Journal of Sedimentary Research

Journal of Sedimentary Research, 2006, v. 76, 1274–1283
Research Article
DOI: 10.2110/jsr.2006.093

GRAVEL WAVES IN AN ANCIENT CANYON: ANALOGOUS FEATURES AND FORMATIVE PROCESSES OF COARSE-GRAINED BEDFORMS IN A SUBMARINE-FAN SYSTEM, THE LOWER PLEISTOCENE OF THE BOSO PENINSULA, JAPAN

MAKOTO ITO[1] AND TAKAHIRO SAITO[2]*
[1]*Department of Earth Sciences, Chiba University, Chiba 263-8522, Japan*
[2]*Graduate School of Science and Technology, Chiba University, Chiba 263-8522, Japan*
e-mail: mito@faculty.chiba-u.jp

ABSTRACT: **Gravel waves have been observed from many modern submarine fans. However, the internal organization and formative processes of gravel waves are still controversial, because features analogous to gravel waves seen on outcrops have been poorly understood. Here, we analyzed cross-stratified pebble conglomerates in a lower Pleistocene paleocanyon-fill succession exposed on the Boso Peninsula of Japan, which exhibit features similar to those of modern gravel waves in terms of texture, size, and geometry. Gravel-wave deposits examined in this study are interpreted to have been formed as traction-sedimentation bedforms that migrated in downslope directions under gravelly, high-density turbidity currents, and are gradationally overlain by weakly graded sandstones from sandy high-density turbidity currents in single depositional events. Thus, erosion and reshaping of coarse-grained deposits to develop the wave forms by subsequent lower-density turbulent flows within single or later depositional events, as proposed by previous studies, are not evident from the present examples. The findings indicate that a formative process of this kind has also been responsible for the development of gravel waves in modern submarine fans, although later modification of the bedforms by subsequent lower-density turbidity currents cannot be excluded.**

INTRODUCTION

Modern submarine-fan systems are characterized by various kinds of depositional and erosional features (e.g., Normark and Piper 1991). These sedimentological features have mainly been investigated by side-scan sonar and submersible observations, and are generally larger in scale than those observed in outcrops, such as ripples and small dunes (Normark et al. 1979). Among these large-scale sedimentological features, wave-like undulating bedforms, which consist of sediments coarser than 0.5 mm and are characterized by wave heights of 1–10 m and by wavelengths of tens to up to several hundred meters, have been reported from channels and canyons in modern submarine fans (Malinverno et al. 1988; Piper et al. 1988; Hughes Clark et al. 1990; Wynn et al. 2002a). These coarse-grained, large-scale bedforms have been termed gravel waves or coarse-grained sediment waves, and are associated locally with sandy deposits termed sand ribbons and sand patches (Wynn et al. 2002a). Although plan-view features of gravel waves in modern submarine fans have been well documented, the internal organization of these bedforms has been poorly understood. Furthermore, possible analogous features of ancient examples of such coarse-grained bedforms have rarely been documented, except for very few examples (Winn and Dott 1979; Piper and Kontopoulos 1994; Vicente Bravo and Robles 1995; Beaubouef 2004), although smaller-scale cross-bedded sandstones and conglomerates with heights of about a few tens of centimeters have commonly been reported from turbidite successions (e.g., Piper 1970; Hiscott and Middleton 1979; Hein 1982; Hickson and Lowe 2002; Kneller and McCaffrey 2003; Mutti et al. 2003). Limited data of cross-sectional views of gravel waves from the Laurentian Fan indicate that these coarse-grained bedforms are characterized by massive or poorly graded-stratified structures without any distinct cross-stratification (Hughes Clark et al. 1990). Internal organization of conglomerates interpreted as gravel-wave deposits from ancient channel-fill successions are also characterized by massive or poorly graded-stratified structures (Piper and Kontopoulos 1994). The absence of cross-stratification in coarse-grained deposits that are interpreted as gravel waves was questioned, and it was suggested that the dune-like features of gravel waves were not formed as a bedform but were comparable to transverse ridges in avalanche debris (Hsü 1989).

There are two other enigmatic features of gravel waves, neither of which have been clearly understood (e.g., Wynn et al. 2002a). First, the morphology of many modern gravel waves suggests that they are formed as bedforms migrated in an upcurrent direction similar to antidunes, although some examples exhibit downcurrent migration like dunes. Second, relative timing of the supply of coarse-grained sediments and the development of wave forms remains unclear.

In general, coarse-grained sediments that constitute the wave forms have been interpreted to be deposits from high-density turbidity currents or concentration density flows (Piper and Kontopoulos 1994). Erosion and reshaping of these coarse-grained sediments during later stages of a single event or even later events have been interpreted to be responsible for the generation of the wave forms (Wynn et al. 2002a). Therefore, documentation of geometry and internal organization of coarse-grained, large-scale bedforms associated with turbidites from good onshore exposures is crucial for the better understand of lithofacies organization and the formative processes of gravel waves. In particular, investigation of relative timing of

* Present address: Graduate School of Science and Technology, Niigata University, Niigata 250-2102, Japan

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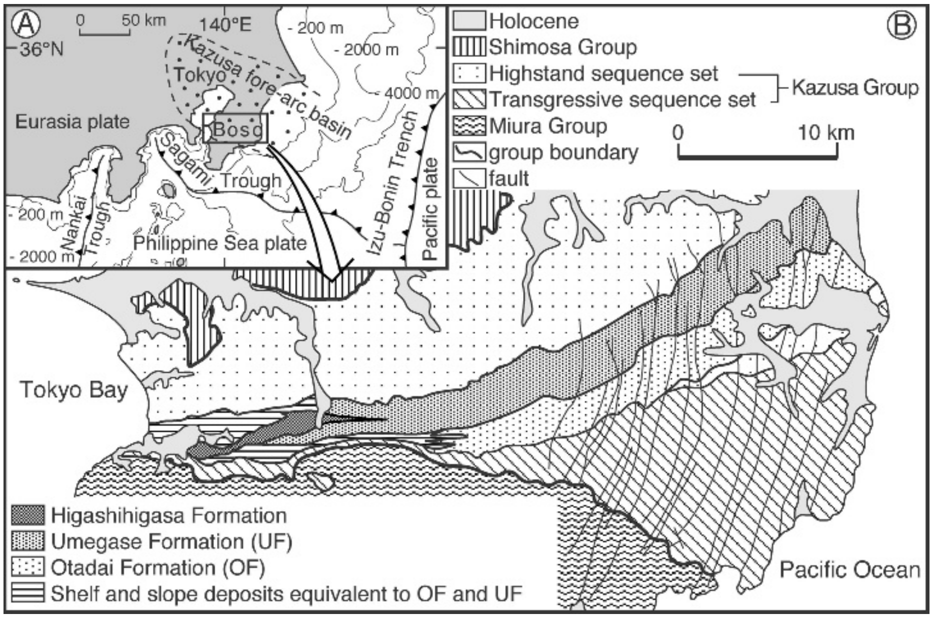

FIG. 1.—**A**) Plate-tectonic framework of the Kazusa forearc basin, Japan. **B**) Geologic sketch map of the central part of the Boso Peninsula. Modified from Ito (1998).

the formation of the wave forms in relation to the supply of the constituent coarse-grained sediments should be crucial for elucidating spatial and temporal variations in depositional processes in a submarine-fan system. In this paper, we examine the cross-sectional features of coarse-grained, large-scale bedforms from the lower Pleistocene infill of an ancient submarine canyon on the Boso Peninsula, Japan (Fig. 1). We use these features to elucidate the formative processes of the enigmatic features of gravel waves reported from modern submarine fans worldwide.

AN ANCIENT CANYON FILL

A lower Pleistocene canyon-fill succession is well exposed on the western Boso Peninsula, Japan. The infill is named the Higashihigasa Formation and represents a unit in the lower part of the Kazusa Group (Figs. 1, 2), which developed in the Kazusa forearc basin during 2.4 Ma through 0.45 Ma in response to the west-northwestward subduction of the Pacific plate beneath the Eurasia plate at the Izu–Bonin Trench (Katsura 1984; Ito and Masuda 1988) (Fig. 1A). The Higashihigasa Formation consists mainly of coarse-grained siliciclastic sediments, such as conglomerates, pebbly sandstones, and medium- to very coarse-grained sandstones, with local intercalations of muddy slumped deposits, and is up to 150 m in maximum thickness (Sato and Koike 1957; Yamauchi et al. 1990) (Figs. 3, 4, 5). Overall, these coarse-grained deposits were interpreted to be products of high-density turbidity currents (*sensu* Lowe 1982) (Katsura 1984; Yamauchi et al. 1990). These coarse-grained deposits laterally fine in the northeastern downslope direction and intertongue with a submarine-fan succession defined as the Umegase Formation (Katsura 1984; Ito 1998) (Figs. 1, 2). The Higashihigasa Formation unconformably overlies the Tomiya and Takamizo formations and gradationally fines upward to the Awakura Formation (Fig. 2). The Tomiya and Takamizo formations consist mainly of moderately and locally intensely bioturbated sandy siltstones intercalated with medium- to very fine-grained, lenticular sandstones (beds 2–20 cm thick). These formations are also characterized by intercalations of slumped deposits and contorted siltstones, associated with slump scars, and are interpreted to be slope and shelf-margin deposits (Katsura 1984; Ito and Katsura 1992). The overlying Awakura Formation is characterized by intensely bioturbated sandy siltstones and silty sandstones, which are intercalated with fine- to very fine-grained, sandstones (beds 1–10 cm thick) with parallel and/or current-ripple lamination, and is interpreted to be upper-slope to outer-shelf deposits (Katsura 1984; Ito and Katsura 1992). Furthermore, marine faunas from the Tomiya, Takamizo, and Awakura formations indicate that paleowater depth is 200–700 m and deepens to the northeast (Baba 1990; Kitazato 1997). Thus, the paleocanyon incised slope and shelf-margin deposits and is interpreted to have acted as a conduit for northeastward-flowing turbidity currents and other types of sediment gravity flows from which submarine-fan successions defined as the Umegase Formation and the underlying Otadai Formation (ca. 0.9–1.1 Ma) were formed (Hirayama and Nakajima 1977) (Figs. 1, 2). Because the paleodepth of these adjacent outer-shelf and slope deposits deepens about 500 m within about an 8 km distance to the downslope direction, the mean gradient of the paleoslope can be estimated at 3–4° and the mean gradient of the paleocanyon is interpreted to have been steeper than this value.

The paleocanyon walls are locally steeply inclined associated with step-like terraces (Fig. 4A). On the basis of the distribution pattern of the Higashihigasa Formation, the paleocanyon is estimated at 8 km long and 1 km in maximum width (inset map in Fig. 3). The paleocanyon shows a bifurcated pattern in the upper reach and is characterized by a sinuosity of about 1.1. On the basis of thickness of the infills of the paleocanyon (Fig. 3), the wall of the paleocanyon is interpreted to have been more than 100 m high. Because a synclinal structure developed along the infill of the paleocanyon, associated with an anticlinal structure in the adjacent slope deposits (inset map in Fig. 3), the development of the paleocanyon was interpreted to have been controlled by tectonic movements of the southwestern margin of the Kazusa forearc basin (Yamauchi et al. 1990). The incision of the slope and shelf-margin deposits and the supply of coarse-grained sediments to the paleocanyon were interpreted to have responded to several lowstand stages of glacioeustasy during the early Pleistocene (Katsura 1984; Ito and Katsura 1992). The coarse-grained paleocanyon-fill succession discussed in this paper changes laterally into the inner-fan deposits of the Umegase Formation (Katsura 1984; Ito and Katsura 1992) in the northeastern, downslope direction and is interpreted to have developed in a canyon-mouth environment.

COARSE-GRAINED BEDFORMS

Coarse-grained deposits of the Higashihigasa Formation are characterized by successions of couplets of conglomerates and overlying pebbly

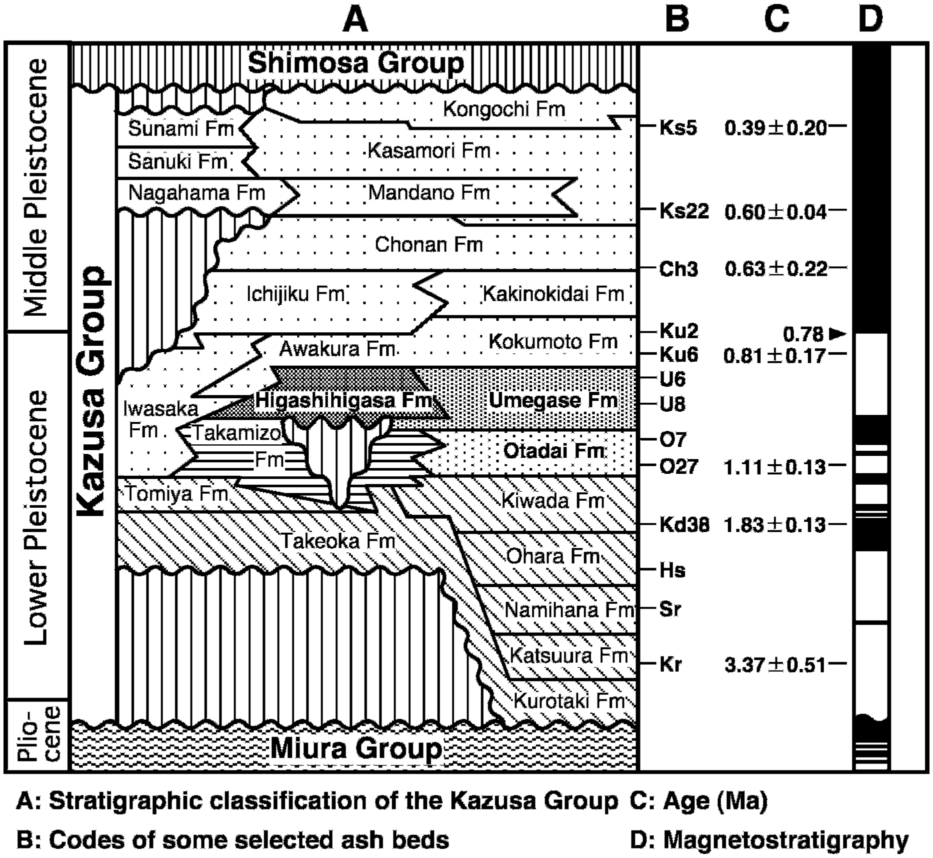

FIG. 2.—Stratigraphy of the Kazusa Group. Slightly modified from Horikawa and Ito (2004). See Ito (1992) and Horikawa and Ito (2004) for data sources.

sandstones and medium- to very coarse-grained sandstones, exhibiting fining-upward patterns 2–5 m thick (Figs. 4B, 6). Repetitions of these fining-upward units constitute larger-scale fining-upward cycles up to 50 m in thickness and are defined by distinct erosional bases scoured up to 10 m deep (Figs. 3, 4B, 7). Conglomerates commonly contain sandy siltstone clasts (up to more than 190 cm in maximum diameter) derived from adjacent slope and shelf-margin deposits (Figs. 4A, 5, 7) and also locally contain molluscan shell fragments, which include brackish and shallow marine faunas (Sato and Koike 1957; Baba 1990) (Fig. 8A).

In general, conglomerates consist of pebble-size clasts and are poorly sorted (Fig. 9). Normally graded, clast-supported texture is common and contains very coarse sandstones and granules as a matrix. Imbrication is well developed associated with trough and planar cross-stratification (Fig. 8A). This cross stratification indicates the mean paleocurrent directions to the northeast (Fig. 3). The bases of conglomerate beds are erosional and locally associated with distinct erosional structures such as large groove-like (ca. 5 m wide and 1.5 m deep) and flute-like (ca. 10 m long and 2 m deep) scours (Fig. 7). These erosional structures are overlain by poorly sorted conglomerates, which contain many sandy siltstone clasts (Fig. 7). In general, cross-stratified conglomerates do not necessarily exhibit the surface geometry of bedforms because of the incision of overlying units and/or to the limitation of outcrops compared with the bedform size (Fig. 4B). In some well-exposed sections, in contrast, these cross-stratified conglomerates exhibit wave-like, asymmetrically undulated upper surfaces 10–63 m long and 0.6–2.2 m in relief (Figs. 6A, 8B, 10), and are characterized by climbing forms (Fig. 6A) similar to the type B climbing-ripple cross-lamination of Jopling and Walker (1968), although the climbing forms are locally associated with distinct foreset bedding (Fig. 6B). The geometry of the wave-like forms can also be described in terms of the symmetry index (i.e., stoss-side length divided by lee-side length), which has been used for distinguishing wave ripples and current ripples (Tanner 1967). The index calculated from the wave-like forms of the conglomerates is in the range of 1.2 to 2.1. Conglomerate beds fine gradationally upward to pebbly sandstones, which are characterized by undulating planar stratification draping over the underlying wave-like forms of conglomerate beds (Figs. 6A, 8B). These pebbly sandstones exhibit features similar to the sinusoidal stratification of Jopling and Walker (1968). These sinusoidally stratified pebbly sandstones pass upward to medium- to very coarse-grained sandstones (Fig. 8B). In general, sandstones are better sorted than the underlying pebbly sandstones and conglomerates and are massive or weakly normally graded (Fig. 9). However, tractional sedimentary structures are not developed in the sandstone beds and convolute bedding is commonly associated with dish structures in places (Fig. 6A, 8B).

GENERATION OF GRAVEL WAVES

Erosional bases of conglomerate beds indicate scoring processes by turbulent flows that operated during the formation of coarse-grained,

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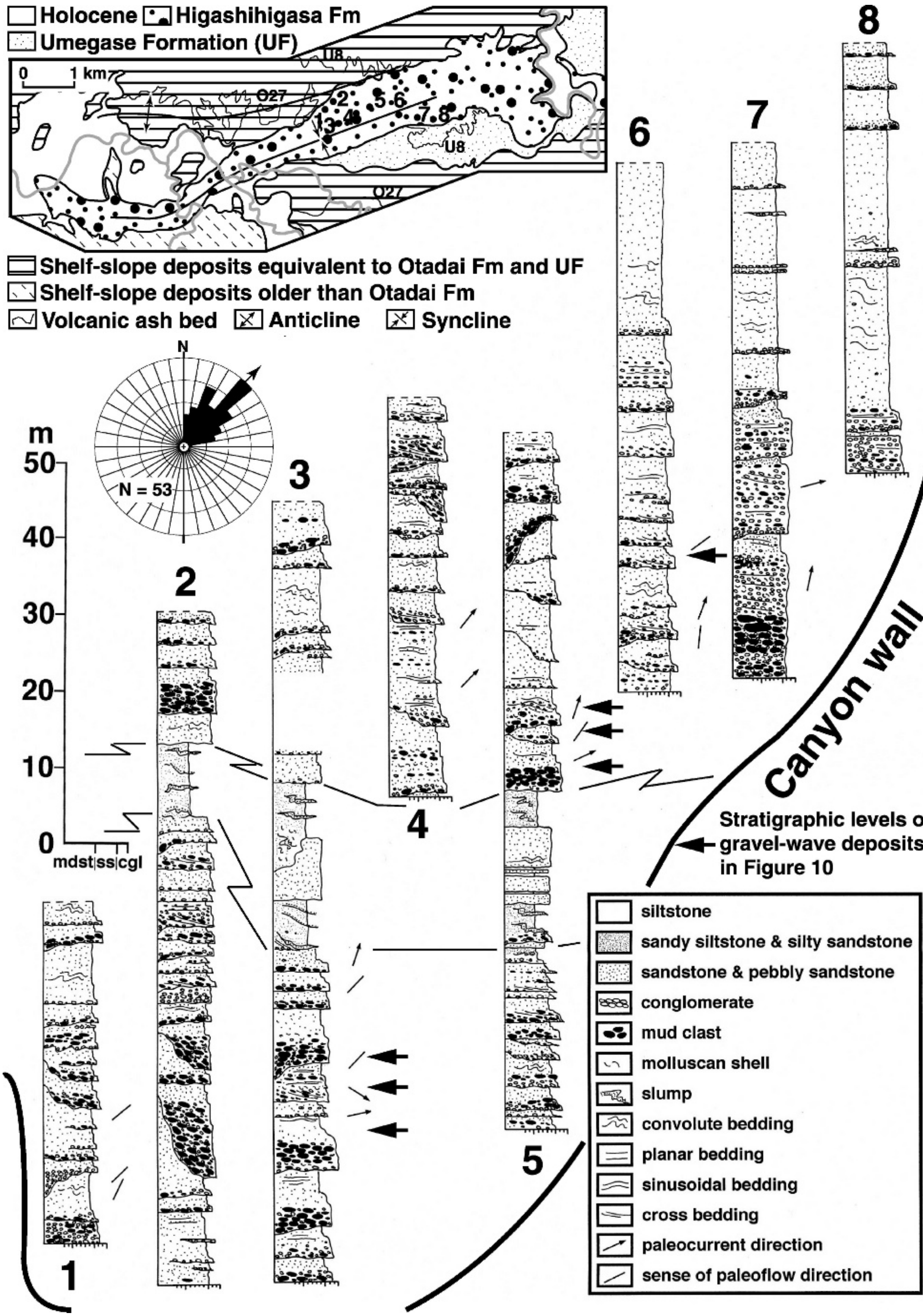
FIG. 3.—Measured sections of paleocanyon-fill deposits of the Higashihigasa Formation. Inset map shows locations of measured sections and distribution of paleocanyon-fill and adjacent deposits (modified from Sato and Koike 1957; Yamauchi et al. 1990). Thin dashed lines indicate distribution of slumped deposits. Rose diagram indicates paleocurrent directions measured from dip directions of cross-bedding planes. A solid arrow indicates the mean paleocurrent direction, and N is the number of measurements.


Holocene
Higashihigasa Fm
Umegase Formation (UF)
0 1 km
U8
O27
Shelf-slope deposits equivalent to Otadai Fm and UF
Shelf-slope deposits older than Otadai Fm
Volcanic ash bed
Anticline
Syncline
N
N = 53
m
50
40
30
20
10
0
mdst|ss|cgl
1
2
3
4
5
6
7
8
Canyon wall
Stratigraphic levels of gravel-wave deposits in Figure 10
siltstone
sandy siltstone & silty sandstone
sandstone & pebbly sandstone
conglomerate
mud clast
molluscan shell
slump
convolute bedding
planar bedding
sinusoidal bedding
cross bedding
paleocurrent direction
sense of paleoflow direction

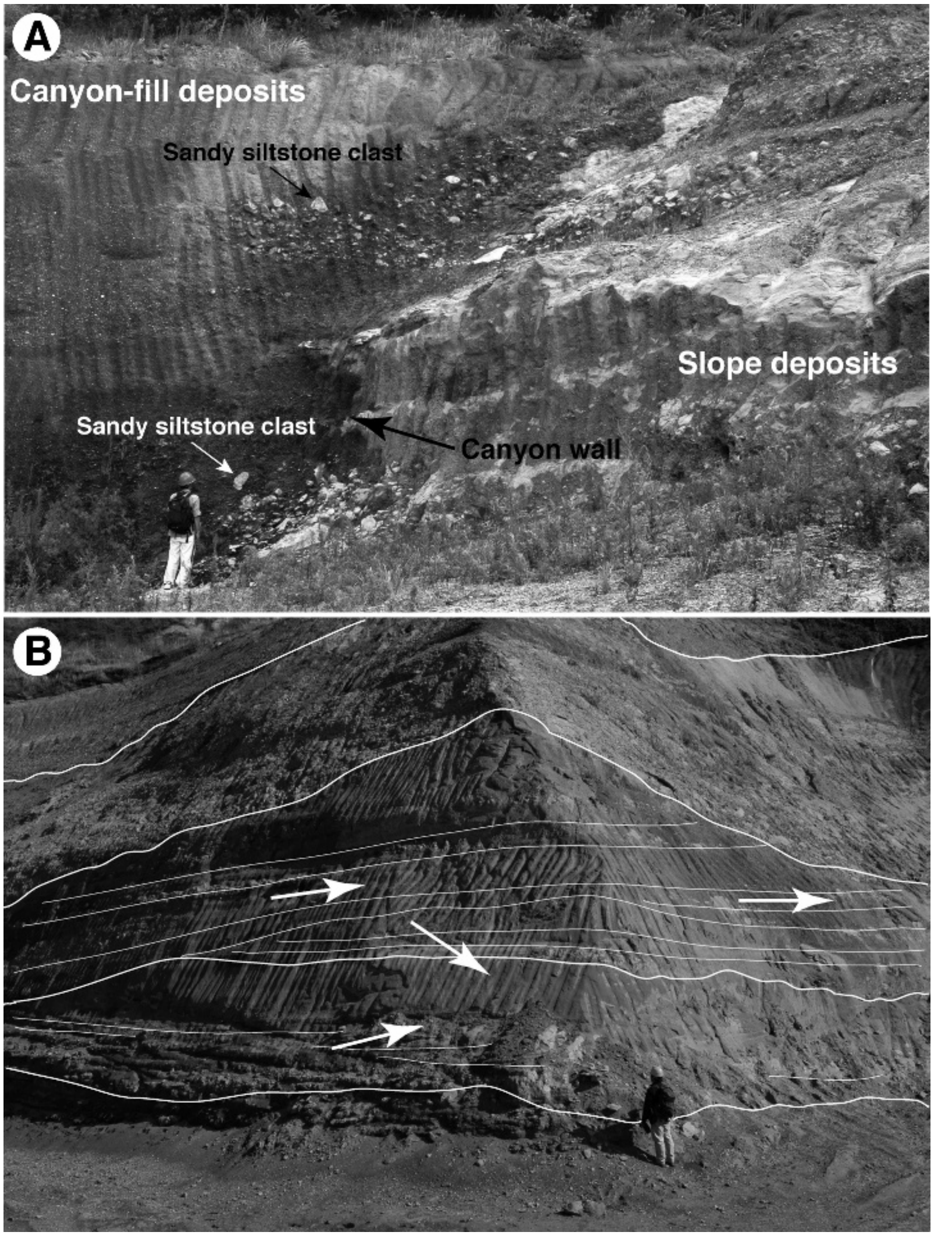


FIG. 4.—**A**) Steeply inclined canyon wall and coarse-grained canyon-fill deposits of the Higashihigasa Formation at location 6 in Figure 3. Figure for scale. **B**) Stacked couplets of conglomerates and overlying sandstones with distinct erosional basal surfaces (solid lines) at location 3 in Figure 3. Thin solid lines indicate cross stratification in conglomerates and pebbly sandstones. Arrows indicate paleocurrent directions (north is up) reconstructed from inclined directions of cross-stratified bedding planes.

cross-stratified deposits (Winn and Dott 1979). Large-scale erosional features, such as groove-like and flute-like scours have been reported from modern deep-water environments, in particular from channel-lobe transitional zones and channel and canyon floors (Morris et al. 1998; Wynn et al. 2002b). Although these modern erosional scours are, in general, larger than erosional structures observed in the Higashihigasa Formation, except for some scours with size largely similar to the present ancient examples (Prior and Bornhold 1989; Carlson et al. 1992), these modern examples are commonly associated with large coarse-grained bedforms and are interpreted to be formed by strong turbidity currents (Morris et al. 1998; Wynn et al. 200b). Thus, poorly sorted conglomerates, which contain many sandy siltstone clasts and infill the erosional structures, are also interpreted to be deposits of high-density turbidity currents in the sense of Lowe (1982).

The wave-like, asymmetrical external geometry of cross-stratified conglomerate bodies is interpreted to represent cross-sectional features of coarse-grained bedforms analogous to gravel waves reported from modern submarine fans and submarine channels in terms of texture, geometry, and size (Normark and Piper 1991; Wynn et al. 2002a), although some are smaller than modern examples (Fig. 10). Climbing forms of the cross-stratification, downslope-directed paleocurrents, and sinusoidal stratification indicate that gravel waves developed as climbing dunes under subcritical flow conditions. That is, the gravel-wave deposits are interpreted to have been generated under conditions in which the rate of deposition of suspended load successively increased compared with that of traction load (cf. Jopling and Walker 1968). Alternatively, the wave-like geometry of the conglomerate bodies, which is characterized by smaller values of the symmetry index, and the overlying sinusoidally stratified pebbly sandstones, are interpreted to be a product of a transitional flow condition between in-phase standing waves and subcritical flows. Therefore, the gravel waves developed in the paleocanyon are interpreted to have initially been formed beneath steady or quasi-steady gravelly high-density turbidity currents (Lowe 1982) or high-concentration gravity flows (Mulder and Alexander 2001).

FIG. 5.—Slumped deposits intercalated in a coarse-grained paleocanyon-fill succession at location 5 in Figure 3. The solid line indicates an erosional basal surface of the overlying pebbly sandstones.

A tidal process is a possible alternative mechanism for developing the cross-stratified conglomerates in the paleocanyon. In general, speeds of tidal currents measured in modern canyons are in the range of 20–50 cm/s (Shepard and Marshal 1978). However, mean current speeds that are required to develop dunes with a median sediment size of about 5 mm, which are similar to the present examples (Fig. 9), need to be up to 80 cm/s or more (Carling 1999). Furthermore, paleocurrent reversal and double mud layers, which are believed to be diagnostic features of

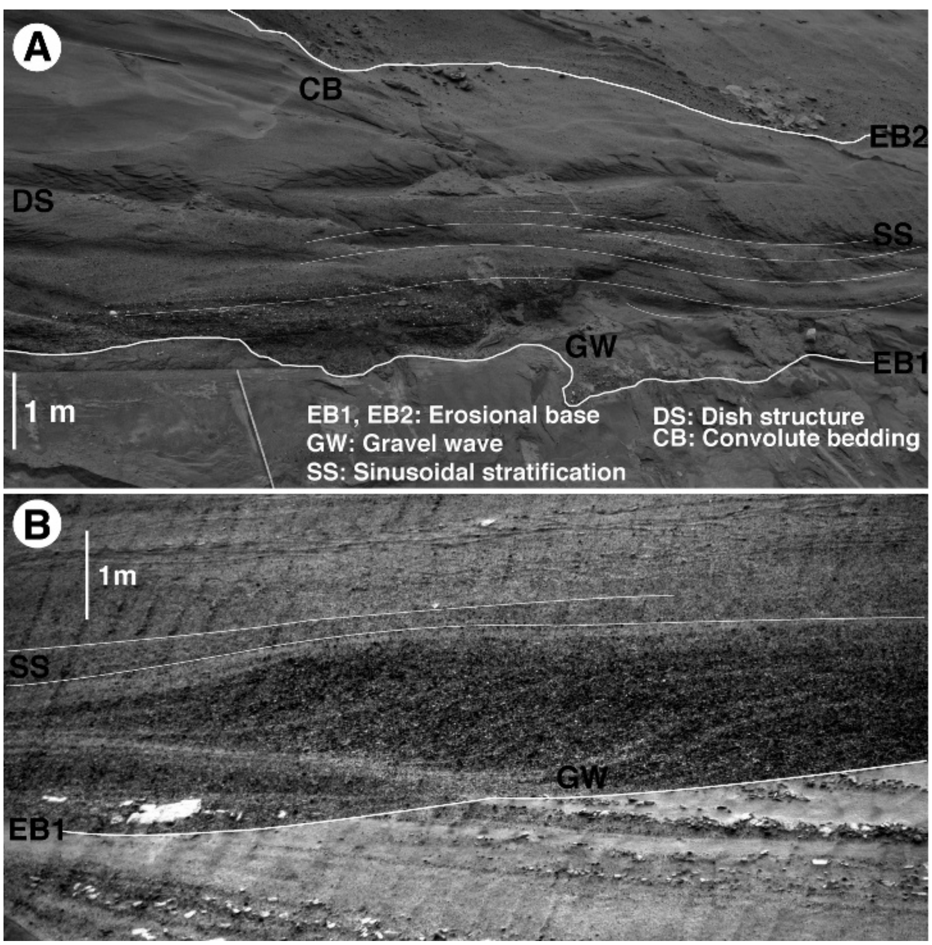


FIG. 6.—**A**) An outcrop example of gravel-wave deposits in the paleocanyon-fill succession at location 5 in Figure 3. Paleocurrents are to the right. **B**) Foreset bedding in the lee side of gravel-wave deposits at location 5 in Figure 3. An erosional base EB1 corresponds to that in Part A. See Part A for the other abbreviations.

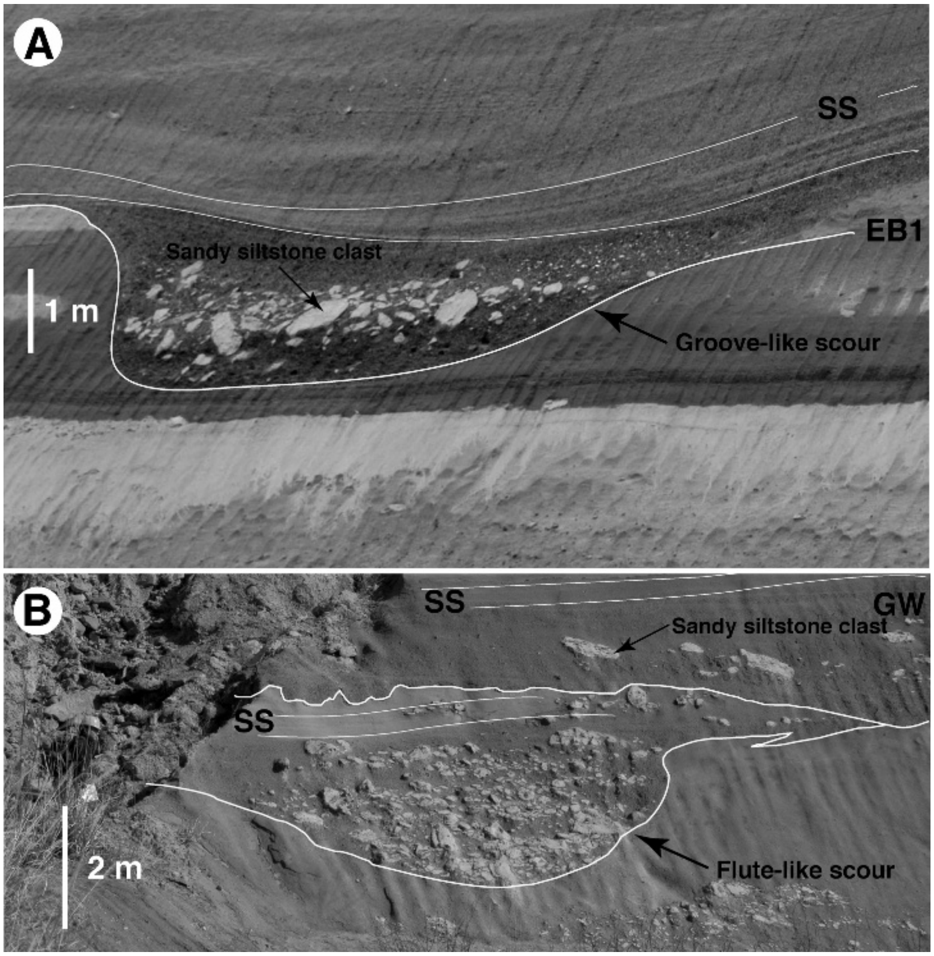


FIG. 7.—**A**) A groove-like scour at a base of gravel-wave deposits at location 5 in Figure 3. This outcrop is largely orthogonal to paleocurrent directions in the northeast, and the scour is mapped more than 50 m in the upslope direction. An erosional base EB1 corresponds to that in Figure 6. **B**) A large flute-like scour at a base of gravel-wave deposits at location 4 in Figure 3. Paleocurrents are to the left. See Figure 6 for abbreviations.

deep-water tidal sands (Shanmugam 2003), are not observed in the present examples. Thus, tidal currents are not interpreted to have been responsible for the formation of cross-stratified conglomerates in the paleocanyon.

The transition from sinusoidally stratified pebbly sandstones to overlying medium- to very coarse-grained sandstones is interpreted as a response to the increase in sedimentation rate from suspension (Lowe 1982; Arnott and Hand 1989). Convolute bedding and dish structures in the sandstone beds also indicate the acceleration of fallout rates of suspended loads from high-density turbidity currents (Lowe 1982), which may have inhibited the development of any tractional sedimentary structures, although Leclair and Arnott (2005) claimed that parallel lamination was formed even at high aggradation rates from high-density turbidity currents. Because the wave forms of the coarse-grained deposits fine gradationally upward to medium- to very coarse-grained pebbly sandstones and sandstones (Figs. 6A, 8B, 9), this lithofacies change does not exhibit any evidence of reworking and molding by subsequent lower-concentration turbulent flows in the single depositional events. Furthermore, the deposition of sandstone drapes over the gravel-wave deposits may have played an important role for excluding any postdepositional modification by later turbidity currents. These overlying sandstone beds are interpreted to be equivalent to sand ribbons and sand patches observed in modern submarine fans (Wynn et al. 2002a).

DISCUSSION

This study has attempted to answer several questions about the internal organization and formative processes of gravel waves on the basis of detailed outcrop analyses of wave-like forms of coarse-grained deposits, which are characterized by texture, size, and geometry to be analogous to gravel waves documented from modern submarine fans. The internal organization of the wave forms is characterized by trough and planar cross-stratification, which indicate downslope migration of large dunes under subcritical flow conditions. This feature is equivalent to large cross-bedded conglomerates reported by Winn and Dott (1979) and Beaubouef (2004), although their outcrop examples do not exhibit wave-like surface geometry because of the limitation of outcrops compared with the bedform size of about 4 m high. Although the ancient examples of gravel-wave deposits interpreted by Piper and Kontopoulos (1994) are characterized by wave-like surface relief similar in size to the present examples (Fig. 10), these deposits generally lack tractional sedimentary structures and exhibit internal features similar to those described from gravel waves in the modern Laurentian Fan (Hughes Clark et al. 1990). Thus, the generation of these ancient and modern gravel waves was interpreted from the standpoint that high-density turbidity currents simply supplied coarse-grained sediments and their surface relief was reshaped by the subsequent lower-concentration turbulent flows in a single depositional event (Piper and Kontopoulos 1994). Although reshaping of upper surfaces of generally massive coarse-grained deposits into the wave forms by the subsequent lower-concentration turbulent flows has also been suggested for the origin of modern gravel waves (Wynn et al. 2002a), the present examples of ancient gravel-wave deposits are interpreted to have been developed initially as dune-like traction-sedimentation bedforms from steady or quasi-steady gravelly high-density turbidity currents and do not

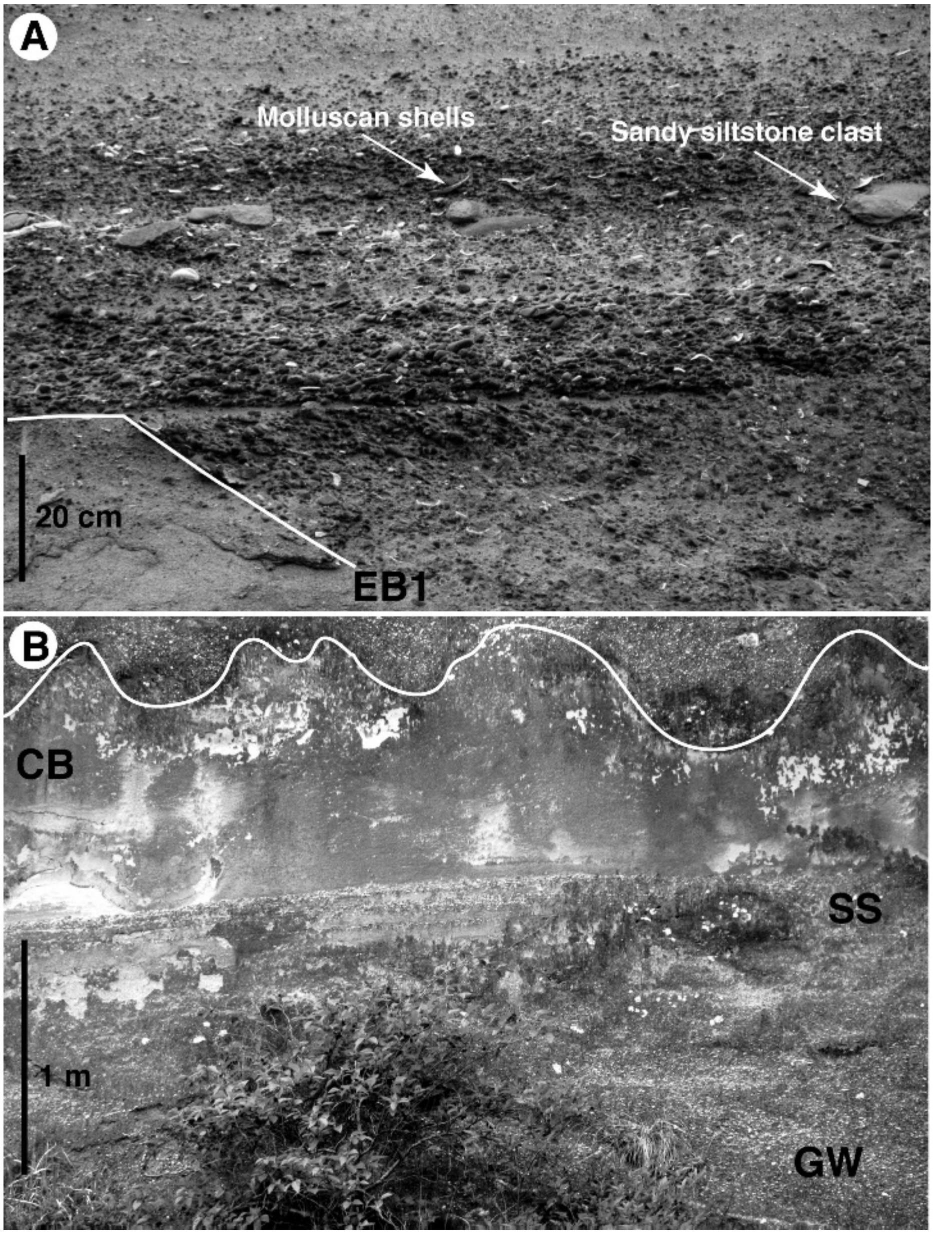


FIG. 8.—**A**) Close-up of the stoss side of gravel-wave deposits in Figure 6A. This conglomerate bed is characterized by clast imbrication, associated with imbricated sandy siltstone clasts and molluscan shell fragments. An erosional base EB1 corresponds to that in Figure 6A and B. Paleocurrents are to the right. **B**) Close-up of sinusoidally stratified pebbly sandstones that gradationally fine upward to medium- to very coarse-grained sandstones with convolute bedding at location 6 in Figure 3. See Figure 6 for abbreviations.

document any evidence of reworking and reshaping of the coarse-grained deposits by subsequent lower-density turbidity currents from which sandstone beds equivalent to the S3 division of Lowe (1982) were successively deposited. Thus, the present examples from the paleocanyon-fill succession indicate that different types of geometry and internal organization of gravel-wave deposits may have developed in a deep-water environment in response to variations in volumes, speeds, and densities of sediment gravity flows.

CONCLUSIONS

Cross-stratified pebble conglomerates in a lower Pleistocene paleocanyon-fill succession exposed on the Boso Peninsula of Japan exhibit wave-like, asymmetrically undulated upper surfaces similar to some gravel waves on modern submarine-fan systems in terms of texture, size, and geometry, although modern gravel waves are, in general, larger than the present examples and some limited lithofacies data from modern gravel waves are characterized by coarser and disorganized textures as discussed above. Gravel-wave deposits identified in the paleocanyon succession are interpreted to have been formed as traction-sedimentation bedforms that migrated in the downslope direction under gravelly, high-density turbidity currents, and are gradationally overlain by weakly graded sandstones from sandy high-density turbidity currents in single depositional events. Thus, the present examples indicate that the wave forms were not a result of erosion and reshaping of coarse-grained deposits by subsequent lower-density turbulent flows within single or later depositional events, although later modification of the bedforms by subsequent lower-density turbidity currents cannot be excluded for gravel waves in modern submarine fans. The outcome of this study can contribute to the better understanding of the depositional dynamics, which has been responsible for spatial and temporal variations in sediment types and bedforms in a submarine-fan system. In particular, the present examples can fill the gap in dimensions and formative processes between cross-stratified sandstones and conglomerates, which

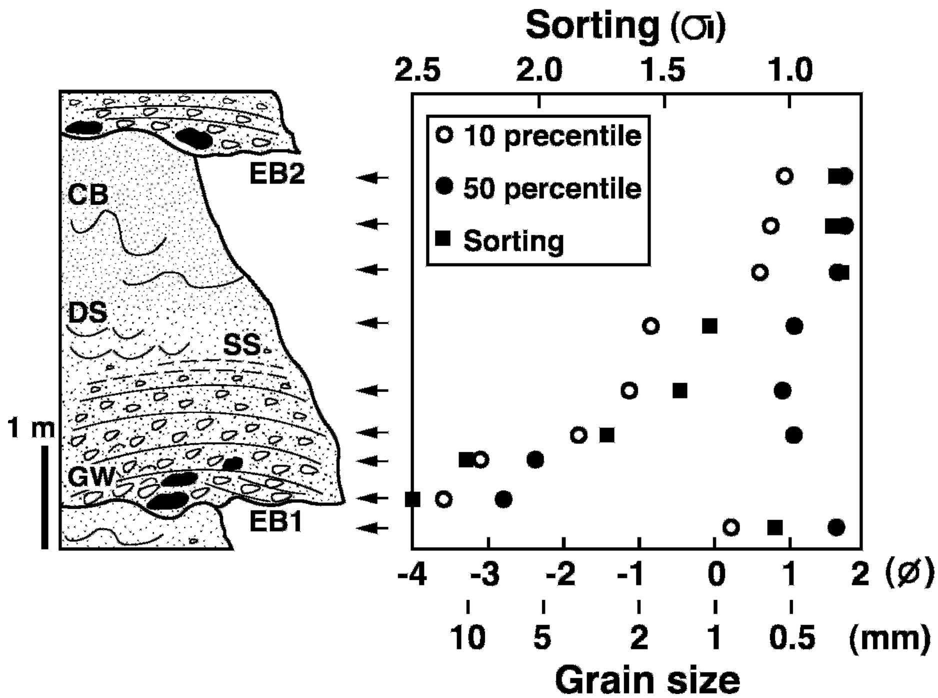


FIG. 9.—Textural features of a couplet of gravel-wave deposits and overlying pebbly sandstones and sandstones given in Figure 6A. EB1 and EB2 correspond to erosional bases in Figure 6A. See Figure 6A for other abbreviations. Solid arrows on the right side of column indicate positions for samples. Grain sizes were analyzed by standard sieves.

have commonly been reported from ancient turbidite successions, and the modern large-scale gravel waves in terms of a spectrum of sediment-gravity-flow processes for the development of coarse-grained bedforms in a deep-water environment.

ACKNOWLEDGMENTS

This research was supported in part by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (no. 15340166). We acknowledge the quarrying companies at the study area for their kind cooperation in investigating outcrops. We would like to thank C. Busby, P. Clift, and P.G. DeCelles for their valuable comments on an early version of the manuscript. Subsequently the manuscript received the benefit of many constructive comments by D.J.W. Piper, R.B. Wynn, D.G. Masson, C.P. North, and J.B. Southard.

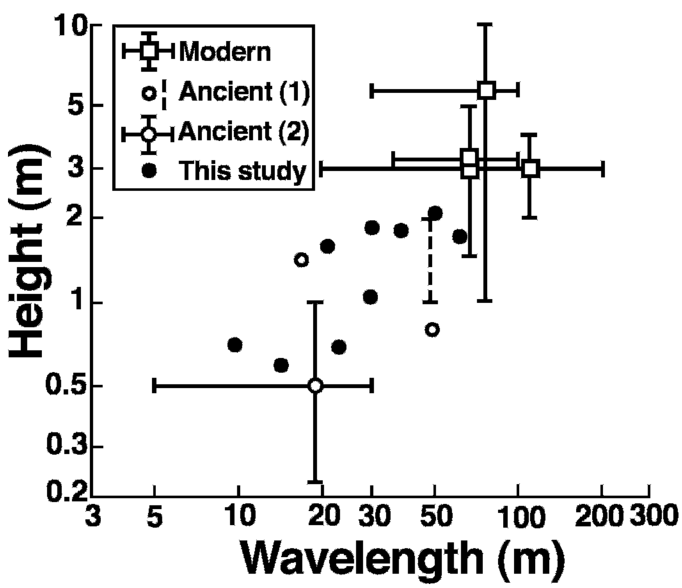


FIG. 10.— Dimension of modern and ancient gravel waves. The vertical and horizontal bars are ranges of data. Modern data are from Malinverno et al. (1988), Normark and Piper (1991), and Wynn et al. (2002a), and ancient data are from (1) Piper and Kontopoulos (1994) and (2) Vicente Bravo and Robles (1995).

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Received 31 March 2005; accepted 11 March 2006.