation (Sakai and Masuda, 1996). The sample was collected from a 15 cm -thick sand bed in the levee deposits (Fig. 2). The bed is characterized by a ca. 3.5 cm-thick massive interval (A division), a 1 cm-thick parallel stratified interval (B division), a 7.5 cm-thick ripple cross-stratified interval (C division), and a 3 cm-thick parallel stratified interval (D division) (Fig. 3). The top of the sand bed is truncated by the overlying sand bed and the E division is absent. This 15 cm-thick bed tends to thin in the down-current direction in this outcrop, trending almost parallel to the paleoflow direction indicated by ripple cross-stratification. At the other end of the outcrop, the bed is characterized by 8 cm-thick sand beds in which division A has almost entirely disappeared over a length of only 15 m. This rapid thickness change, particularly the thinning of division A, implies that the current rapidly waned over a very short distance after spilling over the submarine channel. These features imply that this bed was accumulated from a depletive waning flow (cf. Kneller and Branney, 1995) or surge-like turbidity flow in the sense of Mulder and Alexander (2001). This bed therefore appears to represent a good example to test the findings of experimental turbidity current deposits through detailed grain fabric analysis (Sakai et al., 2002).

Methods

A block sample (5 cm x 5 cm x 15 cm) encompassing the entire bed was collected from the outcrop. The sample was completely dried in the laboratory and slowly impregnated with epoxy resin. The sample was then divided into specimens for imbrication and orientation measurements. The flow-parallel section, as inferred from ripple cross-

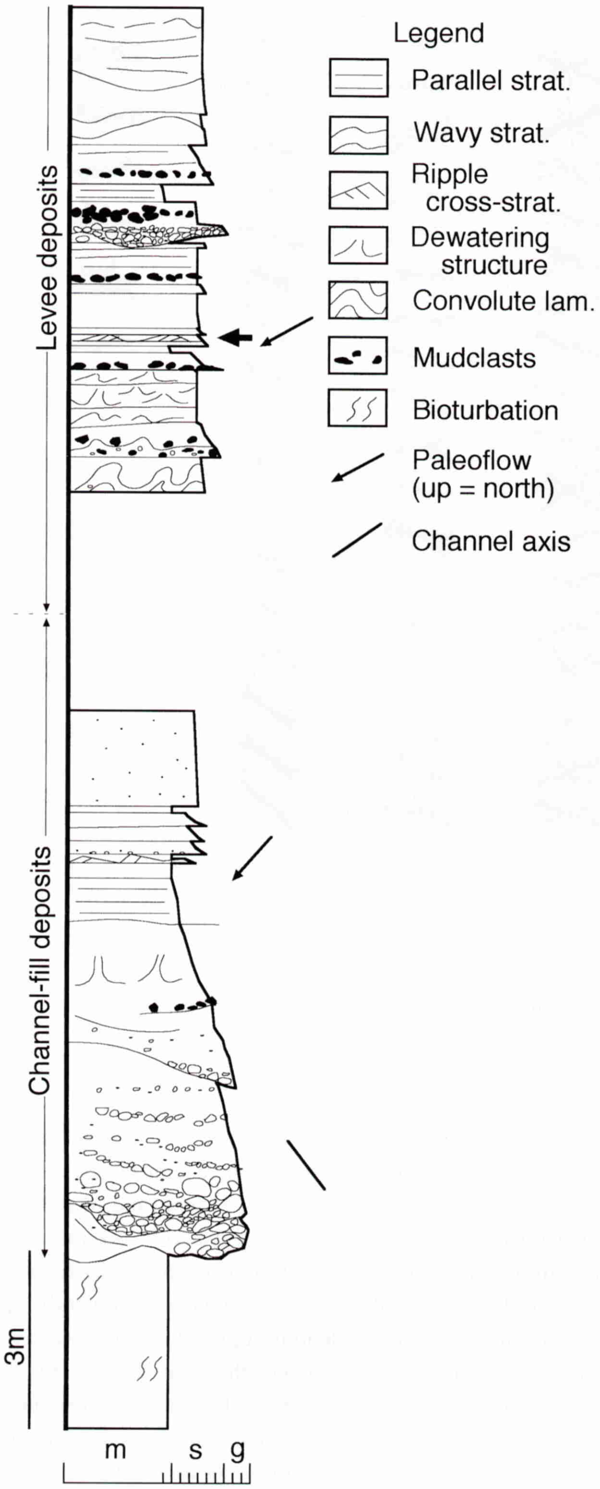

Fig. 2. Columnar section of the sampling site. The analyzed bed is indicated by the bold arrow. m: mud, s: sand, g: gravel.

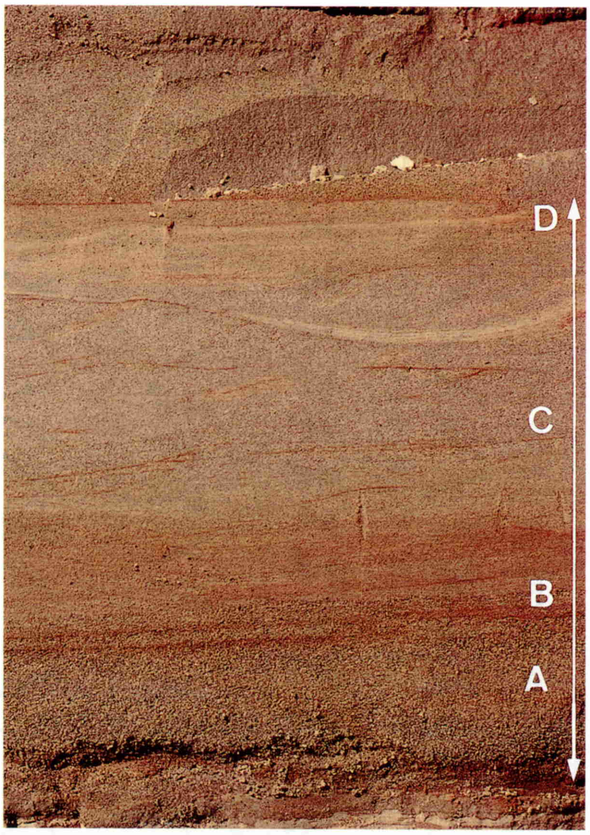

Fig. 3. Photograph of the turbidite bed outcrop. The bed is 15 cm thick. A-D represents divisions of the Bouma sequence.

stratification, was polished for the measurement of imbrications. The other half of the specimen including the A and B divisions was then divided into small chips for orientation measurements. Photomicrographs of the polished sample surfaces were captured and stored on a computer for image analysis. Fabric measurements were conducted by image analysis according to a previously reported method (Sakai et al., 2002).

To account for the differences in grain sizes between divisions A and B (medium sand and fine to very fine sand, respectively), the thickness of the measured intervals was adjusted for each division. Imbrications (inclination angle of individual grains) were measured in 0.4 mm intervals in division A and 0.2 mm intervals in division B, corresponding to roughly two grain diameters in each case. Orientations were measured at 6, 15, 21, 26, and 30 mm (division A) or 36 mm levels (division B) from the base of the bed.

Results

The resultant rose diagrams of imbrication and orientation are shown in Fig. 4, and the fluctuation of the mean imbrication angles is shown in Fig. 5. The orientation of the measured part of the bed tends to elongate parallel to the paleoflow direction determined by ripple cross-stratification. The rose diagram patterns derived for division A (Fig. 4) suggest that this division can be roughly divided into lower and upper parts. In the lower part of the A division (0-22.4 mm in Fig. 4), both up-current and down-current imbricated intervals are observed, with down-current imbrications dominant. Intervals with high

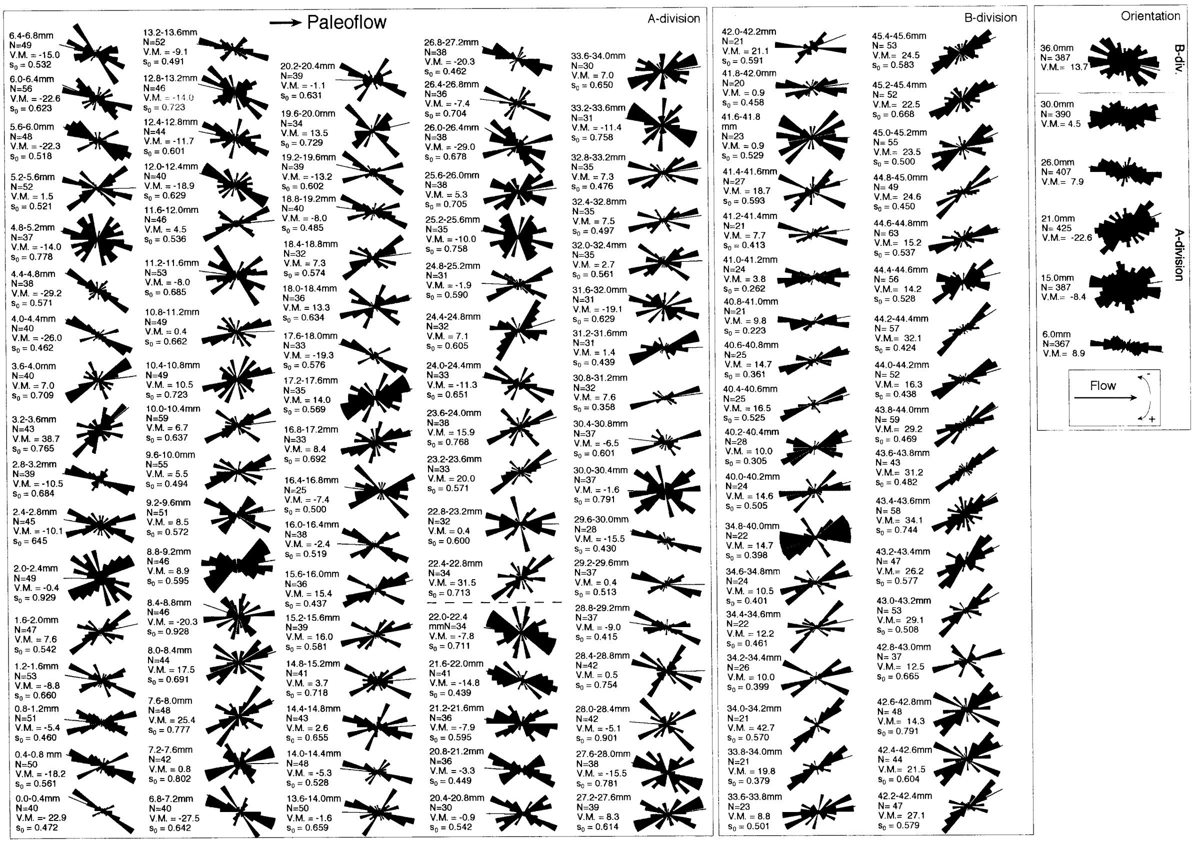

Fig. 4. Fabric measurements for A and B divisions of the sample bed. The dashed line represents the boundary between the lower and upper parts of the A-division. N: number of measured grains, V.M.: vector mean, s_0: circular variance.

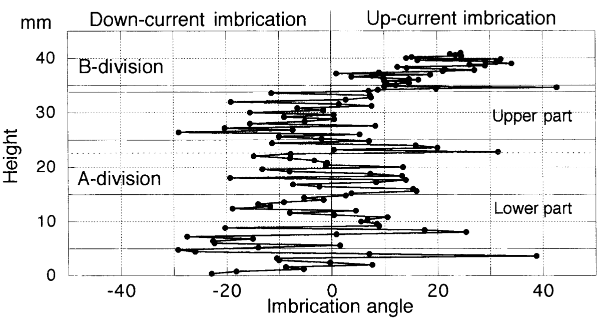

Fig. 5. Fluctuation of mean imbrication angle in each measured interval. The dashed line represents boundary between the lower and upper parts.

imbrication angles (mode of 50°), also appear in this section (e.g., 3.2-3.6 mm). In the upper section (22.4-33.6 mm in Fig. 4), intervals characterized by both up-current and down-current imbrication are also present, with intervals of up-current imbrication predominant. Although the boundary between the lower and upper sections is unclear, it is tentatively marked at the base of intervals in which up-current imbricated intervals are dominant. Imbrication angles of less than 40° are dominant in this section, but high-angle imbrication is also apparent in a few intervals (e.g., 24.4-24.8 mm). The rose diagrams of division B (33.6-45.6 mm) indicate up-current imbrication.

Discussion

As stated above, the presence of down-current imbrications in division A has been recognized by several authors (Sestini and Prazini, 1965; Hiscott and Middleton, 1980). However, the process giving rise to its occurrence in a natural context remains unclear. Bouma (1962) reported that the lower part of the bed exhibits predominantly up-current imbrication, graduating upward to down-current imbrication. It was interpreted that the change in the imbrication angle originated from flow reversal associated with topographic obstacles on the sea floor. Sestini and Prazini (1965) identified down-current imbrication in the A division, but did not infer the origin of this strange imbrication pattern.

From the grain fabrics of turbidite beds deposited in an experimental flume and the fabrics identified in this study, down-current imbrications appear to be related to surge-type or surge-like high-density turbidity currents. Sakai et al. (2002) interpreted that down-current imbrication arises due to shear oscillation in the quick beds (cf. Middleton, 1967), the high-density layers at the base of the flows. In past experiments, however, scale of the flows has been ignored.

In the analysis of experimental gravity-flow specimens, the down-current imbricated intervals are very thin and the average imbrication pattern is up-current (Sakai et al., 1995; Naruse et al., 2003), even though the down-current imbricated layers are visible in photomicrographs. This implies that in the case of small-scale flow, thin interval analysis is needed to detect such tiny layers. In the natural turbidity current, however, it is expected that thicker down-current imbricated intervals will be present because of the scale difference. In a natural setting, thicker down-current imbricated intervals may be created as a result of the larger-scale up-current component of the quick-bed shear fluctuation.

This analysis has demonstrated that care should be taken when determining paleoflow directions based on the grain fabric of A division alone because the presence of down-current imbrications may result in misreading. In Bouma's (1962) interpretation, the change in imbrication pattern was attributed to flow reversal. The results of the present study imply the bed Bouma (1962) analyzed may also have been deposited from a unidirectional current, without necessitating a certain topographic setting of the basin. Paleoflow determination from the fabric in division A should therefore be supported by other indicators. In the absence of other paleoflow indicators, the near-top fabric may yield the most reliable paleoflow estimate.

Conclusions

Grain fabric of massive and parallel-stratified divisions (Bouma A and B divisions) of a turbidite bed deposited from a surge-like turbidity current was analyzed. The lower section of the A division consists of both up-current and down-current imbricated intervals, with down-current imbricated intervals and intervals of larger circular variance predominant. The upper section also contains both up-current and down-current intervals, although up-current intervals are predominant and the inclination angles tend to be smaller. The B-division intervals are characterized exclusively by up-current imbricated intervals.

Although the patterns are similar, the down-current intervals observed in the natural sample are more distinct than in samples obtained from flume experiments, and are possibly related to shear oscillation in the basal high-density layer (quick bed) of the larger and stronger natural current, as discussed in the analysis of experimental specimens. The present sample exhibited down-current imbrication despite a down-current thinning of the bed and the imbrication was particularly distinct in the lower section of division A. As such, paleoflow determination based solely on an analysis of massive division patterns should be performed with care, and ideally in conjunction with other paleoflow indicators. In the absence of other indicators, near-top fabrics in division A may give the most reliable data on which to base a paleoflow estimate.

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（要　旨）

酒井哲弥，2003，サージ様の乱泥流から形成された Bouma A-, B-division の粒子配列：鮮新ー更新統掛川層群の例，島根大学地球資源環境学研究報告，22，173-178

鮮新－更新統掛川層群のタービダイトの塊状部分と平行葉理部（A-，B-division）の粒子配列の解析を行った．対象としたタービダイトは Ta-d ボウマシークェンスからなり，小さな海底流路の自然堤防で堆積したと解釈されるものである．この層は幅およそ 15 m ほどの露頭で下流方向に薄くなる．

塊状部と平行葉理部の粒子配列をそれぞれ 0.4 mm，0.2 mm 間隔で行い，その結果，次のような特徴が見られた．(1) A-division の下部は下流，上流傾斜のインブリケーションの卓越した層準が見られるが，下流傾斜のインブリケーションの発達した層準が卓越し，粒子の角度のばらつきの大きい部分が見られる．(2) 上部も下流傾斜，上流傾斜の卓越する部分の両方が見られるが，上流傾斜のものが卓越し，高角のインブリケーションはあまりみられなくなる．(3) B-division は上流傾斜のインブリケーションの発達する層準のみから構成される．この結果は，下流傾斜のインブリケーションが A-division 下部で卓越すること以外はこれまでの実験水槽での乱泥流堆積物の粒子配列の解析結果に似る．

塊状部に見られた下流傾斜のインブリケーションは実験水槽での結果と同様に，乱泥流下部の高濃度層内部での剪断応力の振動に伴うものと解釈される．また，下流傾斜のインブリケーションの発達した層準が見られることの原因の 1 つに実験との流れのスケールの違いが推定される．この結果からは，塊状部の粒子配列の解析からは誤った古流向を読みとる可能性が指摘される．信頼性の高い古流向データを得るために，別の指標と併せてその方向決定をすべきであろう．