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Thematic Article

Fourth- to third-order cycles in the Hakobuchi Formation: Shallow-marine Campanian final deposition of the Yezo Group, Nakagawa area, northern Hokkaido, Japan

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Abstract The Yezo Group has a wide longitudinal distribution across Hokkaido, northern Japan. It represents a Cretaceous (Early Aptian–Late Maastrichtian) and Late Paleocene forearc basin-fill along the eastern margin of the paleo-Asian continent. In the Nakagawa area of northern Hokkaido, the uppermost part of the Yezo Group consists of the Hakobuchi Formation. Along the western margin of the Yezo basin, 24 sedimentary facies (F) represent 6 facies associations (FA), suggesting prevailing storm-dominated inner shelf to shoreface environments, subordinately associated with shoreface sand ridges, outer shelf, estuary and fluvial environments. The stacking patterns, thickness and facies trends of these associations allow the discrimination of six depositional sequences (DS). Inoceramids *Sphenoceramus schmidti* and *Inoceramus balticus*, and the ammonite *Metaplacenticeras subtilistriatum*, provide late Early to Late Campanian age constraints to this approximately 370-m thick final stage of deposition and uplift of the Yezo forearc basin. Six shallow-marine to subordinately non-marine sandstone-dominated depositional sequences include four 10 to 110-m thick upward-coarsening regressive successions (FS1), occasionally associated with thin, less than 10-m thick, upward-fining transgressive successions (FS2). The lower DS1–3, middle DS4–5 and upper DS6 represent three depositional sequence sets (DSS1–3). These eastward prograding and westward retrograding recurring shallow-marine depositional systems may reflect third- and fourth-order relative sealevel changes, in terms of sequence stratigraphy.

Key words: Campanian, Cretaceous, depositional sequence, Hokkaido, sequence stratigraphy, shallow-marine sediments, Yezo forearc basin, Yezo Group.

INTRODUCTION

The Cretaceous to Paleocene offshore marine to paralic sediments that extend from southern Sakhalin to the Pacific coastal areas of northern Honshu represent the offshore deposition of the Yezo forearc basin that crosses central Hokkaido, extending over 1400 km in a north–south direction (Ando 2003). Because the strata of the basin were not subjected to intense diagenesis and tectonic deformation in comparison with contemporaneous accretionary complexes further east (Ueda & Miyashita 2005), they preserve good geohistorical information on the sedimentary facies of their successions, including micro- and mega-fossils and others. This fossil forearc strata, widely exposed along the Sorachi–Yezo Belt in the longitudinal median zone of Hokkaido, is called the Yezo Group (e.g. Okada 1983; Ando 2003; Ando & Tomosugi 2005; Ando *et al.* 2006) (Fig. 1).

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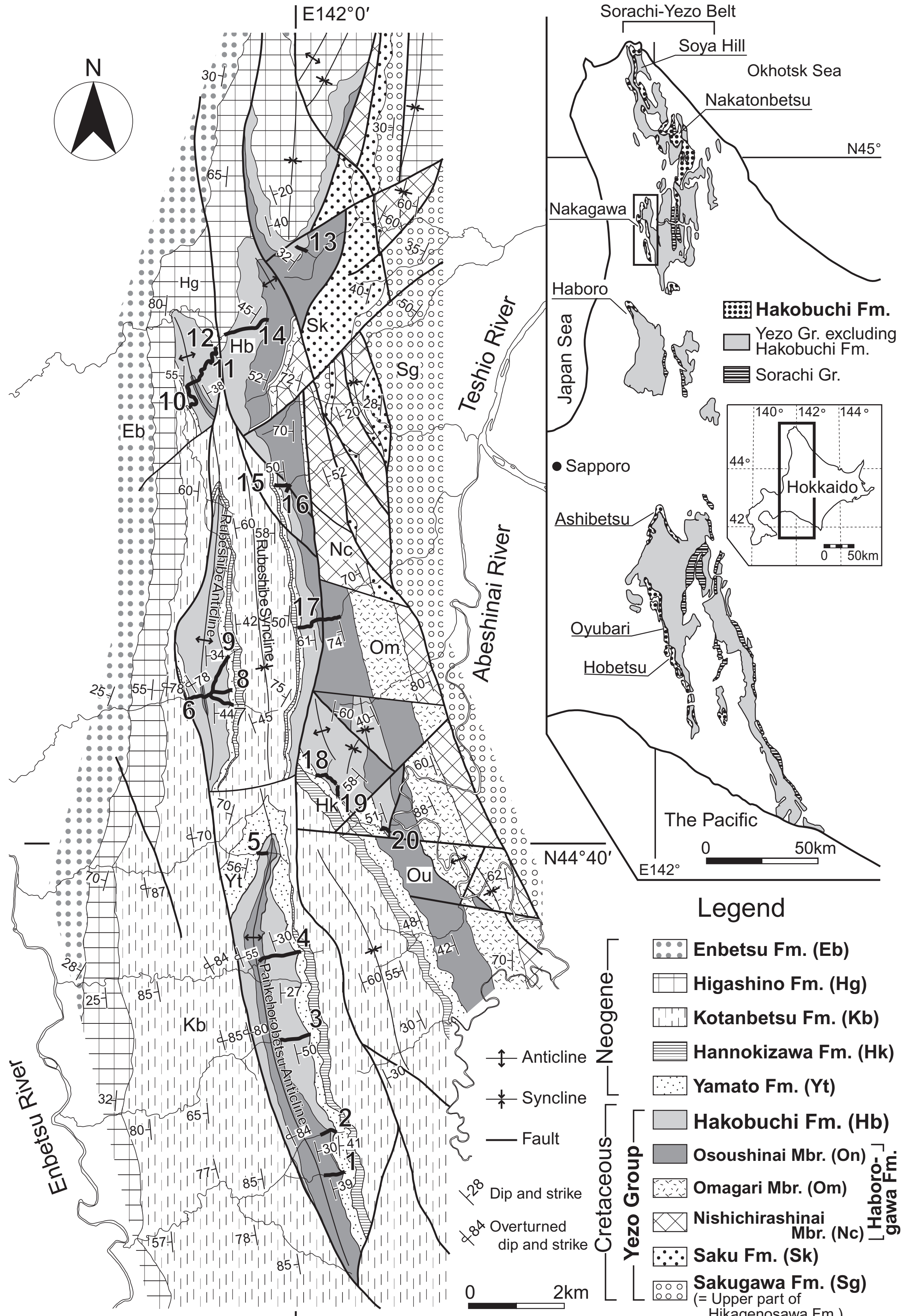


Fig. 1 Geological map of the Nakagawa area, northern Hokkaido. Inset map shows the distribution of the Yezo Group and the locations of well-exposed areas of the Hakobuchi Formation in the Sorachi–Yezo Belt of Hokkaido. The geological map is compiled from Osanai *et al*. (1960), Hata (1961), Nagao (1962), Hata and Tsushima (1969), Takahashi *et al*. (2003) and data of this study.

Although the Yezo Group is dominantly an offshore marine muddy facies, its uppermost unit, the Hakobuchi Formation, is characterized by a western marginal shallow-marine to fluvial sandstone and mudstone with conglomeratic layers. The Hakobuchi Formation extends in the central western part of the Sorachi–Yezo Belt, namely the Ashibetsu (Ando 1993, 1997), Oyubari, and Hobetsu areas (Ando 2003). Also exposed in the Soya hill (Ando and Ando 2002), Nakagawa, and Nakatonbetsu areas of the northern Sorachi–Yezo Belt, the offshore sandy mudstone facies dominates in the Nakatonbetsu area, which is geographically further east (Ando *et al.* 2001; Ando & Tomosugi 2005).

Stratigraphical and lateral facies changes make the Hakobuchi Formation suitable for high-resolution facies and sequence stratigraphical analyses. Macro- and microfossil biostratigraphical evidence such as ammonites, inoceramids, foraminifers, dinoflagellates, and pollens witness a large-scale shallowing facies transition from the Lower Campanian to the Maastrichtian, separated from the Upper Paleocene by a hiatus of the uppermost Maastrichtian to lower Paleocene, throughout the entire basin. This sandy sedimentation seems to represent the last filling stage of the Yezo forearc basin and may have reflected the plate tectonic movements such as the directional change in the relative motion of the Kula–Izanagi Plate (Ando 2003). The Hakobuchi Formation nearly corresponds to the Krasnoyarka Formation in south Sakhalin (e.g. Kodama *et al.* 2002; Maeda *et al.* 2005).

The purpose of this paper is to describe the repetitive depositional sequences that are well developed in the Hakobuchi Formation of the Nakagawa area in northern Hokkaido, using the sedimentary facies successions, their distribution and sequence stratigraphic correlation. It delineates the sedimentary history of the Campanian siliciclastic shallow-marine systems including shoreface-shelf and subordinate estuary-fluvial facies in the western margin of the Yezo forearc basin.

GEOLOGIC SETTING

The Nakagawa area, northern Hokkaido, is a classical region of Japanese Cretaceous biostratigraphy. Since Matsumoto's (1942, 1943) pioneering work, its importance is substantiated by its abundance of well-preserved megafossils. The area is located in the western limb of the anticlinorium formed by the axial Upper Jurassic to Lower Cretaceous Sorachi Group and serpentinite mélanges, and the overlying post-Barremian Cretaceous Yezo Group (e.g. Kawaguchi 1997). The Yezo Group in the Nakagawa area is generally characterized by a north–south striking and westward-facing structure (Matsumoto 1942; Nagao 1962; Takahashi *et al.* 2003; Fig. 1).

The nomenclature of lithostratigraphic divisions of the Yezo Group is complicated and differs among authors and areas, as reviewed by Ando (2003), Takashima *et al.* (2004), Ando and Tomosugi (2005) and Ando *et al.* (2006). Takashima *et al.* (2004) proposed a synthesized stratigraphic scheme based on extensive mapping, and macro- and microfossil biostratigraphy in the central region of the Sorachi–Yezo Belt, Hokkaido. They redefined nine formations, basically characterized by alternations of mudstone-dominant units and sandstone-common units, with intercalations of six distinct stratigraphic key units. These are: (i) Soashibetsugawa (mudstone unit); (ii) Shuparogawa (sandstone-dominant turbidite unit); (iii) Maruyama (felsic tuff and tuffaceous sandstone unit) and (iv) Hikagenosawa (mudstone-dominant unit) Formations (Aptian–Albian); (v) the Saku (sandstone-common turbidite unit) and (vi) Kashima (mudstone unit) Formations (uppermost Albian to lower Campanian); and (vii) the Hakobuchi (shallow-marine sandstone unit) Formation (Lower Campanian–Paleocene). Additionally: (viii) the Mikasa (shallow-marine sandstone unit); and (ix) Haborogawa (sandy mudstone unit) Formations represent westerly shallower facies of the Saku and Kashima Formations, respectively.

On the other hand, the previous researchers named the stratigraphic units of the uppermost part of the Yezo Group in the Nakagawa area differently (e.g. Hakobuchi Group, Yasukawa Group, Yasukawa Formation of the Hakobuchi Group). As this paper follows Takashima *et al.*'s (2004) scheme, the three local lithostratigraphic units underlying the Hakobuchi Formation, the Nishichirashinai, Omagari, and Osoushinai Formations (e.g. Takahashi *et al.* 2003), equivalent to the Haborogawa Formation of Takashima *et al.* (2004), are demoted to members of the Haborogawa Formation in ascending order (Fig. 2).

The Hakobuchi Formation of the Nakagawa area represents the western margin of the Cretaceous strata that consists of a set of folds with north–south striking axes, the Rubeshibe syncline, the Rubeshibe anticline and Pankehorobetsu anti-

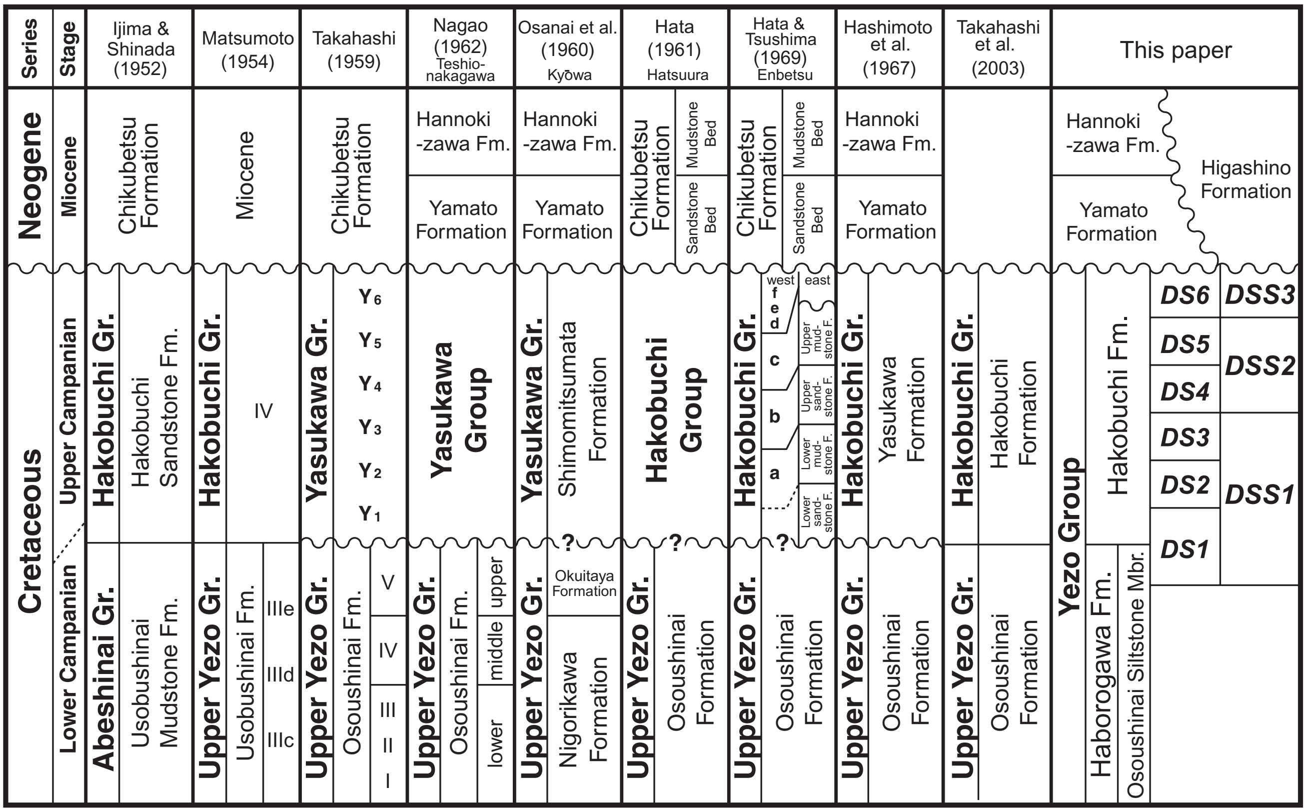


Fig. 2 Comparison of stratigraphic divisions for the upper part of the Yezo Group in the Nakagawa area.

cline. As a result, the Hakobuchi Formation is exposed several times along the valleys crossing the structure in mostly a east–west direction. Our study counts a total of 18 sections within a mountainous area of less than 5 km of east–west width and 20 km in north–south length (Fig. 1).

The Hakobuchi Formation gradually and conformably overlies the Osoushinai Siltstone Member of the Haborogawa Formation, and unconformably underlies the Miocene Yamato or Higashino Formation. The Osoushinai Siltstone Member is characterized by offshore to shallow-marine, gray to dark gray siltstone to sandy siltstone. It reaches over 600 m in thickness. The upper part shows a coarsening-upward and progressively bioturbated facies trend. The ammonite species *Canadoceras kossmati* and inoceramid shells such as *Sphenoceramus schmidti* and their fragments are common. The uppermost part grades into sandier, more massive siltstone. On the other hand, the Hakobuchi Formation is dominated by shallow-marine, greenish gray to bluish gray fine- to medium-grained sandstone and intercalated with dark gray sandy siltstone, coarse-grained sandstone, and thin layers of conglomerate. Its thickness reaches 350 m at the most, although it is variable according to the degree of erosion below the unconformity to the overlying Neogene. The formation is generally tuffaceous and often includes pumice grains, and carbonaceous plant grains and fragments. Medium- to coarse-grained sandstones are often poorly sorted and massive; granule grains are common. However, trough planar and low-angle cross-stratification is developed in well- to medium-sorted sandstones in several horizons. Although fine-grained sandstones are often massive and bioturbated, hummocky cross- and parallel-stratifications are also common in some horizons. Hummocky cross-stratified (HCS) fine-grained sandstones of a few tens of centimeters thick sometimes alternate with sandy siltstones of various thicknesses. Thin or lenticular coaly mudstone layers are intercalated in a few horizons of a few sections. Takahashi (1959) and Hata and Tsushima (1969) roughly mentioned cyclic lithofacies changes in their regional geological surveys, but detailed sedimentary facies remained undescribed.

Megafossil biostratigraphy (Matsumoto 1982; Toshimitsu *et al.* 1995; Kodama *et al.* 2002; Maeda *et al.* 2005) is primarily based on the inoceramid species *Sphenoceramus schmidti* for the upper part of the Osoushinai Member, to which it assigns the Lower Campanian Stage. In the Nakagawa area well-preserved specimens of the ammonite species *Metaplacenticeras subtilistriatum* are common in the middle and upper parts of the Hakobuchi Formation, securing the Upper Campanian Stage. Maastrichtian strata are missing from the study area, due to erosion by the unconformity, but occur in the Soya hill area further north of the Nakagawa area (Ando and Ando 2002).

SEDIMENTARY FACIES ANALYSIS

Twenty-four sedimentary facies (F1 to F24) can be identified in the succession from the upper part of the Osoushinai Member of the Haborogawa Formation to the Hakobuchi Formation in the Nakagawa area, based on lithology, sedimentary structures and biofacies (Fig. 3). Depending on stacking patterns of the sedimentary facies, they are grouped into six facies associations (FA) from A to F. Facies F24 defines a single facies association on its own. Representative outcrop photographs of sedimentary facies and boundary surfaces are shown in Figure 4. Classification of shallow-marine sedimentary environments are based on Saito (1989), Walker and Plint (1992), and Reading (1996).

FACIES AND FACIES ASSOCIATION

Facies association A (FA-A)

Description

FA-A appears only in one horizon of the lower part of the Hakobuchi Formation in the two western-end sections 6 and 10 (Fig. 5). It consists of dark gray to grayish black, coaly to carbonaceous, massive but partly laminated siltstone (F1), medium- to thick-bedded (20–60 cm) fine-grained sandstone with rather discontinuous coaly siltstone laminae (F2), and thick (30–90 cm) massive silty medium-grained sandstone yielding coaly plant remains, sporadically or in swarms (F3). The F1 deposits may rarely contain lenses of fine- to medium-grained sandstone 10 to 20 cm thick. F3 partly includes coarse-grained sand and granule grains. The total thickness of FA-A is less than 10 m. F1 gradually overlies F2 and F3 and is itself overlain erosionally by the latter in general. In the case of sections 6 and 10, F1 directly overlies the marine sandstone facies of FA-D with a sharp boundary (Fig. 4a,b).

Interpretation

FA-A type deposits, being rich in carbonaceous/coaly materials, laminae and poorly-sorted sand grains as a whole, from which wave-formed sedimentary structures such as wave ripple and trace fossils of marine origin are lacking, suggest a fluvial origin. Flood plain, natural levee or crevasse splay, and shallow fluvial channels designate the sedimentary environments of F1, F2, and F3, respectively.

Facies association B (FA-B)

Description

FA-B has a wide range of lithological variation, from massive and thick sandy siltstone (F4), alternating beds of fine- to medium-grained sandstone and massive sandy siltstone (F5), massive and poorly-sorted, graded medium- to coarse-grained sandstone (F7), and massive, mostly matrix-supported and poorly-sorted granule to pebble conglomerate (F8). Low-angle cross-stratified, fine- to medium-grained sandstone (F6) about one meter thick is occasionally intervening in F5 with an erosional sharp channel base. FA-B occurs only in three western sections (sections 7, 8, 9 on Fig. 6).

F4 sometimes contains coaly laminae and small-sized burrows. F5 has bedded intervals of a few centimeters to less than 60 cm thick. While sandy siltstone in F5 contains thin sandy and carbonaceous laminae, sometimes forming thin alternations with current ripples, the sandstone layers show sharp lower and flat upper bedding surfaces. F6 occasionally includes coaly plant remains, laminae and rip-up mudstone clasts. F7 contains sporadic or lamina-forming rip-up clasts and partly shows low-angle cross-stratification (Fig. 4d). Thick disarticulated shells of the trigonid bivalve *Yaadia deckeina* (Nakano 1958) occur in F8 with sporadic mudstone clasts (Fig. 4e). Shell fragments of large ammonites are rare. The few-meters-thick F8 overlies F16 with a sharp erosional base and grades up into F7 (Fig. 4c).

Interpretation

The fine-grained lithology of F4 deposits suggests quiet sedimentary environments where mud in suspension can fall out, as in the case of an inner bay or estuary. F5 shows intermittent sedimentation of sand and mud under closed or quiet estuary environments. The lack of flaser or lenticular bedding impedes detection of a tidal influence for

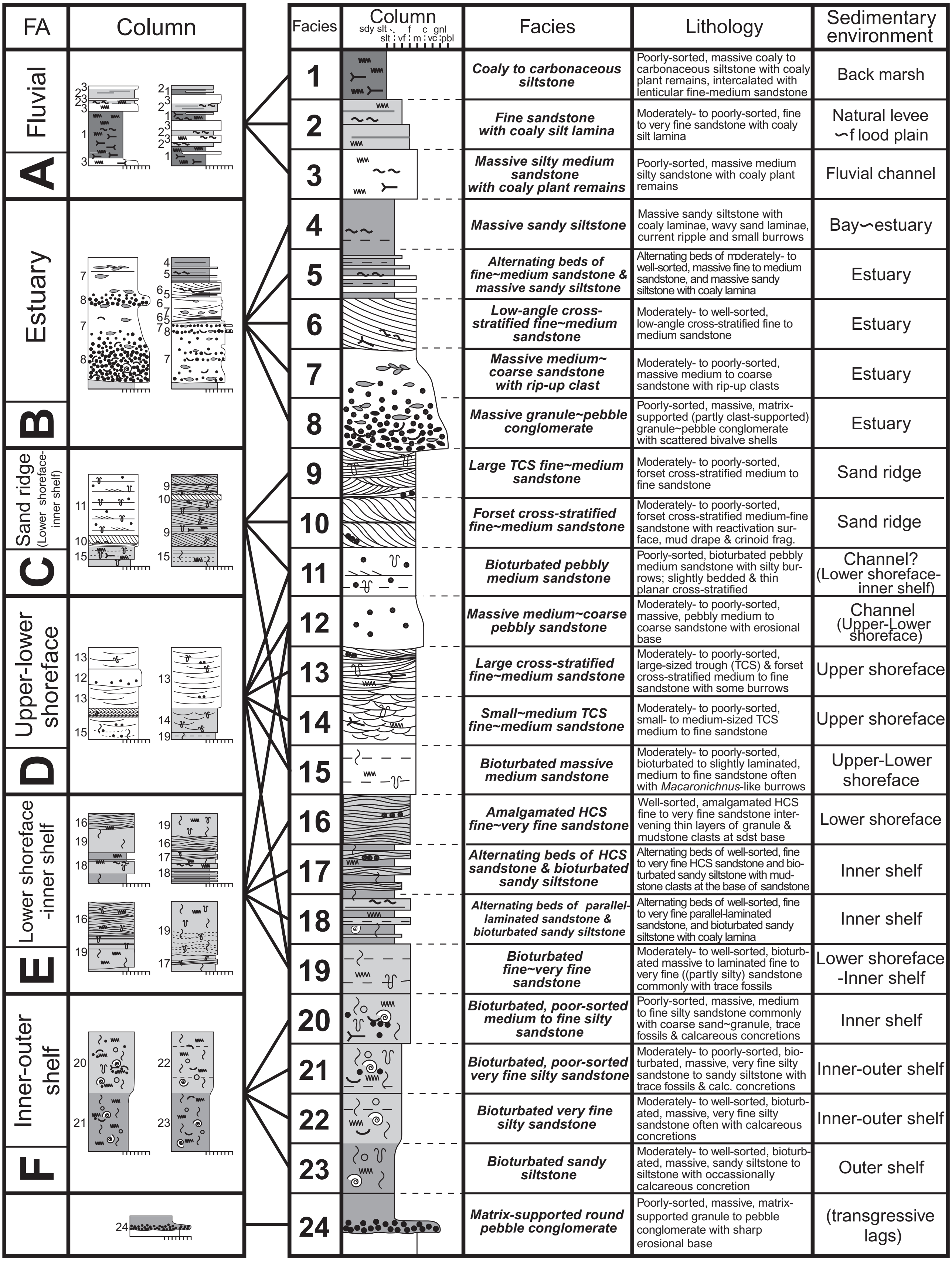
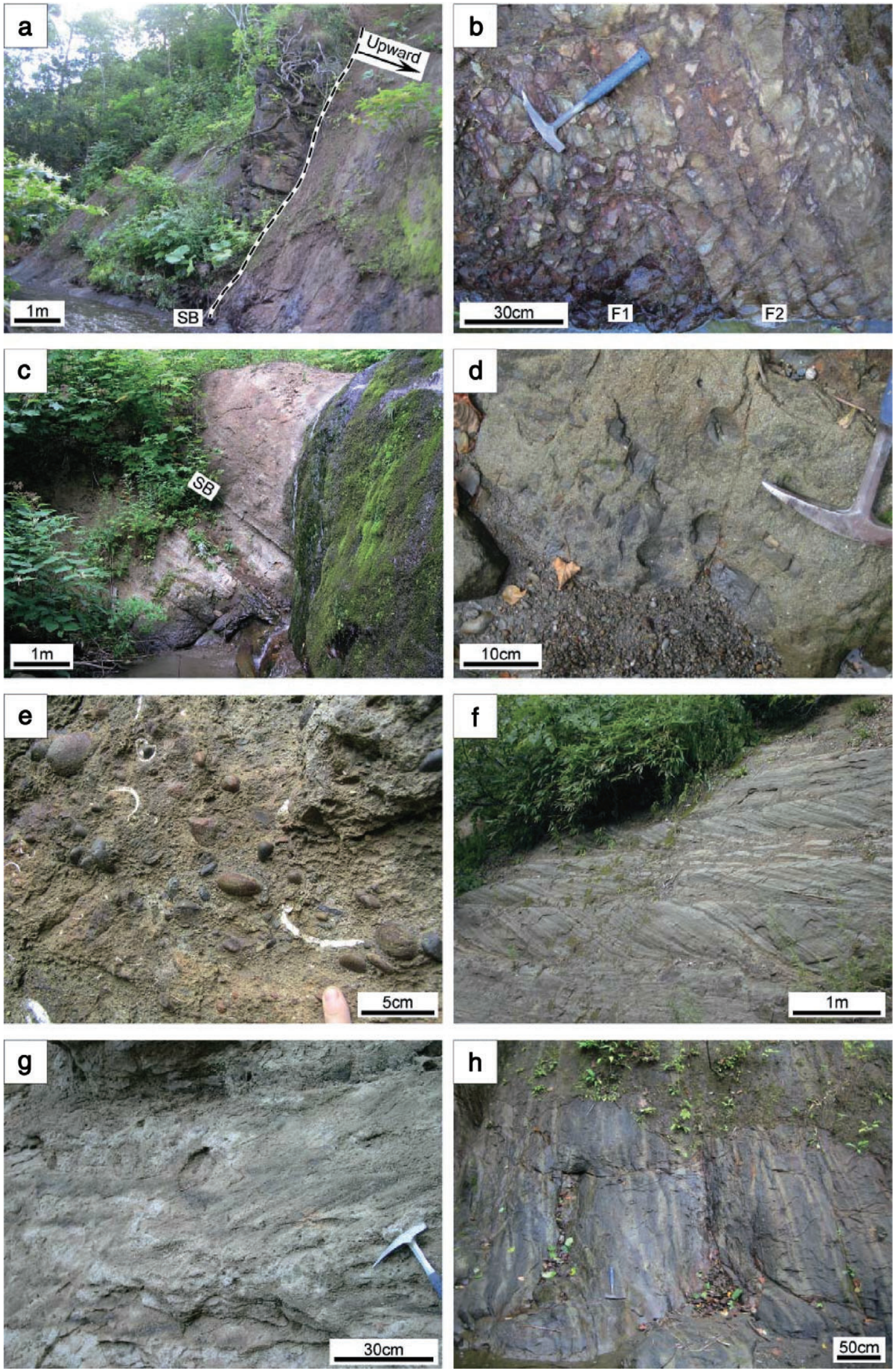


Fig. 3 Sedimentary facies, facies associations and their interpreted sedimentary environments of the upper part of the Yezo Group. Refer to Figure 5 for legend symbols.


a
Upward
1m
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b
30cm
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F2
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1m
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10cm
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5cm
f
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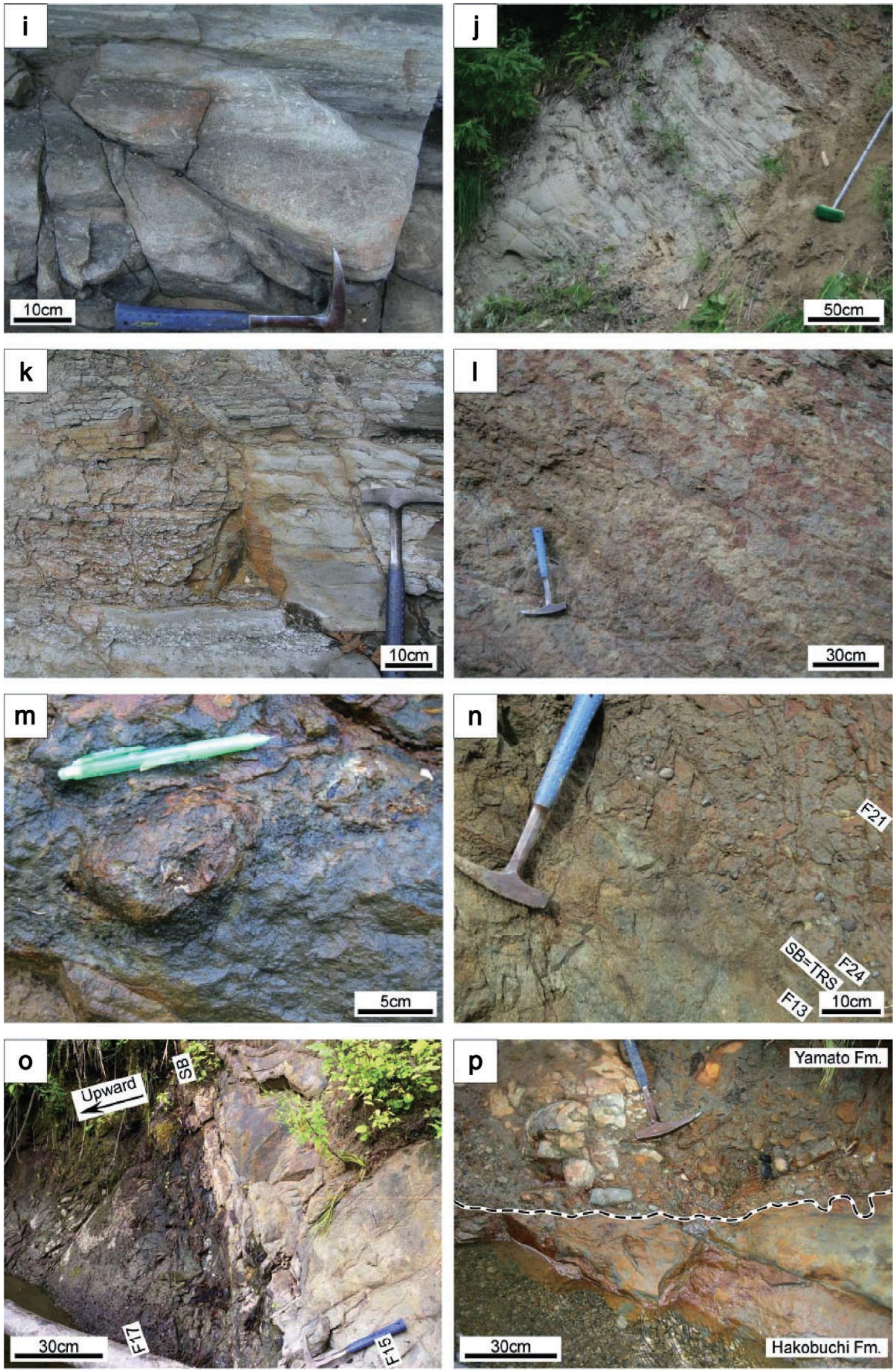
g
30cm
h
50cm


i
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F21
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F13
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SB
Upward
30cm
F17
F15
p
Yamato Fm.
30cm
Hakobuchi Fm.

Fig. 4 Photographs of the representative sedimentary facies of the Hakobuchi Formation, Yezo Group in the Nakagawa area. Refer to Figures 1,5, and 6 for the number of section. (a) erosional sequence boundary (SB) between DS1 and DS2, west Rubesyube River (section 6). F1 on the right side of SB overlies FA-D on the left; (b) facies 1 and 2 (natural levee–flood plain facies) in the lower part of DS2, west Rubesyube River (section 6); (c) sequence boundary (SB) between DS5 and DS6, north Rubesyube River (section 9). F8 above SB overlies F16; (d) facies 7 (estuary) in the lower part of DS6, east Rubesyube River (section 7); (e) facies 8 (estuary) in the lower part of DS6, north Rubesyube River (section 9); (f) facies 10 (sand ridge) in the upper part of DS3, north Rubesyube River (section 9); (g) facies 11 (channel) in the upper part of DS4, east Uttsu Forestry Road (section 12); (h) facies 13 (upper shoreface) in the upper part of DS1, west Rubesyube River (section 6); (i) *Macaronichnus*-like burrows of facies 15 in the upper part of DS1, north Rubesyube River (section 9); (j) facies 16 (lower shoreface) in the lower part of DS4, east Uttsu Forestry Road (section 12); (k) facies 18 (inner shelf) in the lower part of DS3, north Rubesyube River (section 9); (l) facies 20 (inner shelf) in the upper part of DS4, east Uttsu Forestry Road (section 12); (m) facies 20 with a calcareous concretion containing *Metaplacenticeras subtilistriatum* in the middle part of DS4, north Rubesyube River (section 9); (n) sequence boundary between facies 13 of DS2 and facies 24 and 21 of DS3, east Uttsu Forestry Road (section 12); (o) sequence boundary between facies 15 of DS2 and facies 17 of DS3, west Rubesyube River (section 6); (p) unconformity between the Hakobuchi Formation (DS6) and the Yamato Formation (Miocene), north Rubesyube River (section 9).

F5. Channel scour and fill structure observable in F6 suggest tidal channel sedimentation of sand within an estuary. F8 and the overlying F7 suggest that episodic coarse-grained high-energy sedimentation may erosively scrape the filling of estuarine channels. Such facies can be interpreted to be tide-influenced estuarine fillings of an incised valley that was formed by lowstand erosion.

Facies association C (FA-C)

Description

FA-C is dominated by large-scale trough to planar (F9) or forset (F10) cross-stratified, medium-grained sandstone, associated with bioturbated, massive pebbly medium-grained sandstone (F11) and bioturbated massive medium sandstone (F15). Mud drapes of a few millimeters to less than 3 cm thick are frequently intervening between co-sets of cross-strata within F9. Vertical burrows filled with silt or mud often align along bedding surfaces of F9, F10, and F11. F10 shows that several tangential-type cross-sets of 40 to 150 cm in thickness are stacking with some thickening or thinning trend. Commonly observable reactivation surfaces and mud drapes in between co-sets of cross-strata indicate erosion and sedimentary break, respectively (Fig. 4f). Total thickness of F10 reaches 6.5 m in the western section 9 on Figure 6. Paleocurrents measured on cross-stratification of F10 and F9 show southward to SSE directions. F11 and F15 deposits are generally massive and burrowed but occasionally planar cross-stratified (Fig. 4g). FA-C occurs only in the northern part of the western Nakagawa area and laterally grades southward into FA-D.

Interpretation

FA-C gradationally overlies FA-E (lower shoreface to inner shelf deposits described later) without a distinct erosional surface, and underlies FA-E or FA-F (inner to outer shelf deposits) with a sharp facies boundary occasionally associated with an erosional surface and the overlying transgressive lag deposits (F24). Large-scale sedimentary structures of trough cross-stratification and southward-inclined forset cross-stratification, often associated with mud drapes and aligning burrows, represent sand body migration by southward-flowing intermittent high-energy unidirectional currents. F9 and F10 may have been deposited as sand ridges and bars on the lower shoreface to inner shelf where longshore currents flow southward and are much influenced by tidal currents. Judging from the lack of physical sedimentary structure and massive lithology in contrast to F9 and F10, F11 represents inter-ridge/bar deposits on the lower shoreface to inner shelf.

Facies association D (FA-D)

Description

FA-D is somewhat similar to FA-C in lithology, but this association includes a larger amount of massive and bioturbated, medium-grained sandstone. The dominant facies in FA-D, F13 and F14, are characterized by well developed, trough and forset cross-stratification in medium-grained sandstone occasionally bearing granules and coarse-grained sand. Trough cross-stratification in F13 is large, ranging from 0.3 to 1 m in co-set thickness and one to a few meters in wavelength (Fig. 4h). F13 occasionally includes forset cross-stratification 0.4 to 1 m in co-set thickness and low-angle cross-stratification. On the other hand, F14 has the middle size of trough cross-stratification, ranging from 0.2 to 0.3 m in thickness and less than 1 m in wavelength. The other three facies, F11, F12, and F15, consist of massive and often bioturbated, moderately to poorly sorted, medium- to coarse-grained sandstone. The characteristic of the rarely

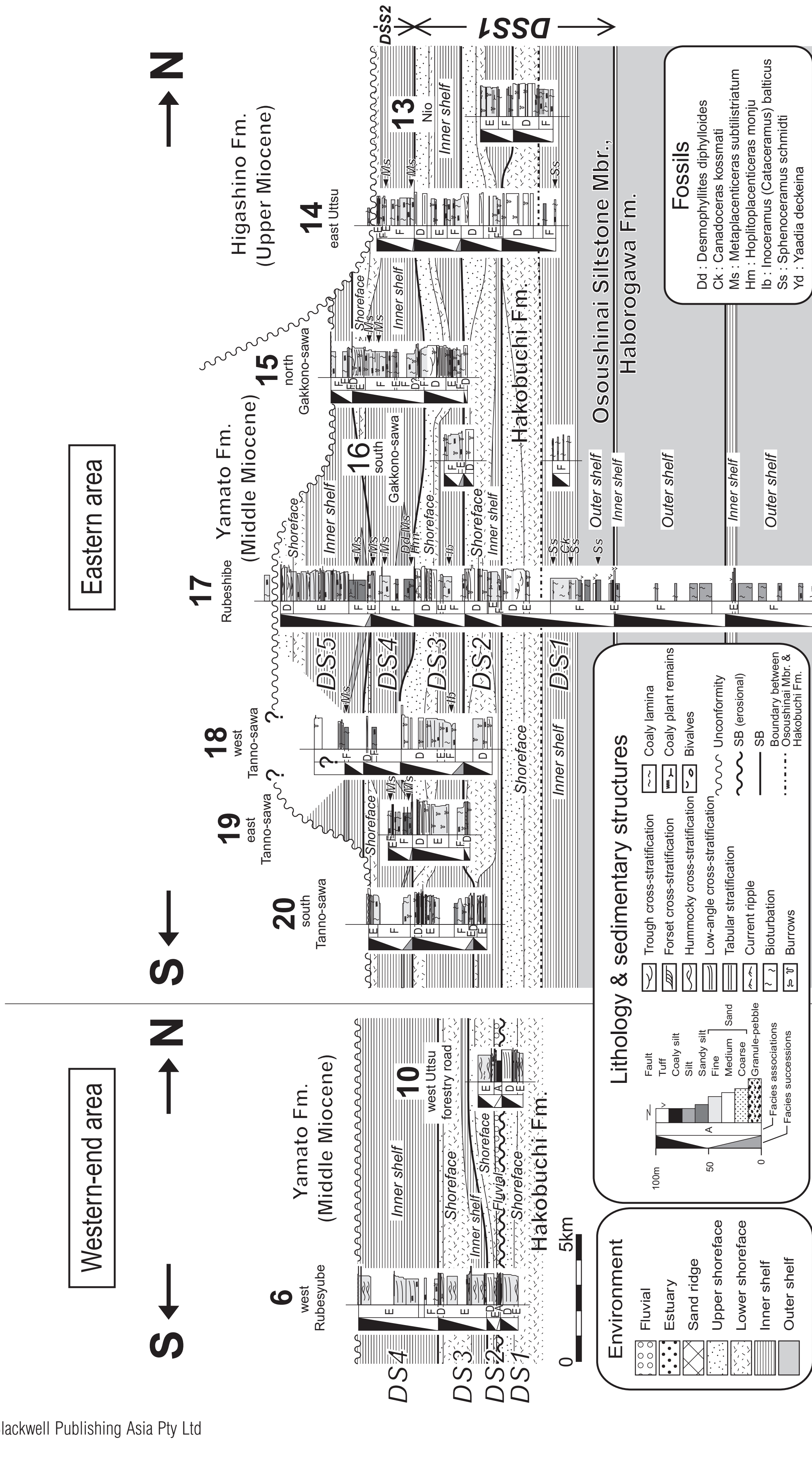

Fig. 5 Correlated columnar sections showing sedimentary facies distribution along the western-end and eastern parts of the Nakagawa area.

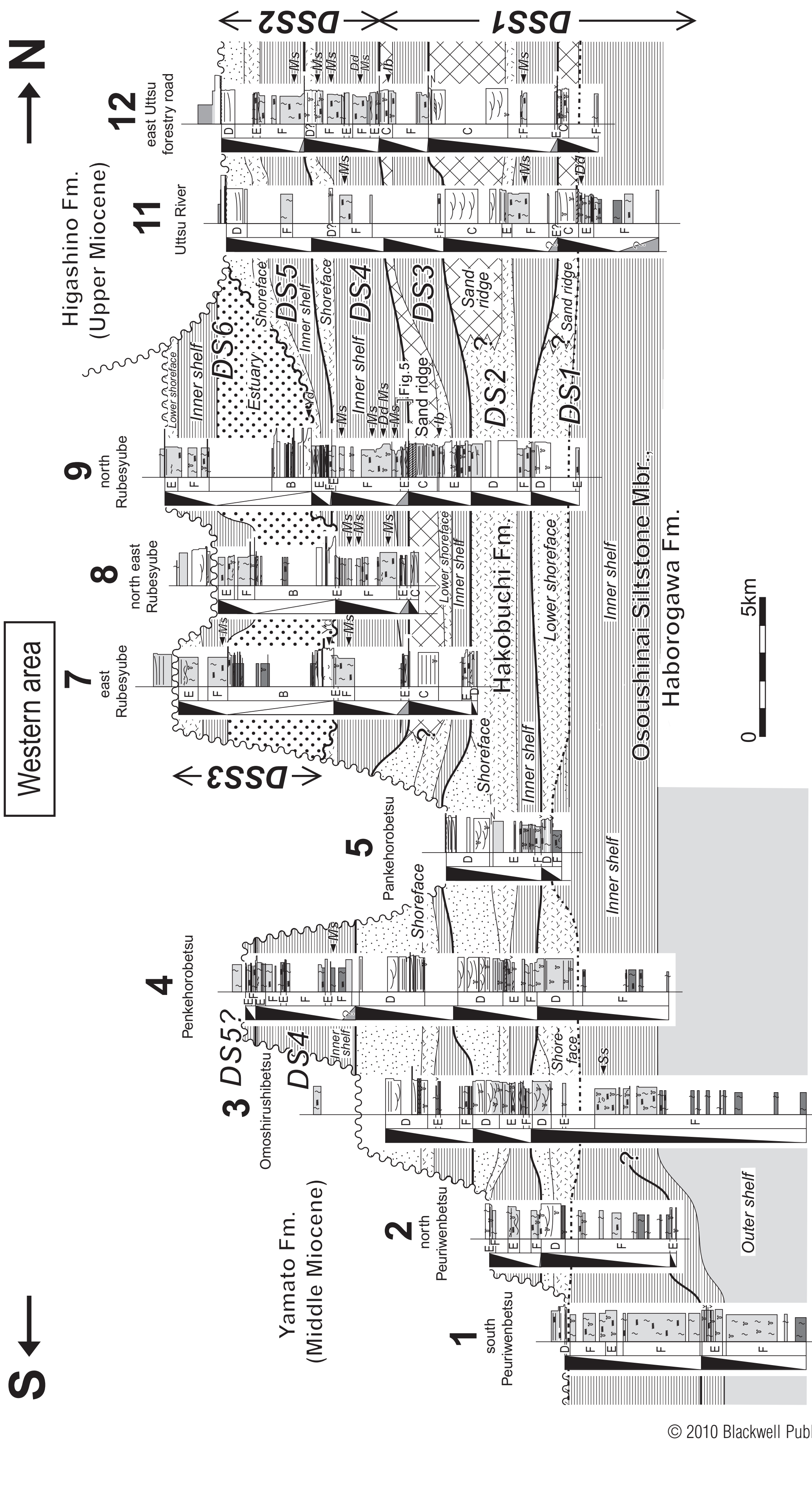

Fig. 6 Correlated columnar sections showing sedimentary facies distribution along the western part of the Nakagawa area. Refer to Figure 5 for legend symbols.

intervening F11 is the mostly bioturbated, often granule-bearing and occasionally tabular bedded/planar cross-stratified lithology. F12, a few meters thick, occasionally intervening in F13 consists of massive, although less bioturbated, medium- to coarse-grained sandstone and partly granulated conglomerate. It often has concave erosional bases, often associated with disarticulated and fragmentary bivalve fossils and mudstone clasts on top. Commonly co-occurring, F15 deposits consist of massive and bioturbated, medium-grained sandstone often bearing coaly plant remains. They also contain rare mollusk fragments of ammonites, bivalves, and gastropods. Obscure parallel-lamination occurs. In F13 to F15, tube-type and *Macaronichnus*-like burrows, 3 to 10 mm in diameter, often swarm in certain horizons (Fig. 4i).

Interpretation

Trough and forset cross-stratification typical in F13 and F14 are interpreted to have formed on the upper shoreface under high-energy environments influenced by waves, rips, and longshore currents. F13 and F14 occur stratigraphically higher than F16 (lower shoreface deposits) described later. Somewhat finer and more bioturbated, F15 is associated with F13 and F14, seemingly part of lower shoreface deposits, slightly more distal than the other two. On the other hand, occasional F11 and F12 show shallow channel-based contacts with underlying F13 or F15, and their coarser sediments were initially deposited on the proximal side, and possibly transported into the distal side on the shoreface through shallow channels during storms.

Facies association E (FA-E)

Description

FA-E consists of hummocky cross-stratified (HCS), parallel-laminated and massive fine- to very fine-grained sandstone, and interbedded sandstone and sandy siltstone to silty sandstone, associated with F12 described above. The definition of F16 is that of amalgamated HCS sandstone with sharp-based lenticular layers of granule to coarse-grained sand as storm lag (Fig. 4j). F17 and F18 consist of interbedded hummocky cross-stratified sandstone (F17) or parallel-laminated/massive (F18) sandstone and bioturbated sandy siltstone. F18 as a whole is more bioturbated even within sandstone layers, and rarely contains ammonites, bivalves, and crinoid stem fragments (Fig. 4k). F19 is composed of 2 to 5-m thick massive, occasionally low-angle cross-stratified or parallel-laminated, but commonly burrowed and mottled by bioturbation, somewhat silty, fine- to very fine-grained sandstone. F12 intercalates with a sharp erosional base only in sections 9 and 20.

Interpretation

As HCS has been interpreted to be formed mainly by storm-induced oscillatory currents (e.g. Dott & Bourgeois 1982), the predominance of HCS in F16 suggests deposition in storm-dominated lower shoreface environments, proximal of F17 and F18 (Saito 1989; Cheel & Leckie 1993). The latter two facies are thought to be inner shelf deposits based on inferred intermittent sedimentation of HCS/parallel-laminated sand and bioturbated mud, which, respectively, represent storm-generated sheet sand and inter-storm suspension mud during fair-weather conditions. Since the character of F19 is intermediate between F16 and F17/18 in lithology, it may belong to lower shoreface to inner shelf deposits. Occasionally associated F12 suggests that shallow channel-fill deposits developed on the lower shoreface to inner shelf. To sum up, FA-E has the characters of lower shoreface to inner shelf deposits.

Facies association F (FA-F)

Description

FA-F includes four similar facies composed of heavily bioturbated, massive and thick silty sandstone to sandy siltstone: poorly-sorted medium- to fine-grained silty sandstone (F20; Fig. 4l), poorly-sorted, medium-grained sand-bearing, very fine-grained silty sandstone to silty sandstone (F21), gray to dark gray, very fine-grained silty sandstone (F22) and dark gray sandy siltstone (F23). Molluscan shells such as ammonites and inoceramids are common (Fig. 4m). Other bivalves, gastropods, and scaphopods are scarcer. Usually well-preserved fossils occur from calcareous concretions, but those derived from host rocks are sporadic and poorly preserved.

The coarsest F20 within the FA-F often contains sporadic patches swarming with mostly fragmentary mollusks, associated with coaly plant remains, coarse-grained sand to granules, pumice grains and rip-up mudstone clasts. These materials, within concretion-like partly calcified patches, do not show any distinct laminae and alignments.

Such fossil occurrence is also observed in F21, but the lithology of concretions and host rocks is finer-grained, comparatively well-sorted and monotonous. Therefore, unbroken fossils are more common in F21 than in F20. F20 and the usually underlying F21 are the finest facies within the Hakobuchi Formation.

F22 and F23, which define the upper part of the Osoushinai Member, are more massive than F20 and F21 and yield more abundant unbroken ammonites and inoceramids in a larger amount of calcareous concretions and finer-grained host rocks. F22 occasionally includes parallel lamination and fragmental inoceramid shell laminae.

Interpretation

F20 underlies the lower shoreface to inner shelf deposit facies of FA-E. It contains patches swarming with shells that seem to have initially accumulated by storm waves or currents as shell lags, but physical sedimentary structures within the patches were possibly disturbed by activity of benthic organisms subsequently. Based on lithology and stratigraphic relationships, F20 apparently resulted from deposition in inner shelf environmental conditions. F21, underlying F20, may have accumulated on the outer side of an inner shelf to the inner side of an outer shelf. The finest F23 and the second finest F22, of monotonous lithology and with an ammonite-dominated biofacies, suggest offshore conditions, such as an outer shelf, and an outer shelf to outer side of an inner shelf, respectively. Therefore, FA-F as a whole indicates inner to outer shelf environments.

Facies 24 (F24)

Description

This facies consists of a matrix-supported rounded pebble conglomerate, a few tens of centimeters thick, with a great amount of fine-grained sand matrix. It independently occurs between FA-C or D and FA-E or F and with a flat or shallowly undulated erosional surface (Fig. 4n). It shows the rapid deepening facies transition above the underlying shallower facies.

Interpretation

This facies is equivalent to a transgressive lag formed by shoreface erosion during transgression, and its base is defined as ravinement surface (Nummedal & Swift 1987).

DISTRIBUTION OF FACIES TYPES AND ASSOCIATIONS

Distribution of facies (F) and of facies associations (FA) within the underlying upper part of the Osoushinai Member of the Haborogawa Formation and within the Hakobuchi Formation can be well observed within the 22-km long (north–south) and nearly 6 km wide (east–west) study area (Figs 5,6). Correlation between sections is based on detailed identification of facies, facies associations and their stacking patterns.

The upper limit of the Hakobuchi Formation is hetero-chronic due to the undulating erosion surfaces of the unconformities at the base of the overlying Middle Miocene Yamato or Late Miocene Higashino Formations (Fig. 4p). The unconformity with the Yamato Formation often cuts deep within the lower part of the Hakobuchi Formation as at the Peuriwenbetsu sections (1 and 2 on Fig. 6) and Penkehorobetsu section (5 on Fig. 6). That with the Higashino Formation covers the middle part of the Hakobuchi Formation in the East Uttsu sections (13 and 14 on Fig. 5). Elsewhere the middle part is preserved below the Yamato Formation, as in west Rubesyube section (6 on Fig. 5) and west Uttsu section (10 on Fig. 5). On the other hand, the estuarine to inner shelf facies of the upper part of the formation overlies the middle part in an unconformity, being preserved under the Yamato Formation also in an unconformity, only in east, northeast and north Rubesyube sections (7–9 on Fig. 6), respectively.

The predominance of FA-D, E, and F among the six facies associations indicates that the Hakobuchi Formation in the Nakagawa area consists mainly of shoreface to shelf depositional systems, subordinately of fluvial and estuary systems. A comparison between the eastern, western and western-end cross-sections (Figs. 5,6) shows thicker shallow-marine sandy sediments (such as FA-D and E) in the western area than in the eastern area. Fluvial sediments (FA-A) occur only in a thin horizon of the lower part of the Hakobuchi Formation along the western-end sections 6 and 10 on Figure 5. Estuary sediments (FA-B) characterize the upper part of the formation in the central western three sections 7–9 on Figure 6. Sand ridge sediments (FA-C) are limited to a few horizons in the northern part of the western area (the lower part of the Hakobuchi Formation in sections 9, 11, 12 on Fig. 6). On the other hand, lateral occurrences of offshore-like facies, characterized by FA-D, E, and F, are more common in the eastern area. Consequently, the westward-shallowing facies trend suggests a paleo-

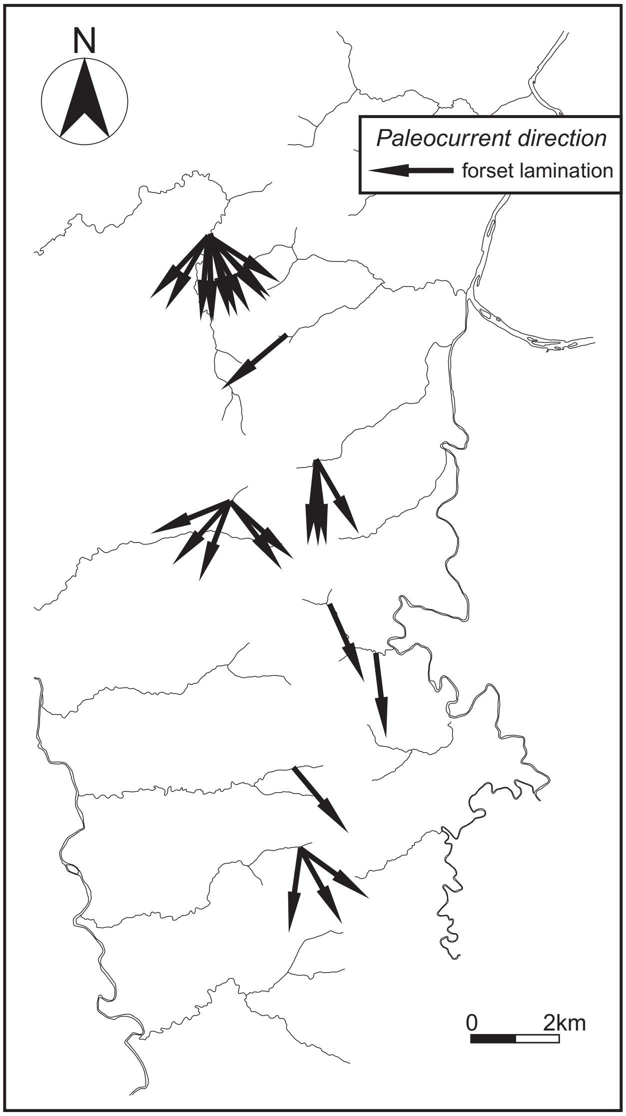

Fig. 7 Paleocurrent directions of the Hakobuchi Formation in the Nakagawa area, inferred from inclination of forset cross-stratification.

geographical setting of a hinterland to the west and a north–south-running coastline.

PALEOCURRENTS

Paleocurrent directions are measured from inclinations of forset or planar cross-stratification developed within F10, 9, and 13 and subsequent horizontal corrections for inclined bedding planes in the Hakobuchi Formation of the Nakagawa area (Fig. 7). The southward directions are dominant within the Nakagawa area as a whole, although they vary to some extent. Taking the west–east onshore–offshore gradient and north–south trending coastline inferred from the facies distribution into account, prevailing southward longshore currents that formed north–south trending sand dune or bar deposits on the lower shoreface to inner shelf, can be suggested.

Figure 8 shows the detailed inner structure observed in a large-scale forset cross-stratified sandstone bed about 1.5-m thick within a large outcrop of F10 in the lower part of the Hakobuchi Formation along the section 11 of the western area. Between the upper and lower bounding surfaces of a co-set of cross-strata there are many sets of cross-strata dipping southward mostly less than 30°, each of which are composed of rhythmically bundled sand lamination and intervening mud drapes. Set boundaries gently eroded the underlying lamination with flat or concave surfaces. In the case of concave erosional surfaces, their boundaries are called as reactivation surfaces (Collinson & Thompson 1989). Some reactivation surfaces have shallow step-like channels that extend east to west perpendicular to the direction of forset inclination. These sedimentary structures suggest intermittent deposition of sand and mud within a co-set, and alternating southward growth and stasis/erosion/reactivation forming each set of cross-strata. Therefore, forset cross-stratified sandstone beds seem to have deposited under prevailing southward longshore currents influenced by east–west tidal currents, judging from the systematically formed, bundled lamination and sets of cross-strata.

SEQUENCE STRATIGRAPHY

FACIES SUCCESSIONS, SYSTEMS TRACTS AND BOUNDING SURFACES

Stacking patterns, facies (F) and facies associations (FA) allow the recognition of four types of facies successions (FS).

Facies succession 1 (FS1)

Facies succession 1 (FS1) is the most frequent, consisting in ascending order of upwards coarsening FA-F to FA-E, and FA-D, with FA-C partly replacing FA-D. The thickness of this succession ranges from 10 to 110 m and is typically composed of bioturbated silty very fine-grained sandstone (F21), massive fine- to medium-grained silty sandstone (F20), bioturbated fine- (F19) to medium-grained (F15) sandstone, and large-scale cross-stratified medium-grained sandstone (F13). Although the facies components somewhat vary among successions and sections, they show regres-

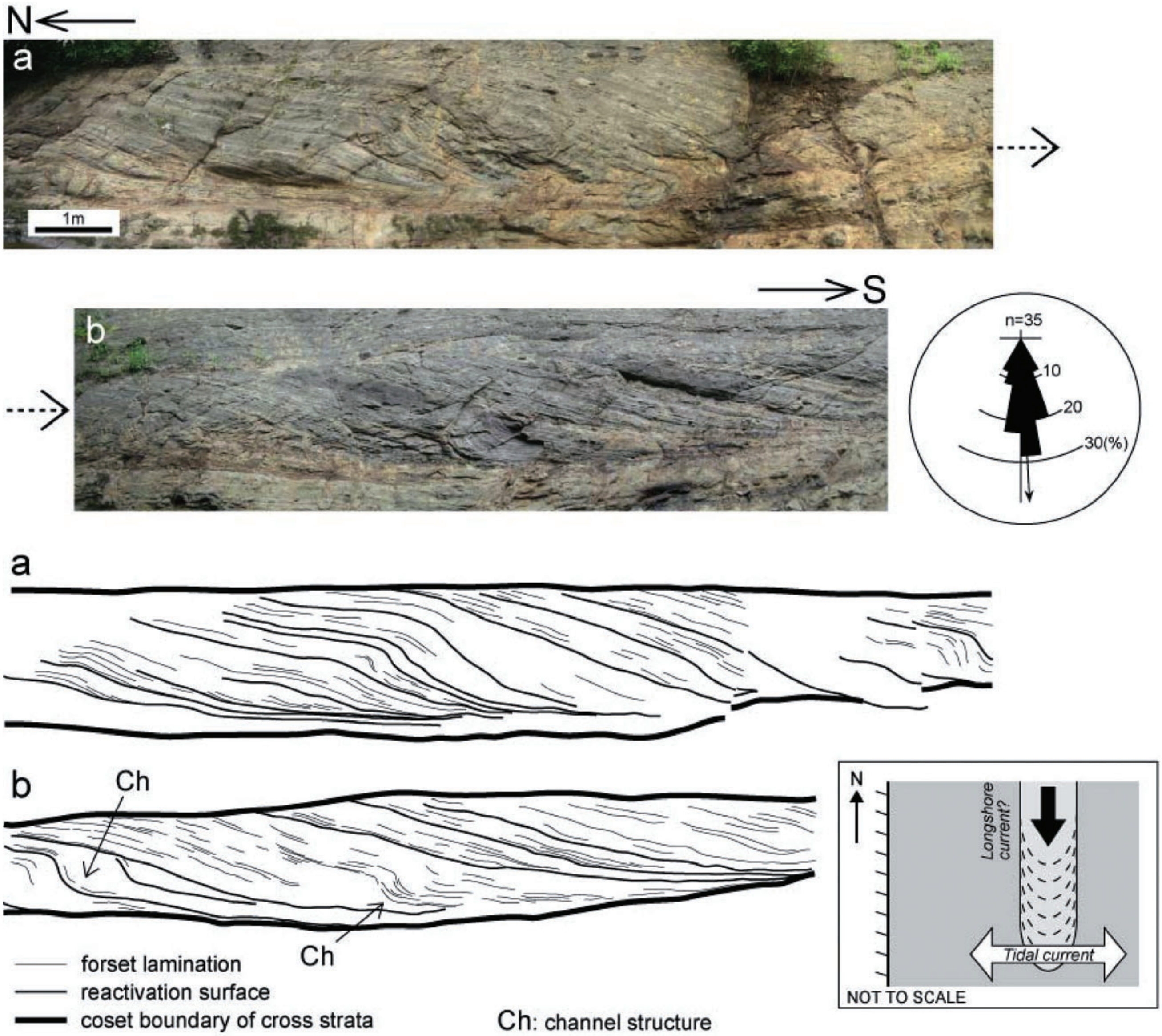

Fig. 8 Photographs and sketches of forset cross-stratified sandstone (facies 10) of DS1 at a large outcrop along the Uttsu River (section 11). (a) left and (b) right half of outcrop. N, number of measured palaeocurrent directions.

sive upward shallowing changes from inner or outer shelf to upper shoreface. These environmental characteristics suggest that FS1 is equivalent to a highstand systems tract (HST) in terms of sequence stratigraphy.

Facies succession 2 (FS2)

The main characteristic of facies succession 2 (FS2) is upward fining over a thin interval of 1 to 10 m thickness. It occurs occasionally beneath FS1, consisting of FA-E to FA-F or FA-F only, F24 being often at its base. The typical succession of FS2 consists in ascending order of F24 (matrix-supported pebble conglomerate) and F21 (bioturbated very fine silty sandstone). Alternatively F24 is followed by F16 (amalgamated HCS fine to very fine sandstone) and 17 (alternating beds of HCS fine sandstone and bioturbated sandy siltstone)/18 (alternating beds of parallel laminated fine sandstone and bioturbated sandy siltstone) and F21 (Fig. 9). Their inferred sedimentary environments show an upward deepening or transgressive trend, prograding from shoreface to inner shelf. The lower boundary of FS2 to the coarser (shallower) FS1 underneath is a sharp and undulated erosion surface. At the top, a sharp and conformable facies boundary ends the finer (deeper) facies of F16/

Fig. 9 Stacking patterns of sedimentary facies successions between two depositional sequences DS3 and 4. Coarsening-upward facies succession (FS1 = HST) and fining-upward facies succession (FS2 = TST) between DS3 and 4, north Rubesyube River (section 9).

17/18 and F21. Erosional surface and rapid facies change between FS2 and FS1 indicate that a transgression took place. This transgressive succession may be equivalent to a transgressive systems tract (TST). The erosional surface is interpreted as a transgressive ravinement surface (TRS: Nummedal and Swift 1987; Catuneanu 2006) formed by shoreface wave erosion during transgression. Therefore, F24 represents a transgressive lag composed of coarse residual clastics. The boundaries between FS2 and the overlying FS1 are generally gradational and the finest-grained horizons that consist generally of massive intensely bioturbated silty sandstone and sandy siltstone (F21) indicate the deepest sedimentary environment, equivalent to a maximum flooding surface (MFS: Van wagoner *et al.* 1990) between TST and HST.

Third and fourth types of facies successions (FS3, FS4) encompass a single facies association such as FA-B or FA-A, occupying a limited stratigraphic interval.

Facies succession 3 (FS3)

FA-B consists typically of an upward fining lower succession of F8/7 to F5, or of F6 to F4, of a thickness of more than 50 m, and of an upward coarsening upper succession of F4 to F7 through F5, less than 10 m thick. Their trend is however less distinct than in FS1, due to poor exposures. Totaling 70 to 90 m thick, FS3 occurs in the upper part of three western sections 7, 8 and 9 (Fig. 6). Considering the estuarine sedimentary environments for FA-B, underlying FS1 and a sharp erosive contact at its base, FS3 suits a TST.

Facies succession 4 (FS4)

The 4- to 7-m-thick fluvial facies association (FA-A) occurs only in the lower part of the two western-end sections 6 and 10 between two FS1 successions (Figs. 4a,b,5), representing a lowstand systems tract (LST).

DEPOSITIONAL SEQUENCES

Stacking patterns and bounding surfaces of the facies successions within the uppermost part of the Osoushinai Member of the Haborogawa Formation and the overlying Hakobuchi Formation reveal up to six depositional sequences (DS) (Fig. 10). No discordance marks the passage between formations. The number of DS varies from section to section, and their occurrence depends largely on the extent of erosion that took place before deposition of the overlying Miocene formations. Most of the DSs are thick stacks of HST, occasionally associated with thin TST. Thickness of a DS ranges from 15 to 120 m.

Many sequence boundaries (SB) correspond to an HST base, the underlying TST or LST often lacking (Fig. 4o). Such units may correspond to the parasequence, defined as 'a relatively conformable succession of genetically related beds or bedsets, bound by marine-flooding surfaces and their correlative surfaces' by Posamentier *et al.* (1988). Significance and definition of the bounding surfaces between SB and maximum flooding surface (MFS) within a DS being widely discussed by Catuneanu (2006), we do not use the term parasequence. We also prefer the term maximum regressive surface (MRS) instead of marine flooding surface according to Catuneanu (2006).

On the other hand, the lower SB for DSs with TST (FS2) may coincide with TRS formed by shoreface wave erosion during early transgression (Fig. 4n). Figure 9 shows the boundary between DS3 and DS4 along section 9 of the western area. Here the upward coarsening succession (FS1 = HST) of DS3 underlies a several-meters-thick succession of upward fining sandstone (FS2 = TST) of DS4. Above a sharp contact, the few tens of centimeter-thick F24 type conglomeratic sandstone layer represents the transgressive lag.

The TST of DS6 consists of very thick estuarine deposits (FA-B) that seem to fill a-few-kilometer-wide and 70- to 80-m-deep valley incised into DS5 and even as deep as the upper part of DS4 during a lowstand stage. It occurs only in sections 7, 8 and 9 of the central part of the western area (Fig. 6). Fluvial deposits (FA-A) interpreted to be LST occur only in the basal part of DS2 of the western-end area.

DEPOSITIONAL SEQUENCE SETS

In terms of their stacking patterns and thickness trends, the depositional sequences (DS) form three depositional sequence sets (DSS).

Depositional sequence set 1 (DSS1)

This set consists of the generally upward thinning and coarsening DS1 to DS3, in which decreasing shelf facies (FA-F) and increasing shoreface facies (FA-D and C) marks an upward sequence trend.

Depositional sequence set 2 (DSS2)

The set consists of DS4 and DS5, which as a whole show predominance of finer facies than DSS1. Each DS includes thick FA-F (inner shelf environment) and FA-E (lower shoreface) in the lower and middle parts of the HST. TST with a transgressive lag bounded by TRS that occurs at the base of DSS2 (DS4) in several sections of the eastern and western areas.

Depositional sequence set 3 (DSS3)

An unconformity separates this DSS from the underlying sequences in sections 7 to 9 of the western area. It consists of DS6, very different in facies and thickness from the DS of the underlying DSS. This estuarine event represents a distinct phase in the history of the Hakobuchi Formation.

BIOSTRATIGRAPHY

The content in both micro- and macrofossils in the Hakobuchi Formation of the Nakagawa area is scarce due to its sandy lithology. As a result the biostratigraphical time control is not so high. The stratigraphic ranges and biostratigraphic zonation of important ammonites, inoceramids, and some other megafossils obtained in this study are shown in Figure 10, referring to the previous works of Toshimitsu *et al.* (1995), Ando *et al.* (2001), Kodama *et al.* (2002), Kodama (2003), Ando and Tomosugi (2005) and Maeda *et al.* (2005). The schematic columnar section includes all fossil occurrence data of the entire area, the represented section being the well-exposed section 17 as a standard column. Therefore, the stratigraphic position of each fossil horizon is inevitably generalized.

Ammonites and inoceramids are relatively common in FA-F and rare in FA-E of the lower part of HST and TST of each DS within the Hakobuchi Formation. Mollusks are very few in FA-D, although inoceramids sporadically occur from DS1 to the lower part of DS4 except DS2. Two inoceramid zones, *Sphenoceramus schmidti* and *Inoceramus (Cataceramus) balticus* zones are

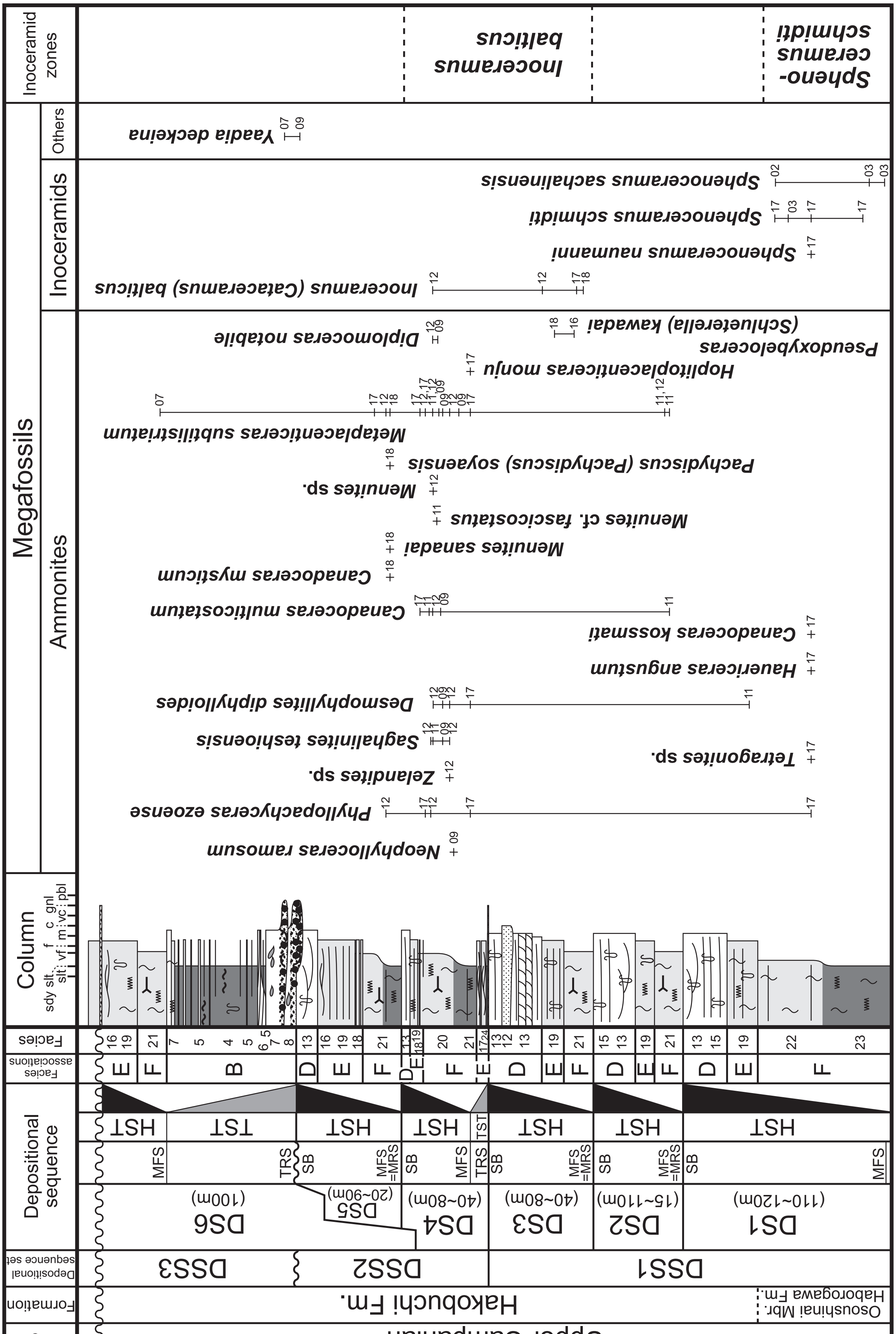

Fig. 10 Composite column of the upper part of Yezo Group in the Nakagawa area summarizing lithology, facies, sequences, sequence sets, and megafossil successions. Numbers are referred to section numbers of fossil localities shown in Figures 5 and 6. DSS, depositional sequence set; DS, depositional sequence; MFS, maximum flooding surface; MRS, maximum regressive surface; TRS, transgressive ravinement surface; SB, sequence boundary; HST, highstand systems tract; TST, transgressive systems tract.

recognized. *Sphenoceramus schmidti* and *Canadoceras kossmati* are reliable index fossils for the upper part of the Lower Campanian, assigning DS1 to the upper Lower Campanian. *Inoceramus (Cataceramus) balticus* is an Upper Campanian index of Toshimitsu *et al.* (1995) that occurs from DS3 to DS4. From the lower part of DS2 to DS6, well-preserved aragonite shells of *Metaplacenticeras subtilistriatum* characterize F20 and 21 (Wani 2006). *Canadoceras multicostatum* ranges from DS2 to DS4. Both these ammonites have a concurrent range within the lower part of the Upper Campanian. In spite of our efforts, Maastrichtian fossils were not obtained here. Therefore, the stratigraphic range of the Hakobuchi Formation in the Nakagawa area covers the upper part of Lower Campanian and the lower part of the Upper Campanian.

The subdivision of the Campanian Stage in Japan (Toshimitsu *et al.* 1995) consists conventionally of the lowest, lower, and upper substages based on inoceramids and ammonites. Cosmopolitan species are rare in the biogeographically endemic North Pacific region. While it is usually difficult to correlate Japanese sections with European standard sections, we estimate that the *Sphenoceramus schmidti* zone is equivalent to the lower Middle Campanian of the European standard subdivision (Gradstein *et al.* 2004).

DISCUSSION

DURATION OF SEQUENCES AND SEQUENCE SETS

The Hakobuchi Formation in the Nakagawa area, based on biostratigraphic data, ranges from the Middle to Upper Campanian of the European stage subdivision. This allows us to estimate its length to about 8 million years (m.y.), from 73 to 81 Ma according to the GTS2004 (Gradstein *et al.* 2004). With an average duration of about 0.75 m.y./DS, we reach a duration of about 2.67 m.y./DSS. In comparison to Haq *et al.*'s (1988) and Hardenbol *et al.*'s (1998) eustasy curves, the DSS may reflect a third-order sealevel change. Six DSs are presumed to be formed by fourth-order relative sealevel changes. We may thus assume that the Hakobuchi Formation and the underlying upper part of the Osoushinai Member in the Nakagawa area represent a combination of third-order eustatic and fourth-order relative and probably local sealevel changes.

These repetitive and high-frequency DSs are traceable to the Soya hill area, 50 km north of the Nakagawa area (Ando and Ando, 2002; Fig. 1). Although reliable biostratigraphic correlation with the Nakagawa area is difficult due to the scarcity of index fossils and poor exposures, four DSs in the Campanian interval of the Hakobuchi Formation occur in the Soya Hill area. On the other hand, in the Oyubari and Hobetsu areas, southern Hokkaido, more than 15 DSs are traceable from the Lower Campanian to Maastrichtian over a distance of 40 km in a north–south direction, running parallel to the inferred paleo-shoreline (Ando 2003). Lowstand systems tracts, as incised valley fills, are represented by fluvial and estuarine facies in several DSs of a greater number of sections than in the Nakagawa area. On the other hand, index megafossils such as *Metaplacenticeras subtilistriatum* and *Inoceramus balticus* do not occur and no Upper Campanian can be recognized in the Oyubari and Hobetsu areas. This suggests the existence of some hiatuses.

SEDIMENTARY HISTORY OF HAKOBUCHI FORMATION, YEZO GROUP IN NAKAGAWA AREA

The Hakobuchi Formation in the Nakagawa area consists dominantly of sandy shallow-marine facies associations represented by FA-C, D, E, and F, which suggest storm-dominated shoreface to shelf environments, especially during highstand stages, widely developed along the western margin of the north–south trending Yezo forearc basin. Paleocurrent patterns measured from forset cross-bedding in facies 9,10, and 13 indicate prevailing southward longshore currents associated with east–west tidal currents. The common FA-C forset bedding suggests that sand ridges aligned north–south on the northwestern part of the shallow shelf.

Sandier shallower facies are more common and thicker within each DS of the western and western-end areas than in the eastern area as a whole, although facies and thickness are also laterally changeable. Fluvial (FA-A) and estuarine (FA-B) sediments are limited to the western-end and western sections, respectively, indicating the paralic to fluvial nature of the sediments occasionally recorded as incised valley fills. As an example of the west–east onshore–offshore gradient, further offshore sandy mudstone facies dominate in the contemporaneous horizons of the Nakatonbetsu area 30 km northeast of the Nakagawa area, as described by Ando *et al.* (2001) and Ando and Tomosugi (2005). Furthermore, fine-grained sandstone facies dominated by FA-E, especially F19, occur in equivalent horizons in the Soya hill area, 50 km north of the Nakagawa area (Ando and Ando 2002; Fig. 1). This suggests an easterly offshore position of the Soya hill area relative to the Nakagawa area on the Hakobuchi shelf. These lines of evidence suggest that siliciclastic materials were generally derived from the westerly hinterland into the storm-dominated shallow shelf and transported under some tidal influence.

Sedimentation of the Hakobuchi Formation is most characterized by stacking of six DSs, each 15 to 120 m thick, and composed of a thick upward coarsening facies succession (FS1) interpreted as HST and occasionally associated with a thin upward fining facies succession (FS2) of usually less than a few meters thick, interpreted as TST.

FORMATIVE MODEL OF DEPOSITIONAL SEQUENCES

A schematic model illustrates the formation of the successive DSs is stage by stage (Fig. 11). While the coastline retrogrades landward during a transgression, induced by a fourth-order relative sealevel rise, a transgressive lag (F24) is formed by shoreface wave erosion above a ravinement surface diachronously (Fig. 11a). Terrigenous sediments are trapped on the proximal side of the shelf and sediment supply to the offshore shelf decreases successively. This condition induces sediment starvation of the thin FS2.

At the next highstand stage shallow marine systems prograde seaward and fill the accommodation space forming FS1 from FA-F to FA-D, and FA-C (Fig. 11b,c).

On the landward side a delta system might have developed, although delta plain facies is hardly preserved in the formation. In case the relative sealevel fell enough to form an incised valley, fluvial sediments (FA-A) fill the valley (Fig. 11d). Later, at an early stage of the subsequent transgression, estuarine sediments (FA-B) fill an incised valley a few kilometers wide at least with an erosional base (Fig. 11e).

The six DSs form three sequence sets (DSS1; DS1–3, DSS2; DS4–5, DSS1; DS6) possibly reflecting third-order relative sealevel changes. DSS1 tends to decrease upward in DS thickness and increase coarser/shallower facies within each DS. This type of stacking pattern means a progradational trend of terrestrial depositional systems associated with decreasing accommodation space by relative sealevel fall (Posamentier *et al.* 1988). The boundary between DSS1 and DSS2 is a conspicuous erosional surface with the overlying F24 indicating a large-scale relative sealevel rise and subsequent shoreface wave erosion during transgression. This third-order sequence boundary has a significance of both TRS and MRS. DSS2 is more abundant in offshore facies such as FA-F than DSS1, but it does not show a clear progradational trend within only two DSs partly because of limited exposures due to an unconformity with the overlying Neogene. Although the boundary between DSS2 and DSS3 can be observed in only three sections of the western area, it suggests a subaerial deep incision during a third-order lowstand into the underlying DS5 and even the uppermost part of DS4.

As already pointed out by Ando (2003), the predominance of shallow-marine to fluvial sandy sediments in the Hakobuchi Group of Hokkaido and its correlatives in north Honshu indicates that a large amount of coarse terrigenous clastics was supplied into the Yezo basin during the Campanian and Maastrichtian, almost filled up by the late Maastrichtian. The cause of this change of sedimentary setting seems to be the uplift of the continental magmatic arc, probably in relation to plate motion (Ando 1997, 2003).

CONCLUSIONS

In terms of facies analyses, 24 facies and 6 facies associations characterize an interval from the upper part of the Osoushinai Member, Haborogawa Formation to the Hakobuchi Formation, Yezo Group, in the Nakagawa area, northern Hokkaido. Their sedimentary environments are inferred to be mainly inner shelf to shoreface, subordinately outer shelf and shoreface sand ridges, and rarely estuary and river. Southward longshore currents, influenced by east–west tidal currents formed north–south trending sand ridges on a storm-dominated shoreface. Stacking patterns of facies associations allow the recognition of four types of facies successions (FS) and six depositional sequences (DS). Thick (10–110 m) upward coarsening (regressive) successions (FS1) are occasionally associated with thin (>10 m) upward fining (transgressive) successions (FS2) that underlay FS1. Furthermore, judging from progradational stacking patterns of DSs, their thickness and facies trends, the lower three, upper two, and the uppermost can be grouped into three depositional sequence sets (DSS1, DSS2, DSS3), respectively. The Hakobuchi Formation in the Nakagawa area ranges from the upper part of the Lower Campanian to the Upper Campanian, in terms of

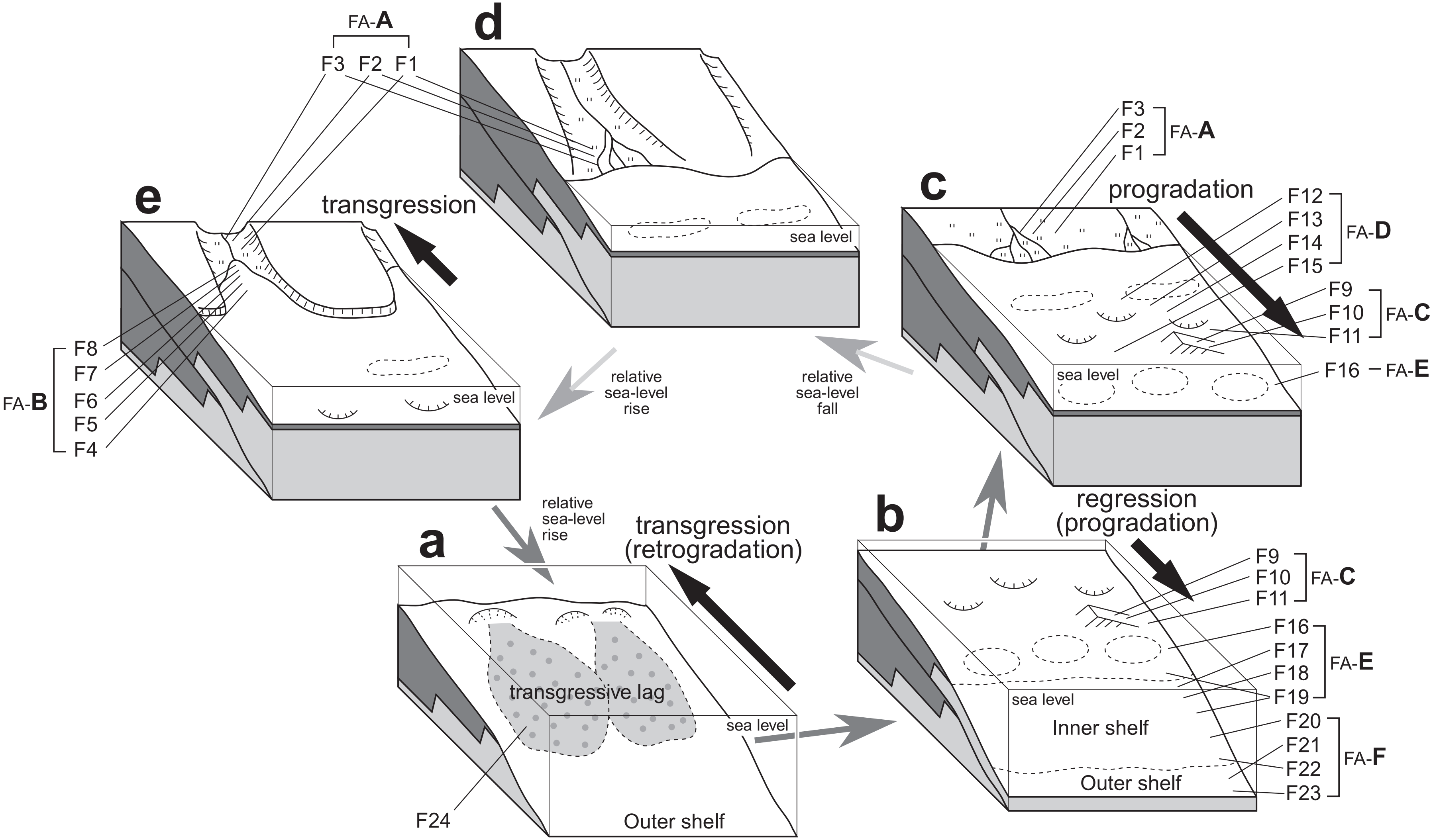

Fig. 11 Depositional model illustrating facies distributions, facies successions and sequences of the Hakobuchi Formation on the western margin of the Yezo basin, reflecting relative sealevel changes.

megafossil biostratigraphy based on the occurrence of *Sphenoceramus schmidti* and *Inoceramus balticus–Metaplacenticeras subtilistriatum*, respectively. These DSs and DSSs may represent repetitive eastward progradation and westward retrogradation of shallow-marine depositional systems on the western margin of the Yezo forearc basin, reflecting third- and fourth-order relative sealevel changes at intervals of about 8 m.y. The Hakobuchi Formation represents the final stage of deposition and uplift of the Yezo basin.

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