Meter-scale bedding cyclicity in storm-dominated shelf deposits in the Tertiary Hokutan basin, southwestern Japan

Wataru Maejima*, Takako Kimoto*,** and Takeshi Nakajo****

The Yubunegawa Black Shale Member of the Muraoka Formation in the Miocene Hokutan basin was deposited during a highstand of the sea level and records storm sedimentation in a middle to outer shelf environment. In the lowermost part of the Yubunegawa shelf sequence which rests on the transgressive deposits, intercalations of a couplet of a thick sandstone bed and an overlying thick mudstone bed produce cyclic appearance of the succession which is principally made up by the monotonous interbedding of thin sandstones and mudstones. Such a couplet intervening the monotonous succession suggests that an extraordinary intense storm carried considerable volume of sand away from the coast and resulted in a sand-starved condition in the coastal zone for some long period, during which sand availability on the stormy shelf was extremely low. The control of sand availability on storm sedimentation was a consequence of rise in base level due to a rapid transgression, which probably caused reduction of the rate of sediment supply through alluvial system into the coastal zone.

Key words: bedding cycle, Hokutan basin, pseudo-cycle, sand availability, sand-starved coast, storm deposits

INTRODUCTION

Ancient storm-dominated shelf sequences commonly show storm-deposited sandstones interbedded with fair-weather mudstone. The sandstone:mudstone ratio and thickness of storm sandstone beds in shelf sequences are governed by many factors including the intensity and frequency of storms, distance from the coast, and water depth. As a matter of course, thicker sandstone beds are regarded as the deposits in a proximal setting (cf. Hamblin and Walker, 1979; Aigner, 1985; Brenchley et al., 1986; Cheel and Leckie, 1993). Storm sandstones generally thin towards offshore with increase in the proportion of fair-weather mudstones within the succession. In this context, vertical trends and cyclic arrangement of storm beds have been commonly accounted for by deepening or shallowing of the water depth, whether it is related to autocyclic processes, eustatic sea-level fluctuations or tectonic means (e.g., Hamblin and Walker, 1979; Bourgeois, 1980; Mount, 1982; Aigner, 1985; Monaco, 1992; Jennette and Pryor, 1993). Such a scheme is valid so far as storm-induced currents transport and deposit sands offshore according to the intensity of the storm and to the distance from the coast. However, intermittent breaks in equilibrium of sand availability for storm-induced currents would produce, without change in water depth of a depositional site, a succession in which storm beds look as if they were arranged into the bedding cycles. This paper is a preliminary note on such a succession having meter-scale bedding cyclicity of storm beds as a
result of the control of sand availability.

GEOLOGIC SETTING AND DEPOSITIONAL BACKGROUND

The Hokutan basin is one of the Miocene basins in the Tertiary San-in—Hokuriku Geologic Province developed along the Japan Sea side of the Japanese Islands (Fig. 1). These basins formed in association with opening of the Japan Sea due to rifting and spreading of the back arc region of Japan. During Early Miocene time, the volcanogenic-terrigenous, chiefly continental deposits were formed in the early stage of basin development. The basins were extensively flooded by the sea in early Middle Miocene time (Tsuchi et al., 1981), and thick sequences of marine mudstones were deposited over the Early Miocene continental deposits in all these basins. This marine invasion occurred under an eustatic control. Marine formations were deposited simultaneously throughout Japanese Islands (Tsuchi et al. 1981), not only in basins of a backarc region but also in intra-arc basins and in basins of northeastern Japan. Global eustatic curves indicate sea-level rise in Early to Middle Miocene (Haq et al. 1987, 1988; Greenlee and Moore 1988).

In the eastern part of the Hokutan basin, the early Middle Miocene marine sedimentary record is well preserved in the Muraoka and the equiva-
Table 1  Summary of facies types and their interpretations of Yubunegawa storm beds.

<table>
<thead>
<tr>
<th>Facies Type</th>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>A: high-angle hummocky</td>
<td>Generally thick (15 to 50 cm); high-angle, isotropic hummocky cross stratification with wave length of 0.4 to 1.2 m</td>
<td>Oscillatory or strongly oscillatory-dominant combined flow</td>
</tr>
<tr>
<td>cross-stratified sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B: low-angle hummocky</td>
<td>Commonly 10 to 20 cm thick; low-angle, anisotropic hummocky cross stratification with wave length of 0.3 to 0.7 m; asymmetric-ripple cross-lamination towards top of some beds</td>
<td>Combined flow in which a unidirectional component was dominated; wave oscillatory motion dissipated in final stage of deposition</td>
</tr>
<tr>
<td>cross-stratified sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C: laminated sandstone</td>
<td>Commonly 5 to 15 cm thick; intergrading of parallel lamination and low-angle, gently undulating cross lamination; asymmetric-ripple cross-lamination at top of bed</td>
<td>Waning of storm-induced depositional current; minimal influence of oscillatory water motion</td>
</tr>
<tr>
<td>D: asymmetric-ripple cross-</td>
<td>Thin (2 to 7 cm); graded; commonly climbing-ripple cross-laminated; crude horizontal lamination towards top of bed</td>
<td>Low-energy waning current; no or negligible influence of storm waves</td>
</tr>
<tr>
<td>laminated sandstone</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E: graded and crudely</td>
<td>Most commonly less than 2cm thick; well-developed grading; finely, horizontally laminated</td>
<td>Deposition of fine materials from slowly moving, dilute suspension cloud</td>
</tr>
<tr>
<td>laminated siltstone</td>
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.....lent Amino formations: the former chiefly comprises terrigenous clastics, whereas the latter is dominated by volcanogenic deposits (Wadatsumi and Matsumoto, 1958). This study concerns the Muraoka Formation (Fig. 2), in which an approximately 500 m thick sequence, the Yubunegawa Black Shale Member consists of shelf mudstones with intercalations of sandstone and siltstone of a storm origin (Maejima, 1994; Maejima et al., 1997; Maejima and Kimoto, 1998). The storm-dominated, Yubunegawa shelf sequence rests on the up to 50 m thick, transgressive deposits comprising fossiliferous, bioturbated muddy sandstones. The thick, mud-dominated, monotonous shelf succession of the Yubunegawa Member represents deposition during a high stand of the sea level (Maejima, 1994; Maejima et al., 1997; Maejima and Kimoto, 1998). The sandstone:mudstone ratio is low, and varies gradually upward within the sequence from approximately 1:1 (lower part) to 1:10 (middle part) and then to 1:1 (upper part), suggesting gradual deepening and then shallowing water depth. No evidences have been obtained on the paleobathymetry of the Yubunegawa shelf deposits. However, mud-dominated lithology and thin beds of storm deposits suggest that the Yubunegawa shelf sequence represents deposition chiefly in a middle (lower and upper parts) to outer shelf (middle part) environment (cf. Maejima and Kimoto, 1998). In the western part of the basin, the mud-dominated deposits of the western extension of the Yubunegawa rocks, the Fuganji Mudstone Member of the Iwami Formation, yields molluscan and foraminiferal assemblages indicative of middle shelf to middle to upper continental slope environments (Matsumoto, 1991a, b).

STORM DEPOSITS

The Yubunegawa storm deposits include a continuum from less than a centimeter thick siltstones to several decimeters thick sandstones. Individual beds are sharply based, are graded, and have a gradational upper contact with the overlying mudstone, indicating deposition in a single storm event. Amalgamated storm beds are rare. The wide variability of facies characteristics of storm deposits can be arranged into a facies spectrum, in which bed thickness, grain size and internal sedimentary structures change systematically. The spectrum of the Yubunegawa storm
deposits is conveniently classified into five major facies (cf. Maejima and Kimoto, 1998). They are: A. high-angle hummocky cross-stratified sandstone; B. low-angle hummocky cross-stratified sandstone; C. laminated sandstone; D. asymmetric-ripple cross-laminated sandstone; and E. graded and crudely laminated siltstone. Their major features and inferred depositional processes are briefly summarized in Table 1. Facies A, B and C contain records of storm wave-work processes, whereas facies D and E show no evidence of wave-work processes.

The facies spectrum of the Yubunegawa storm deposits reveals that the storm beds were originated by waning combined flows across the storm wave base (Maejima, 1994; Maejima et al., 1997; Maejima and Kimoto, 1998). Thicker beds represent deposition from oscillatory-dominant combined flows. Thinner beds tend to show diminished oscillatory water motion in a flow with increase in relative importance of a unidirectional component, and flows finally deposited thin, graded beds comparable with base-cut-out turbidites. All the facies types occur in the middle shelf successions in the lower and upper part of
the Yubunegawa Member, whereas the storm deposits in the outer shelf succession of the middle part are represented only by beds comparable with turbidites.

**BEDDING CYCLICITY**

The Yubunegawa shelf sequence shows, as a whole, large-scale transgressive and then regressive trends (Fig. 2). Smaller-scale vertical trends and bedding cyclicity have been examined in the Mt. Myoken area, Yoka Town, Hyogo Prefecture (Fig. 3). In any intervals of tens of meters thick within the sequence, the succession is generally monotonous and shows no arrangement of storm beds into bedding cycles. However, in the lowermost part of the Yubunegawa shelf sequence, there appears meter-scale bedding cycles of storm beds in the succession. Fig. 4 shows two examples of log measured at about 20 m and 60 m above the base of the Yubunegawa Member, respectively. Both logs reveal cyclic appearance of the succession.

The bedding cycles, although indistinct in some cases, are 1 to 3 m thick and are composed of, in ascending order, mudstone, interbedded sandstones and mudstones, and a thick sandstone bed (Figs. 4, 5). The lower mudstone unit is up to 80 cm, most commonly 30 to 40 cm thick. The mudstone is massive to crudely finely laminated. Storm sandstone beds are almost completely lacking in this unit. The unit of interbedded sandstones and mudstones in the middle part is 1 to 2 m thick. The storm sandstones in this unit are generally no more than 10 cm thick. Facies C, D and E beds are most common, with local occurrence of facies B beds. The sandstones in this unit do not show upward increase in thickness nor in frequency. No preferred succession of storm sandstone facies is also observable. The upper sandstone unit is generally 20 to 50 cm thick. It is represented by a facies A or B bed. The upper thick sandstone consistently occur as one bed in all the cycles.

Arrangement of storm beds into meter-scale bedding cycles occurs most clearly within the basal 60 to 70 m interval of the Yubunegawa Member. Although Fig. 4 shows only small parts of the basal Yubunegawa sequence, similar features are observed in the rest of the sequence. Such a meter-scale cyclicity, however, rapidly becomes indistinct upward within the Yubunegawa Member.

**DISCUSSION AND CONCLUSIONS**

The meter-scale bedding cycles in the lowermost part of the Yubunegawa shelf sequence apparently show upward increase in the proportion of sand (Fig. 4). Facies of storm sandstones suggest that storm-wave processes are well preserved in the sandstone at the top of the cycle, whereas sandstones in the middle part of the cycle reveal no or minor influences of storm waves. The meter-scale cyclicity, thus, could be attributed to variations in hydrodynamic regime as a result of autecyclic processes like delta lobe switching or of fluctuations in relative sea level. However, the interbedded sandstones and mudstones of the middle part of the cycles form a monotonous succession, and the storm sandstones do not show upward increase in thickness nor in frequency (Figs. 4, 5). Moreover, individual cycles are consistently capped by one bed of thick storm sandstone. These facts imply that the cycles are defined only by thick mudstone at the base and one thick sandstone bed at the top. In other words, intercalations of a couplet of a thick sandstone bed and an overlying thick mudstone bed produce cyclic appearance of the succession which is principally made up by the monotonous interbedding of thin sandstones and mudstones. The meter-scale cycles, thus, are pseudo-cycles.

The thick sandstone—mudstone couplets in the monotonous succession of interbedded thin sandstones and mudstones are suggestive of that the thick sandstone and the overlying thick mudstone have a genetic link and that they record an event breaking the equilibrium in shelf storm sedimentation. Episodic deposition of a thick sandstone bed tended to be followed by no records of storm sedimentation for some long
period, resulting in thick accumulation of mudstone.

The storms which generated thick sandstone beds were undoubtedly much more intense than those responsible for deposition of thinner beds that are dominant in the Yubunegawa succession. Powerful currents generated by such extraordinary intense storms would have carried considerable volumes of sand away from the coast, resulting in sand-starved condition in the coastal zone. If the rate of sand accumulation in the coastal zone was high enough, currents generated subsequent storms could have transported and deposited some volumes of sand matching to their capacity. Thick accumulation of mud on the thick storm sandstone bed suggests that the sand-starved condition continued in the coastal zone for some long periods after an intense storm event. During these periods, storm-induced currents tended to carry and deposit too less volume of sand than their capacity. Thus, sand availability on the stormy shelf was extremely low. Storm events during sand-starved conditions would have seldom been recorded in the shelf deposits, especially of middle to outer depths, and fair-weather mudstones vertically stacked to form thick unit without intervening storm beds.

The control of sand availability on storm sedimentation was limited in the early stage of Yubunegawa shelf sedimentation, which followed the extensive flooding of a sea all over the Japanese Islands. Rise in base level due to a

Fig.5 Photograph of the lower part of the section B. (M) mudstone; (A) interbedded sandstone and mudstone; (S) sandstone.
rapid transgression probably caused reduction of the rate of sediment supply through alluvial system into the coastal zone, resulting in the unequilibrium condition of sand availability onto the storm shelf.

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第三紀北但堆積盆の陸棚堆積物中にみられる
メートルスケールの堆積サイクル

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Jour. Sed. Soc. Japan, No. 50, 3－10

中新世北但層群を構成する湯舟川黑色頁岩帯層は中～下部陸棚堆積物で，ストーム起源の砂岩・シルト岩と泥岩の互層よりなる。湯舟川層群の最下部は，ストーム砂岩層がメートルスケールでサイクリックに堆積しているかの様相を呈する。しかし，これらのサイクルは，厚い砂岩層とその上位に重なる薄い泥岩層のカップルが単調な砂岩泥岩薄互層中に介在されることによって作り出されており，真の意味の堆積サイクルとはみなされない。単調な互層中の厚い砂岩と薄い泥岩のカップルは，並外れた規模のストームの後，沿岸域で砂の欠乏状態が一定期間持続したこと，この期間中は陸棚堆積物中にストーム作用が記録され得なかったことを示す。湯舟川層群の堆積初期は広範かつ急速な海進期にあたり，このような状況下で砂の集積能が陸棚におけるストーム堆積作用を制御したといえる。