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Discovery of outcrop-scale fine-grained sediment waves in the lower Halang Formation, an upper Miocene submarine-fan succession in West Java

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A B S T R A C T

We report the first discovery of outcrop-scale, fine-grained sediment waves in the left-side muddy overbank deposits relative to the down-current direction of the adjacent channel deposits in the lower Halang Formation turbidite system in a late Miocene back-arc basin, West Java. The present outcrop examples are characterized by an average wavelength of 10.7 m and an average wave height of 0.13 m, and the aspect ratio is similar to that of modern large-scale, fine-grained sediment waves. The dimension and asymmetry of waveforms decrease in the down-current direction in association with the increase in wave steepness. In particular, aggradation and up-current migrating of waveforms are commonly observed in the proximal part of overbank deposits. Furthermore, the stoss-side deposits locally contain thicker and coarser sandstone and coarse siltstone beds (beds up to 5 cm thick) than those of the lee-side deposits. The basal part of individual waveforms does not contain any sandy bedform and/or irregularity as a precursor for developing asymmetrical waveforms from fine-grained turbidity currents. These spatial variations in geometry and component deposits of the waveforms are interpreted to have been formed under antidune or cyclic-step and standing-wave conditions from the proximal to distal overbank environments, respectively. The present outcrop-scale examples can fill the gap in dimension and formative processes between laboratory-scale bedforms and modern large-scale, fine-grained sediment waves for elucidating scale-independent processes, which are responsible for the development of fine-grained waveforms in a deep-water environment.

1. Introduction

Sediment waves are a large-scale bedform (i.e., wavelengths up to 7 km and wave heights up to 80 m) and have commonly been found in modern submarine-fan systems (e.g., Normark et al., 1980, 2002; Wynn and Stow, 2002), although modern sediment waves have also been found in other depositional environments, such as abyssal plain, continental-rise, continental-slope, and shallow-marine environments (e.g., Kolla et al., 1980; Stow and Holbrook, 1984; Wynn et al., 2000; Lee et al., 2002). Generation of many sediment waves in a deep-water environment has been interpreted to be controlled by turbidity currents and/or by bottom currents (e.g., Normark et al., 1980; Flood et al., 1993; Howe, 1996; Faugères et al., 2002; Wynn and Stow, 2002). In a submarine-fan environment, turbidity currents, which spill over from channels onto adjacent levees, are interpreted to be responsible for the generation of large-scale, fine-grained, sediment waves (e.g., Normark et al., 1980; Migeon et al., 2000; Wynn et al., 2000; Normark et al., 2002; Nakajima and Satoh, 2001; Fildani et al., 2006). In terms of two-dimensional cross-sectional geometry in seismic sections, modern fine-grained sediment waves commonly exhibit upstream-migrating geometry, and have been interpreted to document bedforms developed as antidunes and/or cyclic steps under supercritical flow condition (e.g., Normark et al., 1980; Normark and Piper, 1991; Fildani et al., 2006; Spinewine et al., 2009), although alternative processes for the development of upstream-migrating waveforms have also been proposed as a response to the presence of precursor seafloor irregularities (e.g., Kubo and Nakajima, 2002; Lee et al., 2002; Migeon et al., 2004; Heiniö and Davies, 2009). The formation of lee waves in association with a linear obstruction under subcritical flow condition has also been proposed for the development of up-current-migrating sediment waves (e.g., Allen, 1984; Flood, 1988; Howe, 1996; Lewis and Pantin, 2002; Kane et al., 2010). Furthermore, the dimension and asymmetry of fine-grained sediment waves, in general, exhibit decreases in a down-current direction (e.g., Normark et al., 1980; Carter et al., 1990; Migeon et al., 2000). However, these wave-forming processes on levees from fine-grained turbidity currents still remain controversial (e.g., Wynn and Stow, 2002). Thus, detailed outcrop analyses of ancient sediment-wave deposits should be crucial for the better understanding of the generation processes of fine-grained sediment waves. However, because ancient examples with dimension similar to modern sediment waves have

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generally been considered to exceed outcrop scale, and the recognition of subtle waveforms in outcrops has also been considered not to be practical (e.g., Normark et al., 2002), except for one case study from laterally extensive outcrops in Chile (Savoye et al., 2008). Thus, recognition of outcrop-scale features of waveforms, which are analogous to those of modern sediment waves, should provide an advantage for filling a gap between laboratory-scale bedforms under controlled dynamic conditions and seismic-scale modern fine-grained sediment waves that have been studied for the reconstruction of the generation processes of waveforms in a deep-water environment in terms of scale-independent processes. Here we report the first discovery of outcrop-scale, fine-grained sediment waves, and discuss their formative processes on the basis of spatial variations in the dimension and asymmetry of the waveforms in muddy overbank deposits of the lower Halang Formation, which developed in the Bogor Trough, a late Miocene back-arc basin in West Java, Indonesia (Figs. 1 and 2).

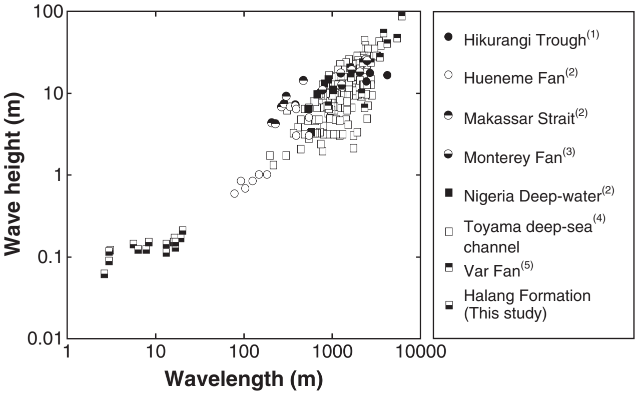

Fig. 2. Dimension of fine-grained sediment waves from modern submarine-fan systems and outcrop-scale examples from the lower Halang Formation. Modern data are from (1) Lewis and Pantin (2002), (2) Normark et al. (2002), (3) Normark et al. (1980), (4) Nakajima and Satoh (2001), and (5) Migeon et al. (2000).

2. Geologic setting

The Halang Formation is a late Miocene infill of the Bogor Trough, which trends from WNW to ESE in a back-arc setting of the Java arc-trench system (Sujanto and Sumantri, 1977; Sribudiyani et al., 2003) (Fig. 1A and B). Within the formation, the lower part (up to 400 m thick) is represented generally by turbidites and interbedded hemipelagic mudstones with local associations with some other types of sediment-gravity-flow deposits (*sensu* Mulder and Alexander, 2001) (Djuhaeni and Martodjojo, 1989; Kastowo and Suwarna, 1996; Martodjojo, 2003) (Fig. 1C). Overall, the lower Halang Formation is represented as a mudstone-dominated turbidite succession, and is characterized by channel-and-overbank deposits and sheet-like turbidites (Fig. 3), which are interpreted to have been formed as frontal-splay and/or crevasse-splay deposits in a longitudinal submarine-fan system (Mukti et al., 2009) (Fig. 1C). The channel deposits are not laterally continuous in downslope directions and locally contain lateral-accretion surfaces (Fig. 4), indicating higher-sinuosity channels in the mudstone-dominated, longitudinal turbidite system (Mukti et al., 2009). On the basis of three-dimensional outcrop analysis of channel deposits, higher-sinuosity channels are interpreted to have been characterized by an average depth of 7 m and an average width of 400 m (Fig. 4). Interbedded mudstones are weakly and locally moderately bioturbated and locally contain bathyal faunas (Muchsin et al., 2002). Fine-grained sediment waves identified by this study are encased in left-hand overbank deposits relative to the downslope direction of the adjacent channel deposits, and are overlain by channel- and channel-margin deposits as a response to the aggradation and lateral migration of a couplet of overlying channel-and-overbank deposits (Fig. 4).

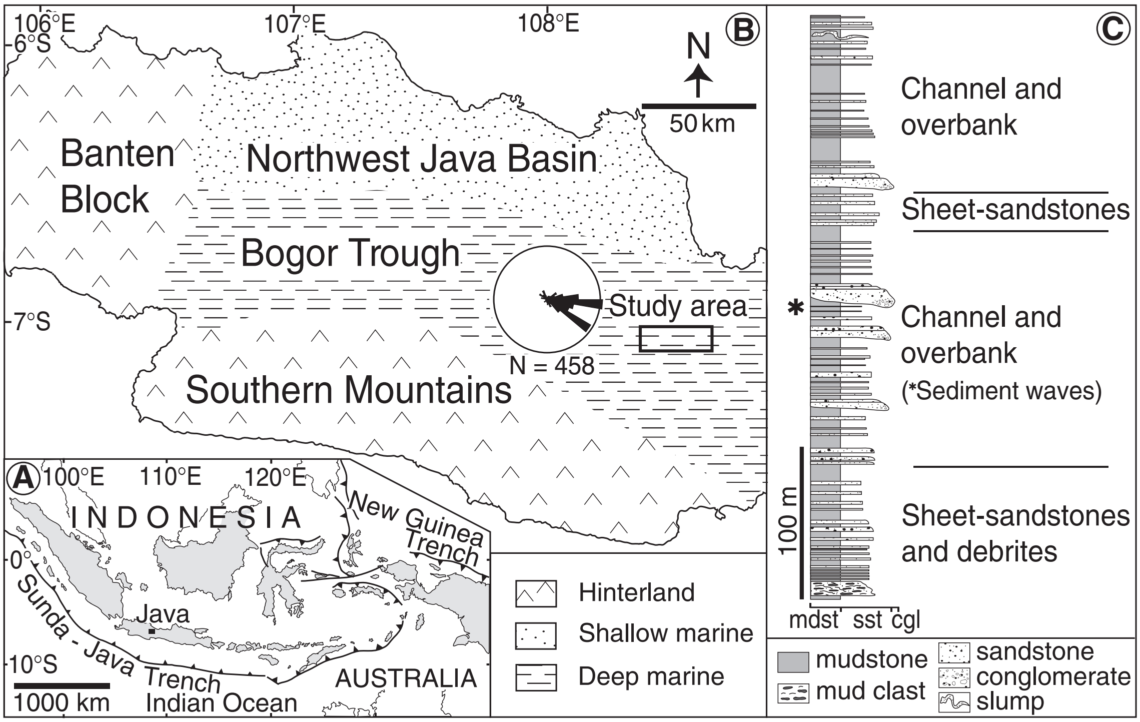

Fig. 1. (A) Plate-tectonic framework of Java and adjacent areas. Modified from Hall (2002). (B) Sketch map of sedimentary basins and hinterlands during late Miocene in West Java. Simplified from Martodjojo (2003). The rose diagram indicates paleocurrents from the lower Halang Formation in the study area (rectangle). N is the number of measurements mainly from groove and flute casts. (C) Composite section and major depositional environments of the lower Halang Formation in the study area.

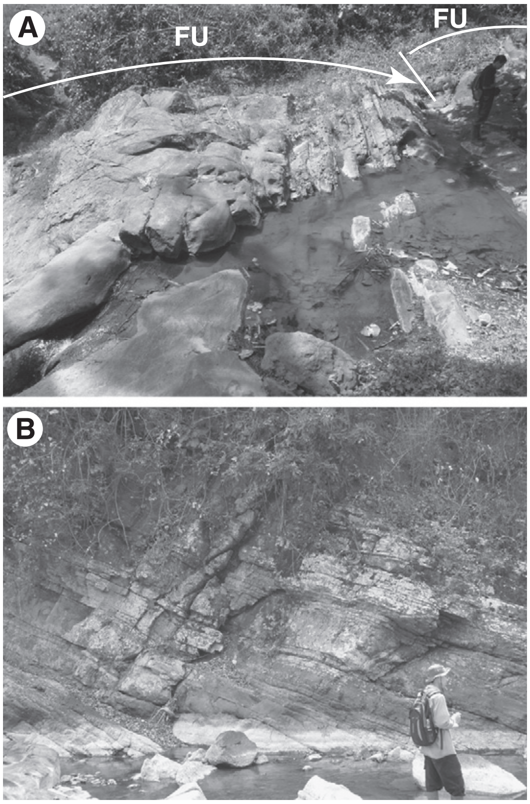

Fig. 3. (A) Fining-upward (FU) successions from channel to overbank deposits along the Ciraseh River. Beds younging to the right. Figure for scale. (B) Sheet-like turbidites along the Cipedak River. Beds younging to the right up. Figure for scale.

3. Outcrop-scale fine-grained sediment waves

Gently undulated waveforms are observed in muddy overbank deposits of the lower Halang Formation (Fig. 5). The overbank deposits are characterized by weakly and locally moderately bioturbated siltstones and mudstones, which are intercalated with medium- to thin-bedded, medium- to very fine-grained sandstones in a proximal area relative to a margin of the associated channel-fill deposits (Fig. 6A), and the intercalated sandstone beds show progressive thinning and fining into the down-current direction to the north (Fig. 6B). The overbank deposits become finer-grained being that they are away from the associated channel-fill deposits (Fig. 6C and D) and contain gently undulated waveforms (Fig. 5). These finer-grained overbank deposits are represented by weakly and locally moderately bioturbated mudstones and laminated mudstones (Figs. 6C and D and 7A), which are intercalated with thin- to very thin-bedded, normally graded, parallel-laminated, and/or current-ripple cross-laminated, very fine-grained sandstones (beds 1–5 cm thick) and coarse siltstones (Fig. 7B). Intercalated sandstones and coarse siltstones occupy about 10–20% of the thickness compared with that of mudstones (Fig. 6C and D), except for local intercalations of thin- to medium-bedded, medium- to very fine-grained sandstones, which are lenticular in overall geometry and are not incorporated in the waveforms (Fig. 7C). Although constituent deposits of the waveforms, in general, do not show any distinct spatial variation within a waveform, intercalations of slightly thicker and/or coarser sandstone and siltstone beds and laminae in mudstones are locally observed in the up-current sides (i.e., stoss sides) compared with those in the down-current sides (i.e., lee sides) (Fig. 7D and E).

The waveforms show multiple vertical stacking of component muddy deposits with gently undulating bedding, and the wavelengths are from 2.6 to 20.4 m with the wave heights of 6 to 20 cm (Figs. 2, 5, 8, 9, and 10). Laterally, series of waveforms are also recognized along

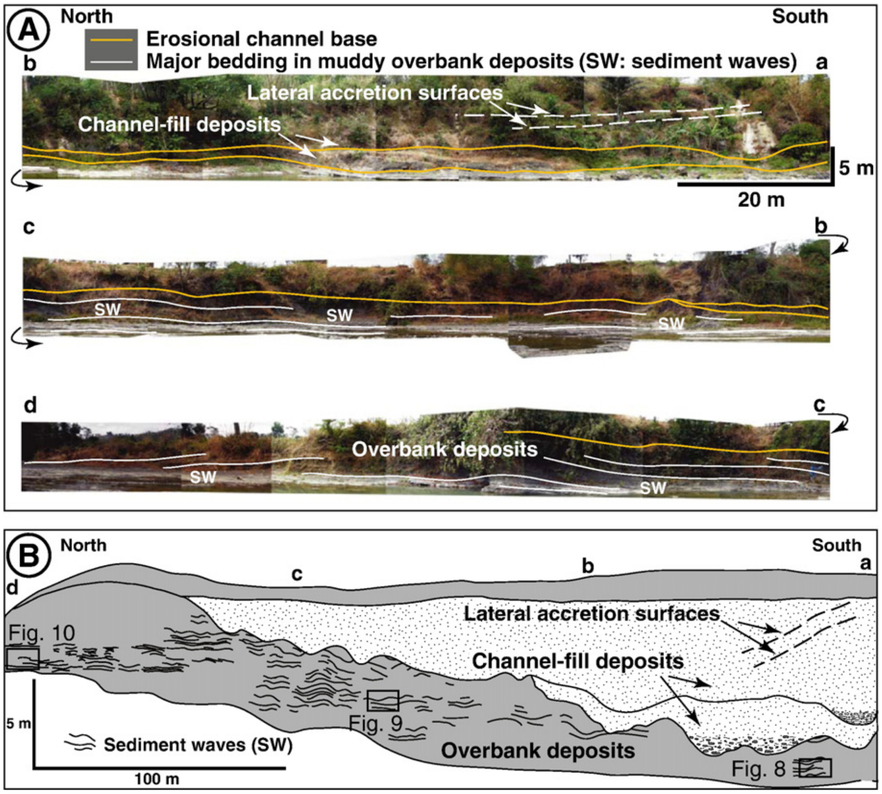

Fig. 4. (A) Panorama photograph of channel-and-overbank deposits along the Cipedak River. This outcrop trends largely orthogonal to paleocurrents of channel-fill deposits to the east (to the panel). Two stacked channel-fill deposits are incased in overbank fine-grained deposits. Some representative sediment waves are denoted by SW. (B) Outcrop sketch of channel-and-overbank deposits of the lower Halang Formation in A. Note the vertical exaggeration of this sketch. Positions and shapes of outcrop-scale sediment waves are also schematically illustrated in this figure. Rectangles indicate locations of Figs. 8, 9, and 10. Locations of a–d in A are indicated in the upper part of the sketch. See Fig. 1C for legend.

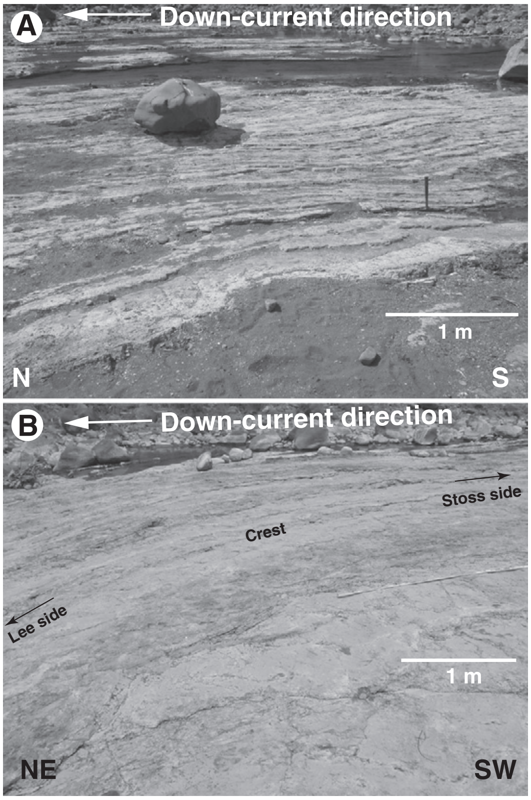

Fig. 5. (A) Gently undulating waveforms in muddy overbank deposits of the lower Halang Formation along the Cipedak River. Beds younging to the left up. Location of this photograph is near b in Fig. 4. (B) Gently curved bedding in muddy overbank deposits of the lower Halang Formation along the Cipedak River. Bed younging to the left up. This is a close-up photograph of the crest part of a sediment-wave deposit in Fig. 8. See Fig. 4B for location of Fig. 8.

the same horizons (Fig. 5A). Locally, internal bedding within a waveform converges in the down-current direction and discordance of bedding within a single waveform is observed (Fig. 8B). Except for locally observed discordance, any distinct soft-sediment deformation structures, syn-depositional faulting and folding, and/or boudinage are not observed within the waveforms.

Thus, gently undulating waveforms are interpreted to represent outcrop features of small-scale, fine-grained sediment waves rather than soft-sediment deformation structures and/or tectonically deformed bedding in muddy overbank deposits. Although the reconstruction of overall geometry of the wave crests is not practical in the gently inclined stratigraphic succession (i.e., dipping about 16° to the east through the muddy overbank deposits) (Fig. 5B), outcrop measurements of the orientation of the crests of the waveforms indicate that the crests of the present waveforms are nearly parallel or slightly oblique to the downslope direction of the associated channel deposits.

4. Spatial variation in dimension and asymmetry

In response to the down-current-directed fining and thinning of intercalated sandstone and coarse siltstone beds in the muddy overbank deposits, the dimension and asymmetry of fine-grained sediment waves exhibit proximal-to-distal variation in respect to the margin of channel deposits: both the wavelengths and wave heights show progressive decreases in association with the increase of wave steepness (Figs. 8, 9, 10, and 11). Furthermore, on the basis of independently reconstructed paleocurrent directions from sole marks and ripple cross-lamination of thin- to medium-bedded sandstones, the degree of asymmetry of waveforms increases in the southern proximal direction, and the stoss-sides become shorter than the lee-sides (Fig. 11D). Along with this asymmetrical geometry of the fine-grained sediment-wave deposits, intercalated sandstone and coarse siltstone beds and laminae in the constituent muddy deposits in the stoss sides become thicker than in the lee sides (Fig. 7D and E). Furthermore, the outcrop-scale fine-grained sediment-wave deposits commonly have climbing forms (Figs. 8 and 9), which are interpreted to have responded to a combination between aggradation and up-current-directed migration of the waveforms, and do not any show compensation stacking of packages of mudstones, siltstones, and minor sandstones.

5. Scale-independent features of waveforms

The present outcrop-scale examples of fine-grained sediment waves in muddy overbank deposits of the lower Halang Formation are characterized by waveforms largely similar to those reported from modern submarine-fan systems in terms of the wave steepness and wave symmetry, although the present examples are very small in dimension compared with modern examples (Fig. 2). This relationship suggests that there remains a resolution mismatch between outcrop studies of ancient examples and marine geophysical studies of modern examples, although small-scale (i.e., 10–20 m long and 1–2 m high) fine-grained sediment waves were reported from the New England continental rise using a side-looking sonar record (Johnson and Lonsdale, 1976; Lonsdale and Spiess, 1977). However, internal structure and symmetry of these small-scale sediment waves were not clearly understood and their geometry is characterized by a larger value of wave steepness of up to 0.1 than that of large-scale sediment waves and of the present examples (see Fig. 2). A down-current decrease in the dimension and asymmetry is also documented in the present outcrop examples (Fig. 11), similar to some modern large-scale, fine-grained sediment waves, although local variations in down-current decreases in the dimension and asymmetry have also been reported from modern submarine-fan systems (e.g., Migeon et al., 2000; Normark et al., 2002; Wynn and Stow, 2002). Furthermore, the present examples document that the stoss sides of sediment-wave deposits are intercalated with thicker sandstone and coarse siltstone beds and laminae than the lee sides, and this textural variation between the up-current and down-current sides within a single fine-grained waveform has also commonly been reported from modern large-scale examples (e.g., Migeon et al., 2000; Normark et al., 2002).

The present outcrop-scale examples of fine-grained sediment waves document up-current migrating geometry (Figs. 8 and 9), along with intercalations of thicker and coarser sandstone and siltstone beds and laminae in the stoss sides than those in the lee sides, and suggest that the waveforms may have developed under supercritical flow condition as have been claimed for the generation of modern large-scale, fine-grained sediment waves (e.g., Normark et al., 1980; Wynn et al., 2000). Alternatively, some fine-grained sediment waves are interpreted to have formed by lee waves under subcritical flow condition (e.g., Flood, 1988). The lee-wave model has been adopted to explain the formation of large-scale, fine-grained sediment waves influenced by bottom currents (e.g., Flood et al., 1993; Howe, 1996), although lee waves that are generated in turbidity currents have also been inferred as one of the major processes for the generation of fine-grained sediment waves on overbanks in a submarine-fan system (e.g., Lewis and Pantin, 2002; Kane et al., 2010). Because intercalated sandstone and coarse siltstone beds in the studied muddy overbank deposits show lithofacies features of turbidites rather than those of contourites (cf., Gonthier et al., 1984; Stow and Holbrook, 1984; Piper and Stow, 1991), the present outcrop examples of fine-grained sediment waves are interpreted to have formed by turbidity currents, which spilled over from the adjacent submarine-fan channels, under supercritical flow condition that has been interpreted to be quite common on an overbank environment (e.g., Normark et al., 1980; Wynn et al., 2000; Fildani et al., 2006), although we do not have any

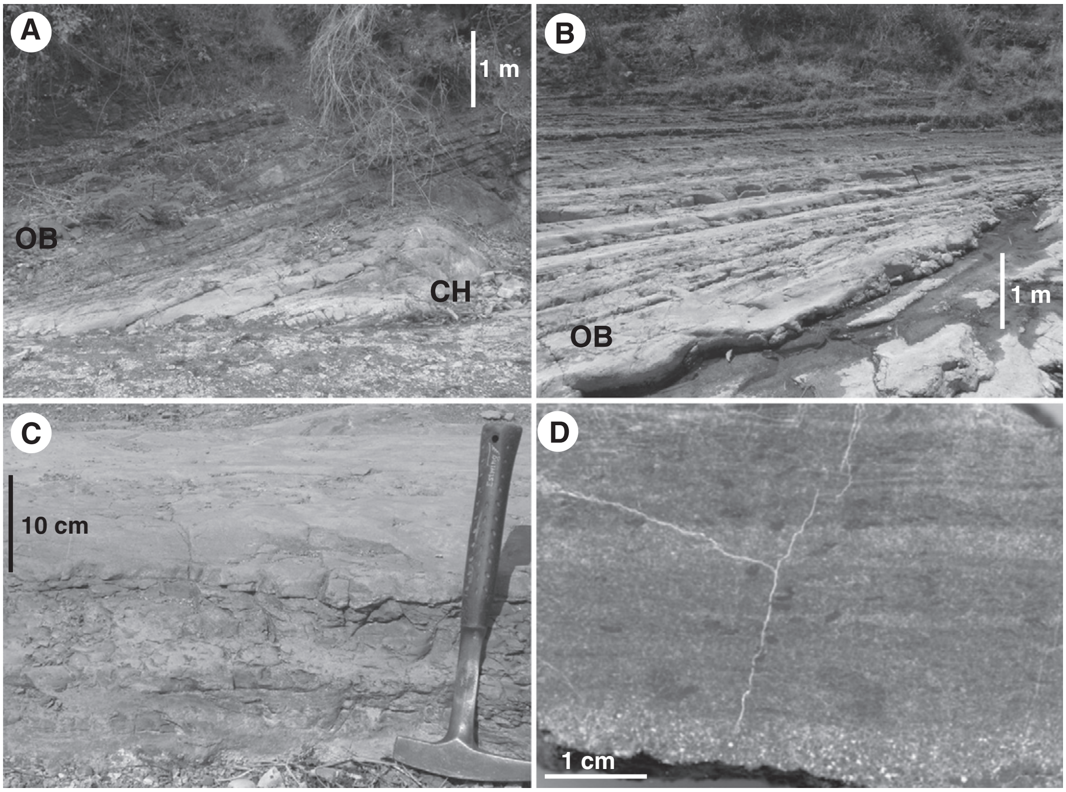

Fig. 6. (A) Thick- to very thick-bedded channel-fill sandstones (CH) and overlying interbedded mudstones, siltstones, and sandstones of overbank deposits (OB). These overbank deposits fine upward and also laterally fine into muddy overbank deposits to the north. Bed younging to the left up. (B) Muddy overbank deposits in a distal area (location d in Fig. 4). Bed younging to the left up. (C) Close-up views of lithofacies features of muddy overbank deposits near location b in Fig. 4. (D) Polished section of mudstones with sandstone and coarse siltstone beds and laminae in muddy overbank deposits near location b in Fig. 4. Minor bioturbation is also observed.

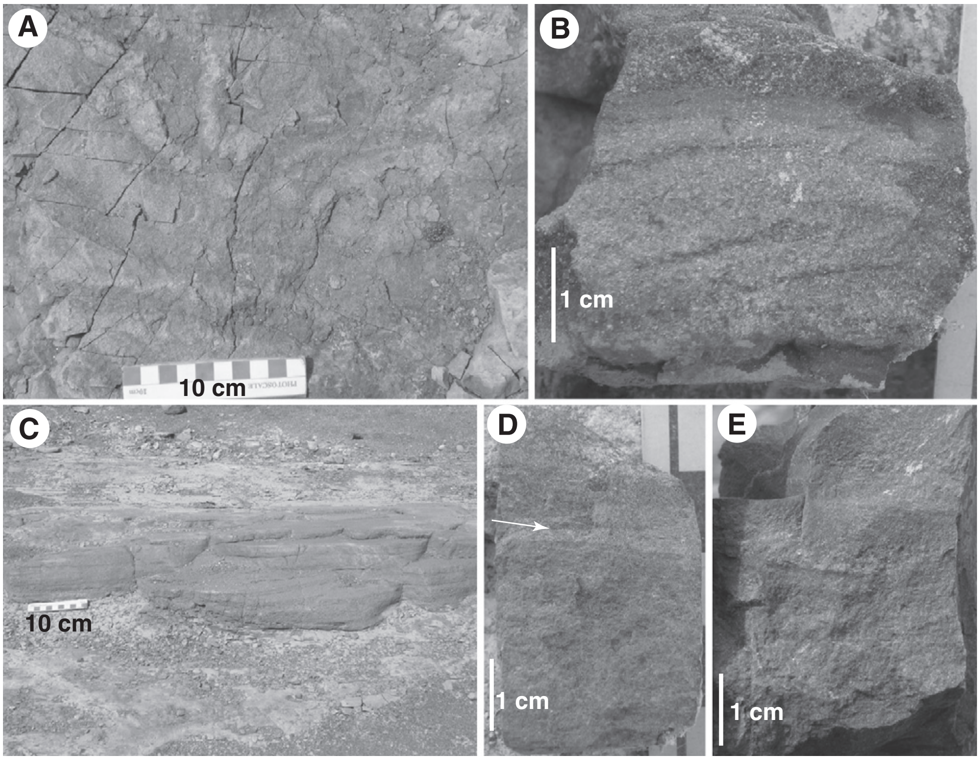

Fig. 7. (A) Locally observed burrowed siltstones in muddy overbank deposits near location b in Fig. 4. (B) A rock sample of a current-ripple cross-laminated sandstone bed in mudstones near location a in Fig. 4. (C) A medium- to very fine-grained sandstone bed locally intercalated in muddy overbank deposits. (D) A rock sample of siltstone with a distinct very fine-grained sandstone lamina (white arrowed) in a stoss-side deposit. (E) A rock sample of mudstones and siltstones in a lee-side deposit.

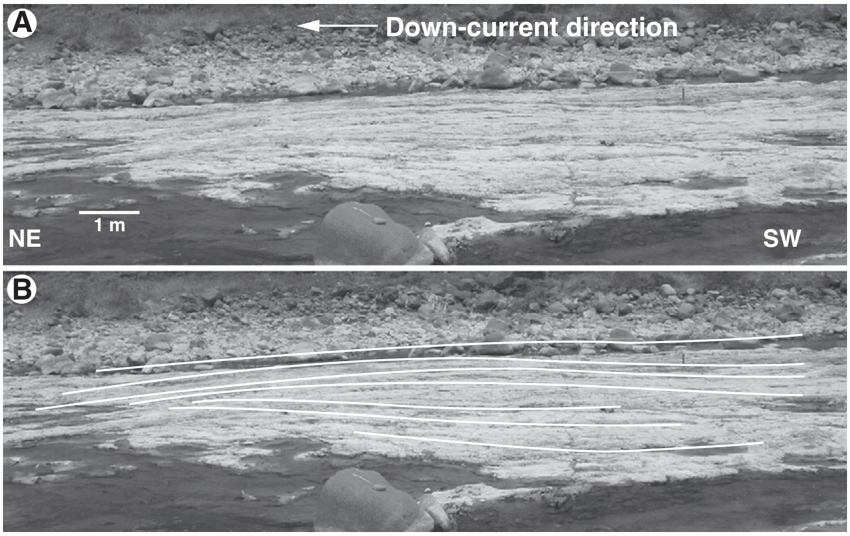

Fig. 8. (A) Aggradational and up-current-migrating stacking of sediment-wave deposits in a proximal portion of muddy overbank deposits in a location between a and b in Fig. 4. (B) Interpretation of major bedding styles within a sediment-wave deposit. Note the truncation of internal bedding in the lee side.

independent evidence of supercritical flow condition in the studied succession. In the basal part of each waveform of the present examples, any distinct sandy bedforms and/or irregularity, which are interpreted to be precursors for developing up-current migrating waveforms by subsequent turbidity currents (Nakajima and Satoh, 2001; Kubo and Nakajima, 2002; Lee et al., 2002; Heiniö and Davies, 2009), are not observed. Because locally observed thin- to medium-bedded, medium to very fine-grained lenticular sandstones are not incorporated in the waveforms, these sandstone beds do not seem to have provided any initial irregularity to the sea floor and may have formed from coarser-grained turbidity currents than those that may have been responsible for the formation of the fine-grained sediment waves.

Because commonly observed climbing forms in the sediment-wave deposits do not show any evidence of compensation stacking patterns, gently undulating wavy forms in the muddy overbank deposits do not seem to have been affected by differential compaction and/or soft-sediment deformation of the muddy deposits. Furthermore, because the muddy overbank deposits are, in general, represented by largely consistent tectonic dips of about 16° to the east in the study location, any post-depositional tectonic deformation does not seem to have affected the formation of the waveforms in the muddy overbank deposits. Locally observed discordance within a waveform does not either represent deformation structure and is interpreted to have formed as a response to up-current-directed migration of climbing forms. These internal truncations of bedding have also been documented in some large-scale sediment waves in seismic sections (e.g., Migeon et al., 2004).

In terms of down-current decreases in the dimension and asymmetry of the waveforms of the present examples, smaller waveforms become dominant in a distal overbank environment and up-current migrating larger waveforms are in a proximal area relative to the margin of associated channel deposits (Fig. 11). These down-current-directed variations in geometrical features of fine-grained sediment waves are also documented from modern large-scale sediment-wave fields, together with several other types of down-current variation (e.g., Migeon et al., 2000; Normark et al., 2002). The increase in wave steepness along with the decrease in asymmetry in distal-overbank deposits is interpreted to have responded to spatial variation in flow types of fine-grained turbidity currents from antidune or cyclic-step to standing-wave dynamic conditions (Cheel, 1990), as a response to the decrease in flow velocities or the increase in flow thickness from the proximal to distal overbank environments in association with the decrease in slope. Subcritical flow condition of turbidity currents has also been interpreted to be responsible for the development of fine-grained sediment waves in a deep-water environment with the interaction between sediment supplies, flow velocities, and seafloor topographic height (e.g., Kneller and Buckee, 2000; Migeon et al., 2000). Thus, lee waves are still an alternative possible mechanism for the formation of the present

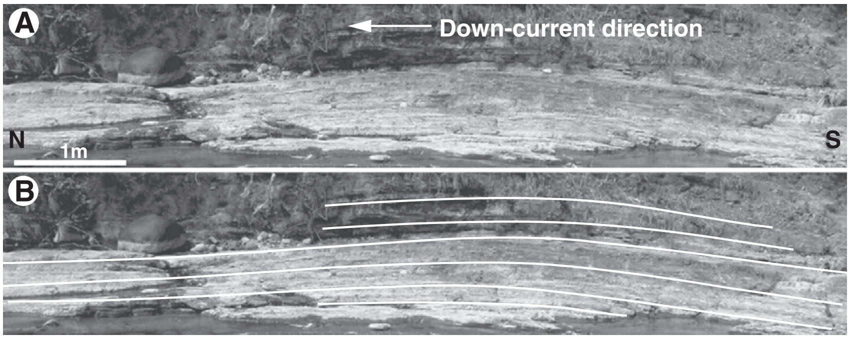

Fig. 9. (A) A weakly up-current-directed migration and distinct aggradational pattern of fine-grained sediment-wave deposits at location c in Fig. 4. (B) Interpretation of internal bedding styles of a sediment wave deposit in A.

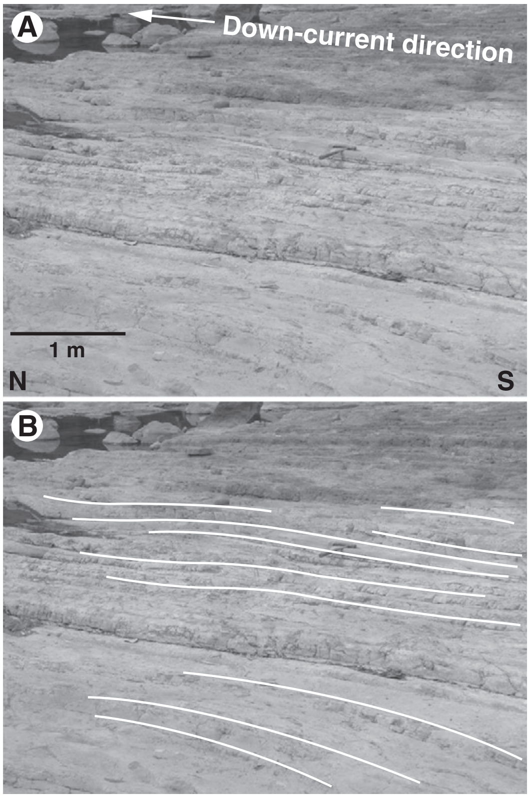

Fig. 10. (A) Symmetrical sediment waves in a distal portion of overbank deposits at location d in Fig. 4. Beds younging to the right up. (B) Interpretation of bedding styles in sediment-wave deposits in A.

examples, although lee waves exist only if the densiometric Froude number is smaller than $1/\pi$ and this condition does not seem to be common in turbidity currents (Allen, 1984).

6. Conclusions

Fine-grained sediment waves are commonly found in modern deep-water environments on the basis of marine geophysical techniques, and the dimension commonly exceeds outcrop scales. Thus, recognition of ancient fine-grained sediment waves in outcrops has been considered to be problematic, except for one case study from the Cerro Toro Formation in Chile (Savoye et al., 2008). This paper is the first description of outcrop-scale, fine-grained sediment waves in overbank deposits of the lower Halang Formation in a late Miocene back-arc basin in West Java, Indonesia. The present outcrop-scale examples exhibit geometrical and internal features of fine-grained sediment waves quite similar to some examples from modern large-scale sediment waves. Furthermore, down-current decreases in the dimension and asymmetry of fine-grained sediment waves that were revealed from the present examples have also been documented from some large-scale modern sediment waves. These similarities between ancient outcrop-scale and modern large-scale, fine-grained sediment waves suggest that the generation of waveforms in fine-grained sediments in a deep-water environment must have been controlled by scale-independent processes of fine-grained turbidity currents. The present outcrop-scale examples also suggest that the formation of any initial irregularity on the sea floor is not necessarily a pre-requisite for the initiation and subsequent up-current migration of waveforms. The outcrop-scale sediment waves examined by this study can fill the gap in dimension and formative processes between laboratory-scale bedforms and modern large-scale, fine-grained sediment waves in terms of scale-independent physical processes for the development of waveforms in a deep-water environment.

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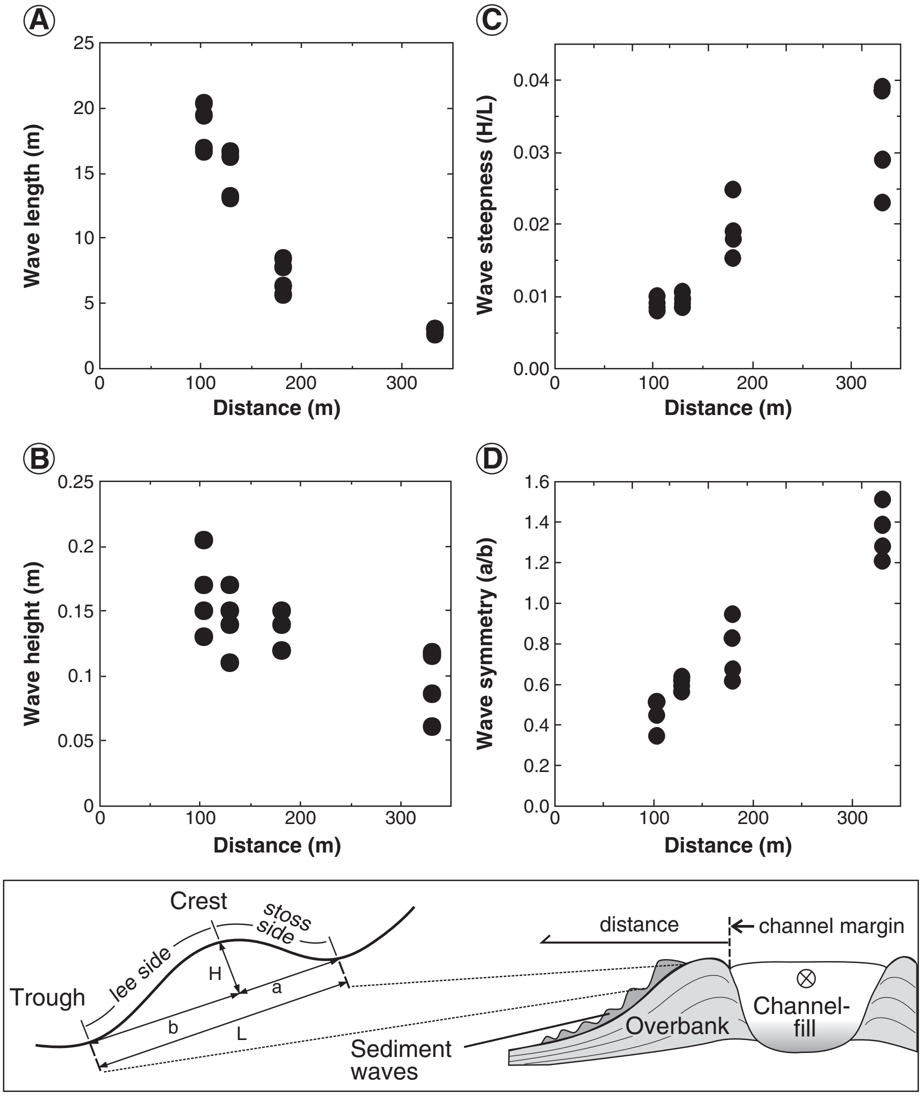

Fig. 11. Spatial variations in wavelengths (A) and wave heights (B), wave steepness (C), and wave symmetry (D) of the Halang Formation fine-grained sediment waves. Sketch in the lower right illustrates definition of variables.

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