Temporal variation in the wavelength of hummocky cross-stratification: Implications for storm intensity through Mesozoic and Cenozoic

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ABSTRACT

Hummocky cross-stratification is believed to be one of the diagnostic sedimentary structures of storm-dominated shallow-marine environments. The wavelength of this stratification increases with the increase in bed thickness of tempestites and decreases with the increase in paleowater depth. The hummocky cross-stratification wavelength is interpreted to be a function of the orbital diameters of storm-induced oscillatory currents near seafloors and may reflect the intensity of storm waves. Temporal variation in the wavelength was investigated as a proxy for storm intensity through Mesozoic and Cenozoic time. The hummocky cross-stratification wavelength shows a secular change, and a major peak in the middle Cretaceous. This variation largely corresponds to one of the two greenhouse and icehouse supercycles of global environmental changes during the Phanerozoic and provides a geologic perspective of the possible increase in storm intensity with an ongoing greenhouse phase in the future.

Keywords: hummocky cross-stratification, tempestites, storm intensity, greenhouse.

INTRODUCTION

Geologic records preserve long-term fluctuations in global environments and are key to understanding what may happen with ongoing global warming in the future. Recent estimates of the ongoing global greenhouse climate predict the increase in wave energy and frequency of major storms in many areas associated with the rise in global mean sea level (e.g., Emanuel, 1987; Houghton et al., 1996). The thickness of storm deposits (i.e., tempestites) is interpreted to be a measure of ancient storm intensity (Brandt and Elias, 1989). Tempestites formed in an inner shelf environment commonly contain hummocky cross-stratification that is interpreted to be a product of an oscillatory dominated combined flow condition (e.g., Duke et al., 1991).

According to some measurements of the wavelength of hummocky bedforms in a flow duct (Southard et al., 1990) and on a modern shelf floor (Li and Amos, 1999), the hummocky cross-stratification wavelength (λ) is proportional to the orbital diameters (d_0) of storm-induced oscillatory flows near seafloors (i.e., $\lambda \approx 0.5$–$0.62\ d_0$) (Wiberg and Harris, 1994; Li and Amos, 1999). This relationship indicates that the wavelength may be a measure of the orbital diameters of ancient storm waves and possibly reflects the intensity of ancient storms, provided that other factors, such as water depth and grain size, are largely equal. Nonetheless, there is little systematic description of the hummocky cross-stratification wavelength, except for a few case studies (e.g., Craft and Bridge, 1987; Banerjee, 1996). In this paper we investigate variation in the hummocky cross-stratification wavelength in terms of bed thickness and paleowater depth of tempestites and discuss temporal variation in the wavelength as a proxy of storm intensity through the Mesozoic and Cenozoic.

BED THICKNESS AND WAVELENGTH

The hummocky cross-stratification wavelength from 221 outcrop examples was measured across crestlines on the plan view of ancient hummocky bedforms. Cross-sectional views of complete hummocky cross-stratification were also used for measurements when plan views were not exposed. The measurements were selected from ancient tempestites that are interbedded with background muddy deposits formed during poststorm, fairweather conditions, and indicate individual sedimentation episodes during storms. These tempestites, in general, are fine-grained to very fine grained sandstones and are interpreted to be deposits of an inner shelf environment (e.g., Harms et al., 1975; Hamblin and Walker, 1979; Dott and Bourgeois, 1982). Hummocky cross-stratification has also commonly been documented from lower shoreface storm deposits that are associated with swaley cross-stratification (e.g., Leckie and Walker, 1982; Brenchley, 1985). These lower shoreface storm deposits are characterized by amalgamation and represent multiple storm episodes. Therefore, we excluded amalgamated shoreface storm deposits when investigating the relationship between bed thickness of tempestites and the hummocky cross-stratification wavelength.

In general, the hummocky cross-stratification wavelength increases with the increase in bed thickness (Fig. 1). This relationship shows

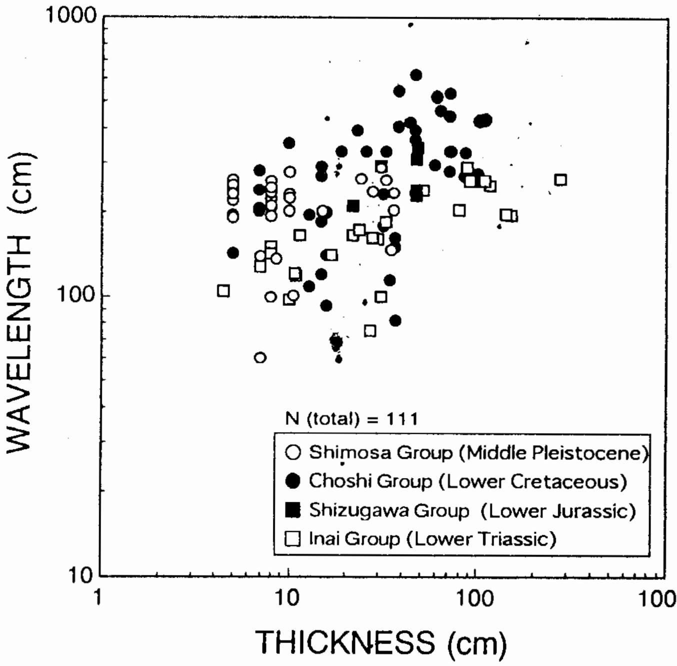

Figure 1. Relationship between bed thickness of tempestites and wavelength of hummocky cross-stratification. Data are from inner shelf deposits of four different stratigraphic successions on Japanese islands.

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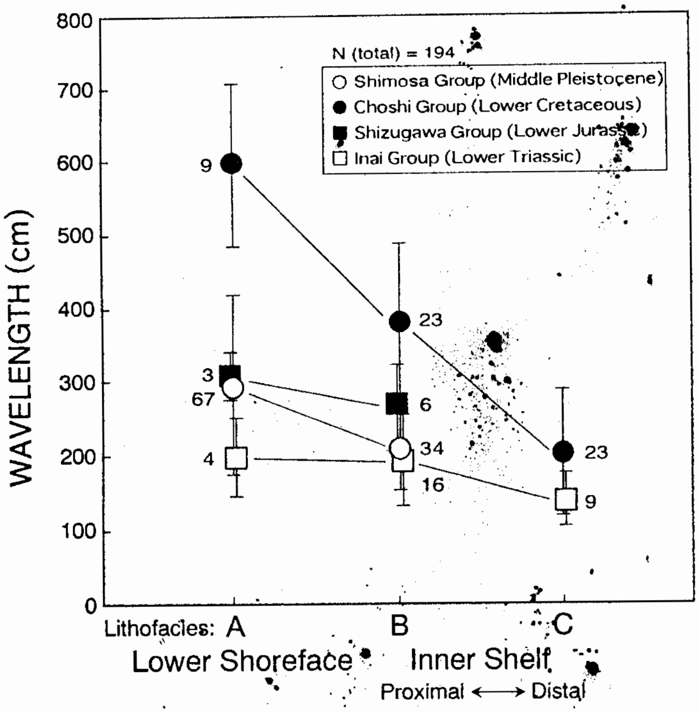

Figure 2. Examples of spatial and temporal variation in average wavelength of hummocky cross-stratification from four different stratigraphic successions on Japanese islands. Hummocky cross-stratified deposits are classified into three major lithofacies and represent lower shoreface (A) and proximal (B) and distal (C) parts of inner shelf environments. Vertical bars are standard deviation. Figures attached to symbols indicate number of measurements.

variation among samples from four different stratigraphic successions. This variation possibly reflects the amount of sediments delivered from a nearshore environment in response to mobilization and availability of nearshore sands and/or to the storm track relative to the depositional site. The relationship between the bed thickness of tempestites and the hummocky cross-stratification wavelength suggests that the wavelength reflects ancient storm-induced sediment transport controlled primarily by intensity of storm waves (Brandt and Elias, 1989) that may be reflected in the orbital diameters near seafloors. However, this interpretation has one potential uncertainty; bed thickness of tempestites shows a proximal-distal change and decreases with the increase in paleowater depth (e.g., Aigner and Reineck, 1982; Brenchley, 1985).

PALEOWATER DEPTH AND WAVELENGTH

In a stratigraphic succession, a proximal-distal change in tempestites can be analyzed from transgressive and regressive lithofacies successions (e.g., Hamblin and Walker, 1979; Aigner and Reineck, 1982; Brenchley, 1985). The relationship between the hummocky cross-stratification wavelength and paleowater depth is qualitatively interpreted by lithofacies features of tempestites (lithofacies A–C), as shown in Figure 2. Lithofacies A is amalgamated, fine-grained to very fine grained sandstones that contain hummocky cross-stratification associated with swaley cross-stratification and wave ripple lamination. Lithofacies B is fine-grained to very fine grained sandstones (beds 50–100 cm) with interbedded thinner muddy sandstones and sandy mudstones (beds 10–30 cm). Lithofacies C is fine-grained to very fine grained sandstones (beds 5–50 cm) and interbedded thicker sandy mudstones and siltstones (beds 20–70 cm). The hummocky cross-stratification of lithofacies B and C is locally associated with planar stratification and wave ripple lamination. The associated muddy deposits generally show intense bioturbation. These lithofacies features are interpreted as follows: lithofacies A is a lower shoreface deposit and lithofacies B and C indicate, respectively, proximal and distal parts of an inner shelf environment (Ito and Matsukawa, 1997).

In general, the hummocky cross-stratification wavelength decreases with the increase in paleowater depth (Fig. 2). This relationship likely reflects the decrease in orbital diameters of storm-induced oscillatory currents in the offshore direction. Although the relationship between water depth, orbital diameter, and wave climate does not necessarily determine the spacing of wave ripples in an inner shelf environment (e.g., Komar, 1974), the relationship in Figure 2 suggests that the hummocky cross-stratification wavelength is proportional to the orbital diameters of ancient storm waves. Wave ripples developed in a distal inner shelf environment influenced by storm waves with a higher wave period also show the decrease in the spacing with the increase in water depth (Komar, 1974), a pattern similar to that shown in Figure 2. Furthermore, some tempestites show an upward decrease in the wavelength of hummocky cross-stratification in individual beds (Craft and Bridge, 1987; Maejima and Kimoto, 1998) and may reflect the decrease in the orbital diameters near seafloors in response to the waning of storm waves (Li and Amos, 1999).

TEMPORAL VARIATION

Despite the inherent variation in the hummocky cross-stratification wavelength due to paleowater depth, the wavelength from each lithofacies shows temporal variation among four examples of different geologic ages from Japan (Fig. 2). For elucidating temporal variation in the wavelength through Mesozoic and Cenozoic time, we reviewed nine literature sources that described ranges of the hummocky cross-stratification wavelength and/or illustrated the occurrence of hummocky cross-stratification on outcrops and seafloors by figures and photographs (Fig. 3). Data we reviewed are mainly from tempestites that are interbedded with mudstones and were interpreted as inner shelf deposits. Data available from the literature, together with our own measurements from tempestites of 12 different geologic ages, indicate that the hummocky cross-stratification wavelengths may have varied since the early Mesozoic and show an increase and decrease cycle (Fig. 3). The middle Cretaceous is characterized by hummocky cross-stratification with the largest wavelengths and the early Mesozoic and late Cenozoic are represented by smaller wavelengths. The increase and decrease cycle of the wavelength shows a pattern similar to the long-term eustatic and climatic changes that are interpreted to have been caused by temporal variation in the rate of seafloor spreading and plume-related volcanism (e.g., Fischer, 1984; Larson, 1991). Therefore, the long-term increase and decrease cycle in the hummocky cross-stratification wavelength may document temporal variation in intensity of storm waves through the Mesozoic and Cenozoic. However, shorter term fluctuation in atmospheric CO_2 contents, for example during the Late Jurassic and late Paleocene (e.g., Berner, 1991; Bralower et al., 1997), cannot clearly be detected by the data given in Figure 3.

DISCUSSION AND CONCLUSIONS

The long-term relationships between storm intensity and global environmental change evidenced from the temporal variation in the hummocky cross-stratification wavelength can provide insight on what could happen in an inner shelf environment in response to global warming. Although the wavelength is interpreted to be proportional to the orbital diameters of oscillatory currents near seafloors, the relationship is mainly from modern and experimentally produced hummocky cross-stratifications that have wavelengths <~2 m. Ancient hummocky cross-stratifications commonly have wavelengths >2 m. Thus, the relationship for hummocky cross-stratifications with wavelengths >2 m should be further tested based upon modern and experimentally produced bedforms. Although we still do not know the pre-

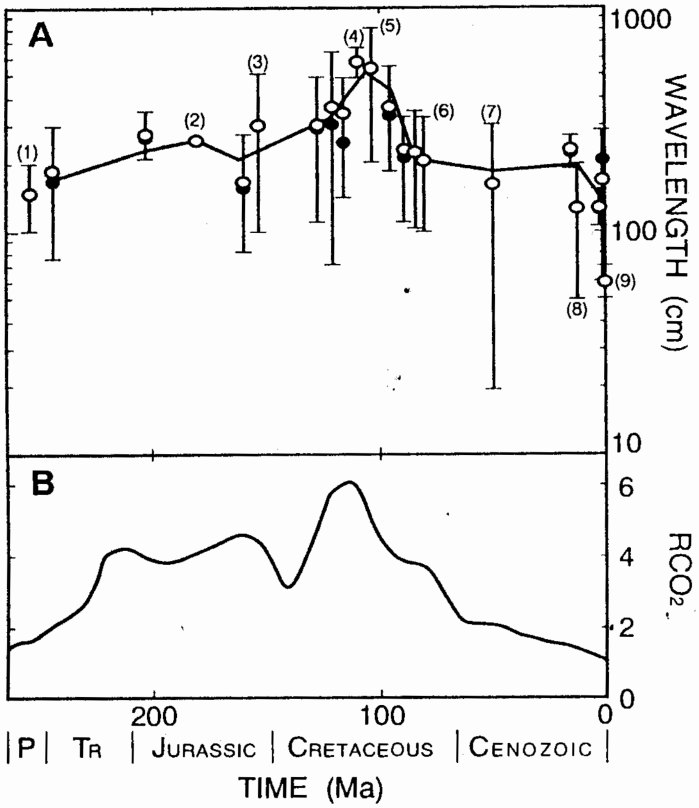

Figure 3. A: Temporal variation in wavelength of hummocky cross-stratification through Mesozoic and Cenozoic. Data are from inner shelf deposits equivalent to lithofacies B and C discussed in text. Vertical bars are ranges of wavelength, and open and filled circles represent midpoints and averages of wavelength, respectively. Solid line indicates curve of two-point moving averages of midpoints. Data are plotted on geologic time-scale calibration of Harland et al. (1990). P is Permian; Tr is Triassic. Literature sources: 1, McKie (1994); 2, Fielding (1989); 3, Hamblin and Walker (1979); 4, Nottvedt and Kreisa (1987); 5, Midtgaard (1996); 6, Bourgeois (1980); 7, Dott and Bourgeois (1982); 8, Maejima and Kimoto (1998); 9, Li and Amos (1999). Unlabeled bars represent data measured from 221 outcrop examples from Japan. B: Relative change in atmospheric CO_2 content through Mesozoic and Cenozoic (Berner, 1991). RCO_2 = ratio of atmospheric CO_2 mass at any time to that at present.

cise physical relationships between orbital diameter, water depth, and storm waves on the development of hummocky cross-stratification in an inner shelf environment, the relationships between the wavelength, and bed thickness and paleowater depth of tempestites from geologic records, suggest that the hummocky cross-stratification wavelength is a measure of the orbital diameters of ancient storm waves near seafloors and thus reflects storm intensity. Storm intensity is also interpreted to be affected by paleogeography and some ancient storm deposits were also influenced by winter storms rather than by tropical storms (Marsaglia and Klein, 1983; Duke, 1985; Barron, 1989).

More detailed data on the hummocky cross-stratification wavelength within precise stratigraphic and paleogeographic frameworks should be combined with more precise physical relationships of wavelength, orbital diameter, water depth, and storm waves, in order to refine the relationships between long-term as well as short-term variations in storm intensity. Future work can constrain the correlation to the greenhouse and icehouse climatic changes through the Phanerozoic, as suggested by this research.

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