Cretaceous Research 26 (2005) 85–95

CRETACEOUS RESEARCH

www.elsevier.com/locate/CretRes

Unconformity between the Upper Maastrichtian and Upper Paleocene in the Hakobuchi Formation, north Hokkaido, Japan: a major time gap within the Yezo forearc basin sediments

Hisao Ando[a,*], Takashige Tomosugi[b]

[a]*Department of Environmental Sciences, Faculty of Science, Ibaraki University, Bunkyo 2-1-1, Mito 310-8512, Japan*

[b]*Department of Earth Science, Graduate School of Social and Cultural Studies, Kyushu University, 4-2-1, Ropponmatsu, Chuo-Ku, Fukuoka 810-8560, Japan*

Accepted in revised form 15 November 2004

Available online 12 January 2005

Abstract

Cretaceous sediments of the Yezo Group in the Yezo forearc basin-fill are widely distributed along the meridian zone of Hokkaido, Japan. The uppermost part of the Cretaceous sequence, namely the Hakobuchi Formation, ranges in age from Early Campanian to Late Maastrichtian and partly into Late Paleocene. It is subdivided into, in ascending order, the Kamikoma, Heitaro-zawa, Oku-utsunai and Utsunaigawa members in the Nakatonbetsu area, north Hokkaido. Recently, an unconformable sequence boundary was found between the Heitaro-zawa and Oku-utsunai members. A Lower Campanian and two Lower Maastrichtian inoceramid zones are established in the lower half of the Hakobuchi Formation. A lower Upper Maastrichtian ammonite fauna, composed of *Anagaudryceras matsumotoi*, *Pseudophyllites indura* and *Zelandites varuna*, can be recognized above the inoceramid extinction horizon in the upper Heitaro-zawa Member. Although there are no good index megafossils in the two overlying members, *Glycymeris* shell-beds of the basal Oku-utsunai Member overlie the Upper Maastrichtian Heitaro-zawa Member with a sharp, undulating, erosional surface. As Late Paleocene nannofossils were reported from the two upper members, the uppermost Maastrichtian and Lower Paleocene appear to have been eroded away at the unconformity. The K/Pg gap can be traced into the Oyubari and north Hobetsu areas of central Hokkaido and four drillholes offshore from Honshu in the Pacific Ocean. This might indicate large-scale subaerial erosion caused by a relative sea-level fall throughout the Yezo Basin.

Keywords: Biostratigraphy; Yezo Group; Sequence boundary; Maastrichtian; Paleocene; Inoceramid; Ammonite; North-west Pacific

1. Introduction

The Cretaceous/Palaeogene (K/Pg) boundary is important in connection with attempts to reconstruct Cretaceous to Cenozoic environmental changes and geohistory. Although Cretaceous sediments are widely distributed throughout the Japanese Islands, and include non-marine sediments and accretionary complexes, uppermost Cretaceous and Paleocene strata are limited to only a few areas, apart from within accretionary complexes. Only the Kawaruppu section of the Nemuro Group in east Hokkaido was documented by Saito et al. (1986) as a K/Pg boundary section. This group is regarded as the forearc basin-fill

* Corresponding author.

E-mail address: ando@mx.ibaraki.ac.jp (H. Ando).

0195-6671/$ - see front matter

doi:10.1016/j.cretres.2004.11.001

of the palaeo-Kuril arc-trench system (Nanayama et al., 1993). However, in this section it is difficult to determine precisely the faunal, floral and environmental changes between the Cretaceous and Paleocene owing to the presence of monotonous offshore mudstone lithofacies and limited fossil occurrences, except for some microfossils.

On the other hand, the Cretaceous Yezo forearc basin-fill of the palaeo-Japan arc-trench system facing the palaeo-Asian continent is widely distributed from south Sakhalin to the meridian zone of central Hokkaido. It has been called the Yezo Group (Matsumoto, 1951). As reviewed by Hirano et al. (1992), this group has been well studied geologically and palaeontologically. It contains well-preserved molluscan fossils such as ammonites, inoceramids and other bivalves, and microfossils occur in many beds and areas. The group includes thick, continuous, mostly marine siliciclastic deposits from the Lower Aptian to the Upper Maastrichtian (Matsumoto, 1942, 1943; Okada, 1983; Toshimitsu et al., 1995; Takashima et al., 1997, 2004). However, the uppermost Maastrichtian and its continuation into the Paleocene have not been biostratigraphically documented anywhere in the basin, apart from the presence of Paleocene planktonic foraminifers in the offshore siltstone facies of the upper part of the Hakobuchi Formation in the Nakatonbetsu area of north Hokkaido (Yasuda, 1986), and Late Paleocene dinoflagellate cysts and nannofossils in the upper part of the Hakobuchi Formation in the Oyubari (Suzuki et al., 1997) and Nakatonbetsu (Okada et al., 1998) areas. Recently, Ando et al. (2001) and Ando (2003) found an unconformity in the Nakatonbetsu area. Biostratigraphic data indicate that the uppermost Maastrichtian and Lower Paleocene have been eroded away.

In this paper a biostratigraphic zonation for the Campanian–Paleocene of the Hakobuchi Formation in the Nakatonbetsu area is described, based on our recent research on the megafossils and the microfossil studies of previous workers. We also describe the unconformity based on the field observations of outcrops and discuss its significance for reconstructing the sedimentary history of the Yezo forearc basin.

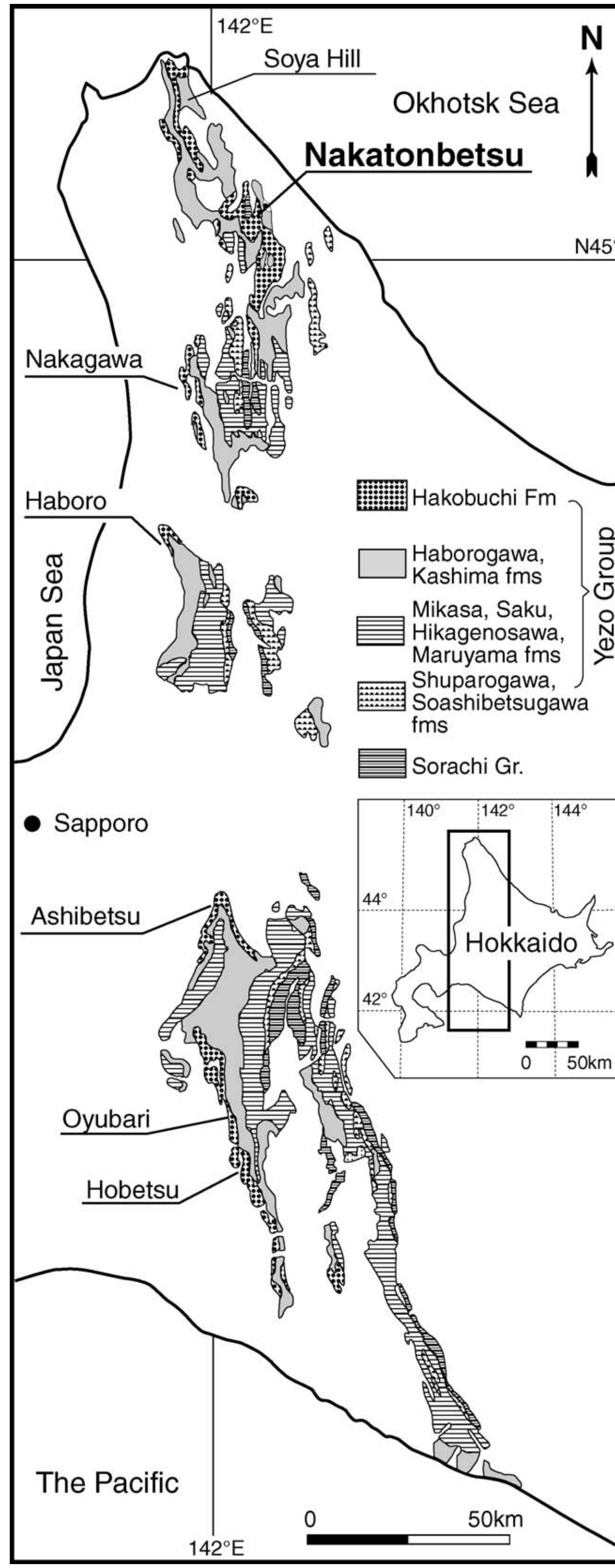

Fig. 1. Distribution of the Yezo Group and the location of the Nakatonbetsu area in the meridian zone of Hokkaido.

2. Geologic setting of the Hakobuchi Formation in the Nakatonbetsu area

Cretaceous sediments filling the Yezo forearc basin, called the Yezo Group (Matsumoto, 1951), are widely distributed over a distance of 800 km from south Sakhalin to the meridian zone of central Hokkaido and have a North–South trend (e.g., Matsumoto, 1942, 1943; Hirano et al., 1992; Ando, 2003; Takashima et al.,

2004) (Fig. 1). This very thick siliciclastic sequence conformably overlies the Sorachi Group, an ocean floor sequence that was deposited during the Late Jurassic-Barremian. It is 10,000 m thick in the type section in the Oyubari area (Matsumoto, 1942; Motoyama et al., 1991; Takashima et al., 2004). It is separated by a disconformity or a gentle angular unconformity from the overlying Middle–Upper Eocene coal-bearing Ishikari Group, the Upper Eocene–Lower Oligocene Poronai Group, or Miocene marine strata. As reviewed in Takashima et al. (2004), the nomenclature of the lithostratigraphic divisions of the Yezo Group are complicated and differ between the areas investigated within Hokkaido. Several names have been used synonymously for the same lithostratigraphic unit: e.g., the Yezo Supergroup (Okada, 1983) was proposed to unify the conventionally-used Lower, Middle and Upper Yezo groups and Hakobuchi Group in ascending order. Although Ando et al. (2001) and Ando (2003) adopted this usage, this paper follows Takashima et al. (2004), who proposed a new, synthesized stratigraphic framework based on extensive macro- and microfossil biostratigraphy in the central region of Hokkaido: the Soashibetsugawa, Shuparogawa, Maruyama and lower Hikagenosawa formations (Aptian–Albian), the Hikagenosawa, Saku and Kashima formations or the Mikasa and Haborogawa formations (uppermost Albian–lower Campanian) and the Hakobuchi Formation (Lower Campanian–Paleocene).

Within the offshore mudstone-dominated Yezo Group, the Hakobuchi Formation is characterized by the presence of shallow-marine to fluvial sandstones except in the Nakatonbetsu area (Fig. 1). It overlies the Kashima Formation, which is composed of monotonous offshore mudstone, in some places conformably with gradational facies changes, in other places unconformably with erosional and abrupt facies changes. The Hakobuchi Formation seems to have been deposited along the western margin of the Yezo forearc basin during the Early Campanian–Late Maastrichtian and partly during the Late Paleocene at the final filling stage of the basin. It is distributed in the Soya Hill, Nakatonbetsu, Nakgawa, Haboro, Ashibetsu, Oyubari and Hobetsu areas. In the Nakatonbetsu area it is dominated by offshore marine strata composed of siltstones, sandy siltstones and silty fine-grained sandstones that commonly yield ammonites and inoceramids. As a result it is suitable for establishing a megafossil biostratigraphic zonation of the Campanian–Maastrichtian, detecting patterns of ammonite and inoceramid extinctions, and determining the appearance of Paleocene fauna. The stratigraphic framework and geologic structure of the Nakatonbetsu area have been described in detail previously by Ando et al. (2001).

The Hakobuchi Formation in the Nakatonbetsu area is lithostratigraphically subdivided into four members (formations in Ando et al., 2001), namely: the Kamikoma, Heitaro-zawa, Oku-utsunai, Utsunaigawa members (Fig. 2). The thickness of the formation reaches about 2600 m, which is several times thicker than in the other areas.

The Kamikoma Member is 1000 m thick and composed mainly of dark grey to bluish grey massive siltstones and sandy siltstones. Rarely intercalated are fine-grained sandstones less than 10 m thick and acid tuffs less than 3 cm thick. Fossils are scarce. It differs from the Kotobuki Member of the Kashima Formation in being somewhat sandier with frequent sandstone intercalations, although their stratigraphic relationship is conformable and their lithologies are similar overall.

The Heitaro-zawa Member consists mainly of massive or bioturbated sandy siltstone, often associated with fine- to very fine-grained sandstone layers several to a few tens of metres thick. Acidic tuff layers a few to several tens of centimetres thick are also occasionally present. Hummocky cross-stratification (HCS) in fine-grained sandstone has been noted in a few horizons in the lower part of the member. The member ranges from 500 to 1000 m in thickness. Calcareous concretions are often contained in the lower and middle parts and some of them enclose fossils such as ammonites, inoceramids and other bivalves, gastropods, and less commonly solitary corals and echinoid spines. However, both concretions and fossils are rare in the upper part of the member.

The Oku-utsunai Member overlies the Heitaro-zawa Member with an erosional surface and disconformity. It is largely composed of greenish grey to grey, silty, very fine- to fine-grained sandstone with subordinate sandy siltstone. Acid tuff layers a few centimetres to a few tens of centimetres thick are occasionally intercalated. The basal erosion surface separates offshore siltstone from overlying shallow-marine sandstone. Except for the glycymerid shell-beds at the base, only small bivalves and brachiopods occur, and these are rare and poorly preserved.

The Oku-utsunai Member grades conformably into the overlying massive or bioturbated sandy siltstone of the Utsunaigawa Member in which fine- to medium-grained sandstones are rare. Calcareous concretions and fossils are also rare, but small bivalves less than 1 cm in maximum dimension occur occasionally. The member is disconformably overlain by the Upper Eocene–Lower Oligocene Utsunai Formation, which is composed of pale–medium grey siltstone and sandstone (Kaiho, 1984).

3. Biostratigraphic zonation

The Late Cretaceous molluscan fauna in the North Pacific region is biogeographically endemic. Cosmopolitan species are rare; hence, it is usually difficult to correlate Japanese sections with European standard sections. However, the biostratigraphic work of Matsumoto (e.g., Matsumoto, 1959; Matsumoto et al., 1985) and Toshimitsu et al. (1995), has established an ammonite and inoceramid zonation of the Yezo Group in Hokkaido. Recent bio- and magnetostratigraphic studies in Sakhalin (Shigeta et al., 1999; Kodama et al., 2000, 2002) generally support Matsumoto's zonal scheme.

Fig. 2 is an integrated columnar section showing the stratigraphic ranges of important ammonites, inoceramids and some other fossils and their biostratigraphic zonation compared with the previous microfossil zonations. Since the megafossil occurrences are not common enough to enable the establishment of a zonation at a single section in this area, all occurrence data are integrated into a single column species by species, using the boundary between the Kamikoma and Heitaro-zawa members as a base line. Therefore, stratigraphic positions of the fossiliferous horizon are inevitably generalized.

Megafossils such as ammonites and inoceramids are very rare in the Kotobuki Member and rare in the Kamikoma Member. They are common in the lower and middle parts of the Heitaro-zawa Member but rare again in the uppermost Heitaro-zawa Member and, apart from the basal glycymerid beds and some poorly preserved small bivalves and brachiopods in the Oku-utsunai Member, they are absent from this and the Utsunaigawa Member.

As inoceramids occur frequently and continuously in contrast to ammonites, four inoceramid zones are recognized based on their first appearance and stratigraphic ranges, namely the *Sphenoceramus schmidti*, *Inoceramus shikotanensis*, *Sphenoceramus hetonaianus* and *Inoceramus balticus* zones. The first two are regarded as interval zones (Salvador, 1994) defined by the first appearance of two successive species. The third is equivalent to a taxon range zone (Salvador, 1994), and the last is based on only one horizon with *Inoceramus* cf. *balticus*.

The occurrence of *Sphenoceramus schmidti* Zone in the upper part of the Kotobuki Member and the lower and middle parts of the Kamikoma Member indicates an Early (but not earliest) to Middle Campanian age according to Toshimitsu et al. (1995) and Kodama et al. (2002). This zone may be subdivided into *Gigantocapulus transformis* and *Anomia* sp. subzones.

Inoceramus cf. *balticus*, as an index fossil of the Upper Campanian, occurs at two exposures of the upper part of the Kamikoma Member, but one of these cannot be placed within the stratigraphic succession because of fault disturbance. The other is just below the *Inoceramus shikotanensis* Zone, suggesting that thin Late Campanian strata are present in the Nakatonbetsu area.

Inoceramus shikotanensis and *Sphenoceramus hetonaianus* were thought by Toshimitsu et al. (1995) to be indicative of the Lower Maastrichtian and the upper Lower–lower Upper Maastrichtian, respectively. According to the recent biostratigraphic and magnetostratigraphic studies of Kodama et al. (2000, 2002) in Sakhalin, these two species are considered to indicate the lower Lower and upper Lower Maastrichtian, respectively. Since no inoceramids have been found above the highest occurrence of *S. hetonaianus* and *Inoceramus kusiroensis*, the overlying deposit seems to represent the inoceramid extinction event in this area. *Tenuipteria awajiensis*, a very thin-shelled bivalve species somewhat similar to inoceramids, occurs at a few horizons. It is, however, different from them and is referred to the Bakevellidae.

A taxonomically restricted ammonite fauna consisting of some smooth-flanked species, such as *Anagaudryceras matsumotoi*, *Pseudophyllites indura* and *Zelandites varuna*, occurs above the inoceramid extinction horizon. Because of a lack of short-ranging species and the fact that its upper limit was eroded at the unconformity, it is difficult to determine this ammonite zone. Based on the data of Kodama et al. (2000, 2002), it suggests the lower part of the Upper Maastrichtian and, therefore, appears to be a fauna that has not been well known previously in the north-west Pacific region. As a result, the Kamikoma and Heitaro-zawa members are assigned to the upper Lower Campanian–lower Lower Maastrichtian, and upper Lower–lower Upper Maastrichtian, respectively.

The unnamed ammonite zone is overlain by the basal conglomerate and sandstone beds of the Oku-Utsunai Member but is separated from them by a sharp erosional unconformity. Both the Oku-utsunai and Utsunaigawa members contain only a few species of poorly preserved small bivalves and brachiopods. According to the foraminiferal biostratigraphy of Yasuda (1986), the latter is Paleocene in age. More recently, Okada et al. (1998) found Maastrichtian nannofossils in the uppermost Heitaro-zawa Member and late Paleocene species in the Oku-utsunai and Utsunaigawa members. They regarded the latter occurrences to correlate with the CP4 nannoplankton zone.

Judging from both the mega- and microfossil biostratigraphy, the uppermost Maastrichtian and Lower Paleocene as well as the K/Pg boundary seem to have been eroded away at the boundary between the Heitaro-zawa and Oku-utsunai members. The unconformable relationship between the two members has been confirmed in five of a total of 49 sections investigated in the Nakatonbetsu area (Ando et al., 2001). The time gap is estimated to be 8–10 myr, according to the time scale by Berggren et al. (1995) and Gradstein et al. (1995).

4. Exposures of the unconformity within the Hakobuchi Formation

Fig. 3 is a photograph and sketch of the exposure that best shows the stratigraphic relations and disconformity between the Heitaro-zawa and Oku-utsunai members. It

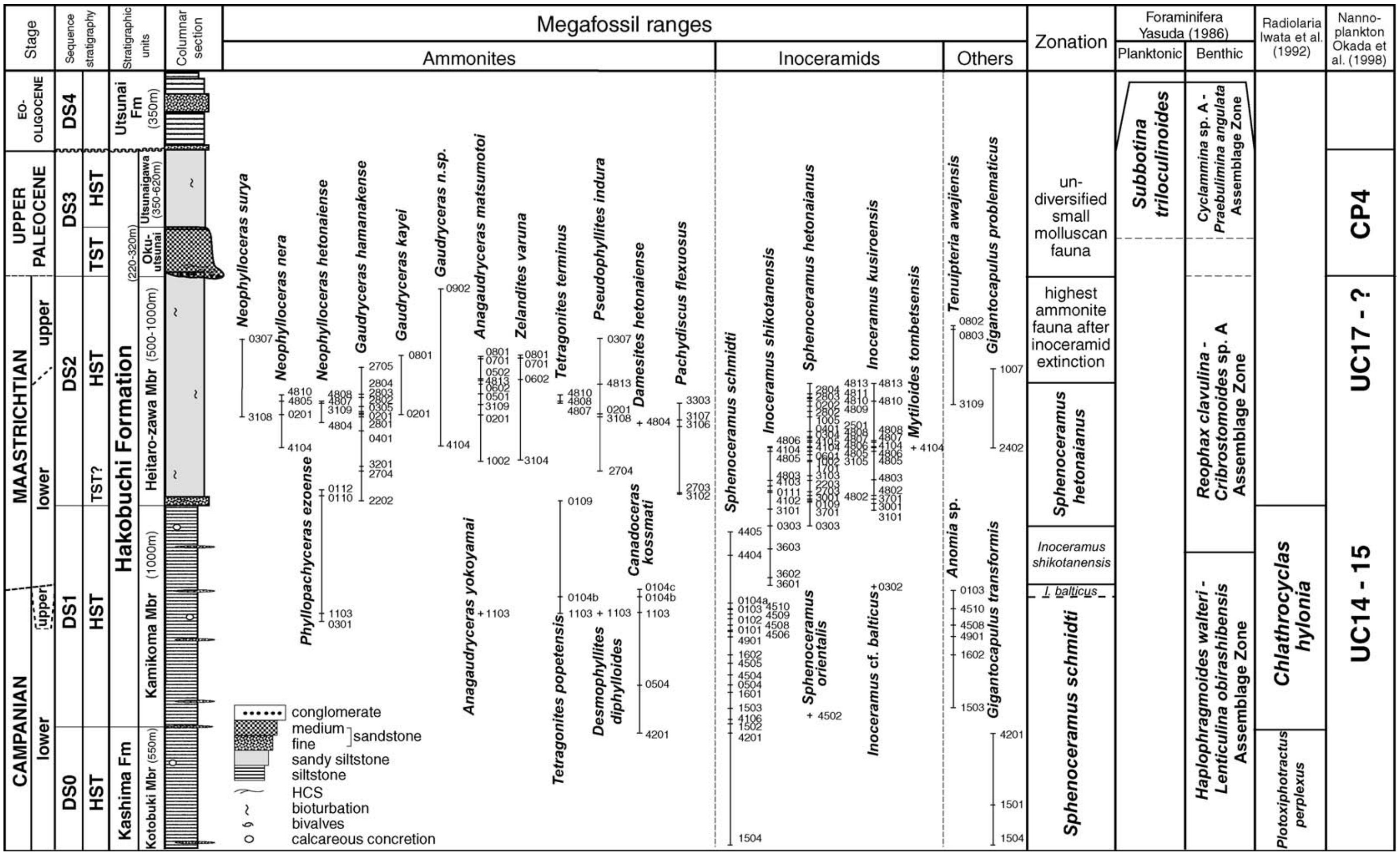

Fig. 2. Integrated mega- and microfossil biostratigraphic zonation of the Hakobuchi Formation in the Nakatonbetsu area. Numbers refer to fossil localities noted in Ando et al. (2001).

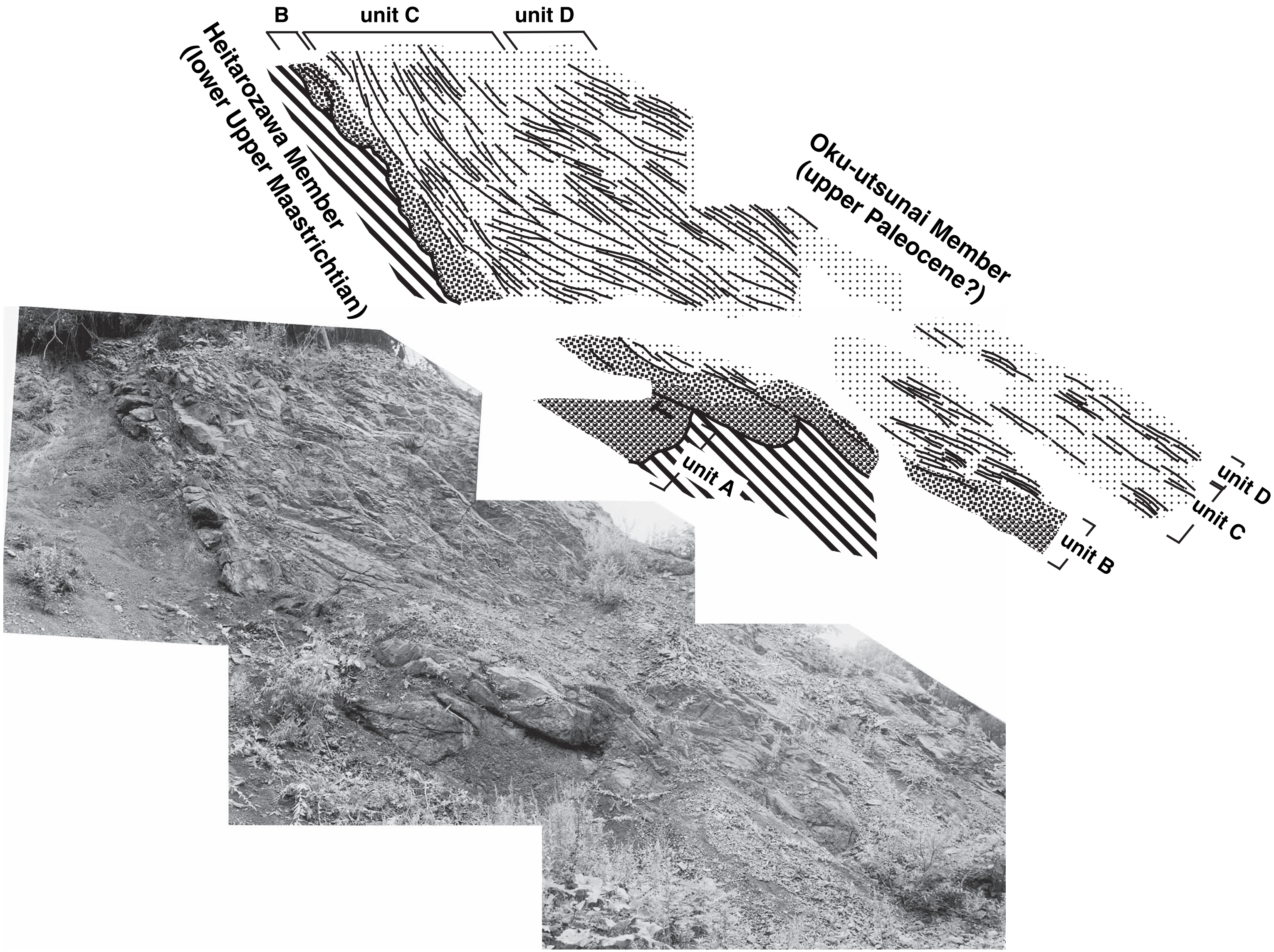

Fig. 3. Photograph and sketch of the unconformity at outcrop in the upper course of the Utsunai River, Nakatonbetsu area, north Hokkaido.

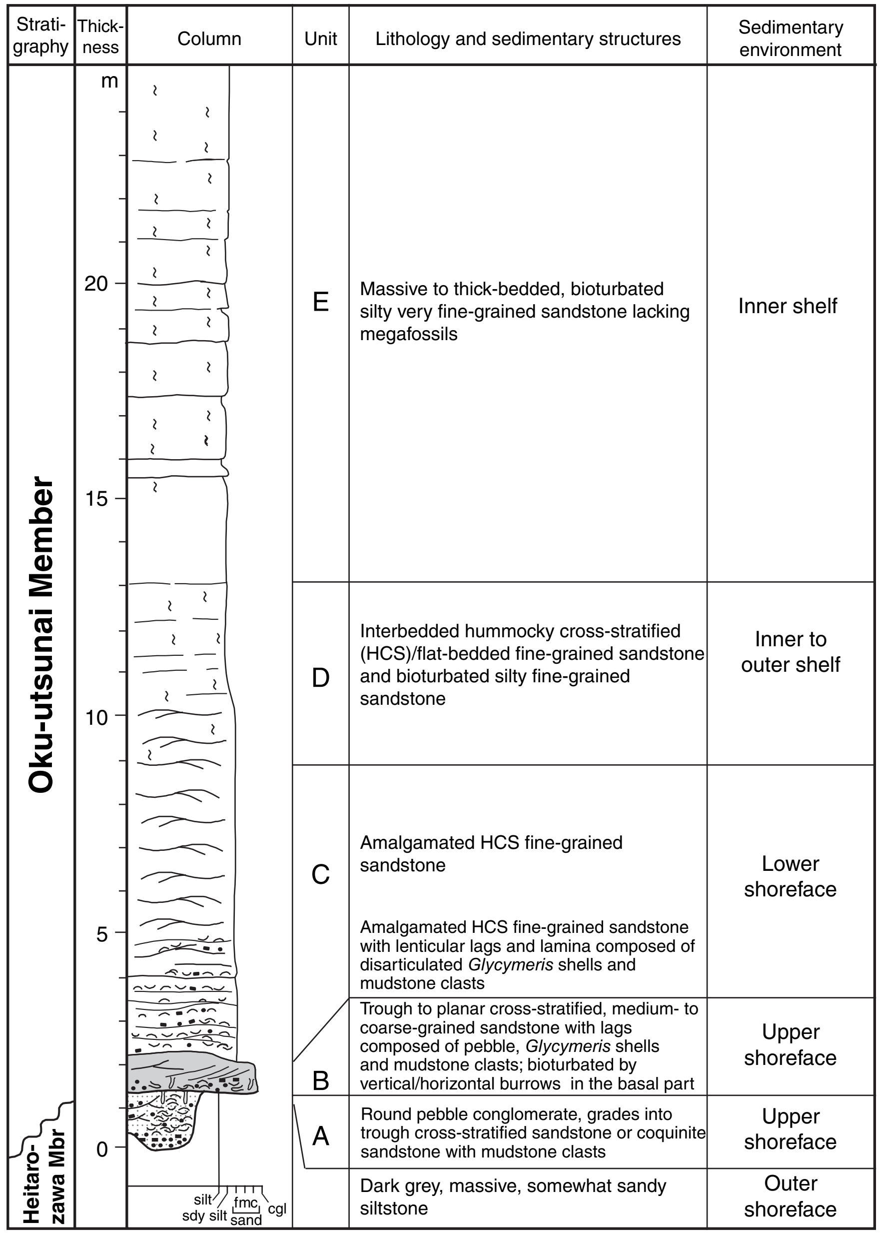

Fig. 4. Geological columnar section of the unconformity between the Heitaro-zawa and Oku-utsunai members at outcrop, showing an erosion surface and the transgressive facies succession.

is in the upper course of the Utsunai River. An irregularly undulating and channel-based erosion surface separates the offshore-marine massive siltstone of the Heitaro-zawa Member from the lower shoreface to inner shelf, fine-grained sandstone of the Oku-utsunai Member. The latter is subdivided into five lithologic units (A–E), the lowest two of which are described below in more detail.

An intermittent lenticular layer of conglomerate to coarse-grained sandstone several tens of centimetres up to 2.2 m thick overlies the erosional surface (units A and B in Figs. 3, 4). Unit A is limited to the central part of the outcrop whereas unit B has laterally variable lithology. The conglomerate of the two units is composed of round pebbles of chert, andesitic volcanic rocks, quartz porphyry, acid tuff and subangular mudstone clasts (Fig. 5A). It is partly gravel-supported but usually matrix-supported; the matrix is moderately sorted coarse- to medium-grained sand. The upper part of unit A grades into trough cross-stratified sandstone, or shelly sandstone (coquina) containing a small number of scattered pebbles (Fig. 5B). The rock is too hard to extract fossils, with the result that they cannot be identified at species level; however, they seem to be mostly composed of glycymerid bivalves (*Glycymeris* sp.). Other small bivalves and brachiopods are subordinate and cannot be identified owing to their poor preservation.

Unit A is terminated by a sharp, almost flat erosional surface. It is overlain by unit B, which consists mainly of coarse- to medium-grained sandstones, several tens of centimetres thick that are vertically and horizontally bioturbated, with some burrows penetrating into unit A (or even into the Heitaro-zawa Member) and forming sole marks on the erosion surface (Fig. 5C). They are filled with coarse- to medium-grained sand. The basal part of the unit B is a lenticular pebble conglomerate that encloses mudstone clasts and shell lags less than a few tens of centimetres thick (Fig. 5A). The occurrence of trough and planar cross-stratification in the unit suggests a high-energy environment of deposition caused by waves or current agitation.

Units A and B are overlain by hummocky cross-stratified (HCS) fine-grained sandstones (7 m thick: unit C), HCS fine-grained sandstones interbedded with bioturbated sandy siltstone (4 m: unit D), and bioturbated sandy siltstone (more than 12 m: unit E), showing a fining-upward or transgressive facies succession. The lowest 3 m of unit C often contain lenticular shell-beds a few centimetres thick composed of disarticulated *Glycymeris* shells, other small bivalves, and mudstone clasts (Fig. 4D).

The erosional surface is interpreted to be sequence boundary (SB), formed by subaerial erosion or non-deposition during a relative sea-level fall in the latest Maastrichtian–early Paleocene. The basal conglomerate and sandstone (units A and B) can be regarded as transgressive lags (Walker and Plint, 1992).

5. Significance of the unconformity: a major time gap in the forearc sedimentation

It has been recognized through stratigraphic and sedimentological studies that the Hakobuchi Formation shows the complicated stacking patterns of third- and fourth-order sequences (or parasequences) in the western marginal facies apart from in the Nakatonbetsu area (e.g., Ando, 1993, 1997, 2003, 2004; Ando et al.,

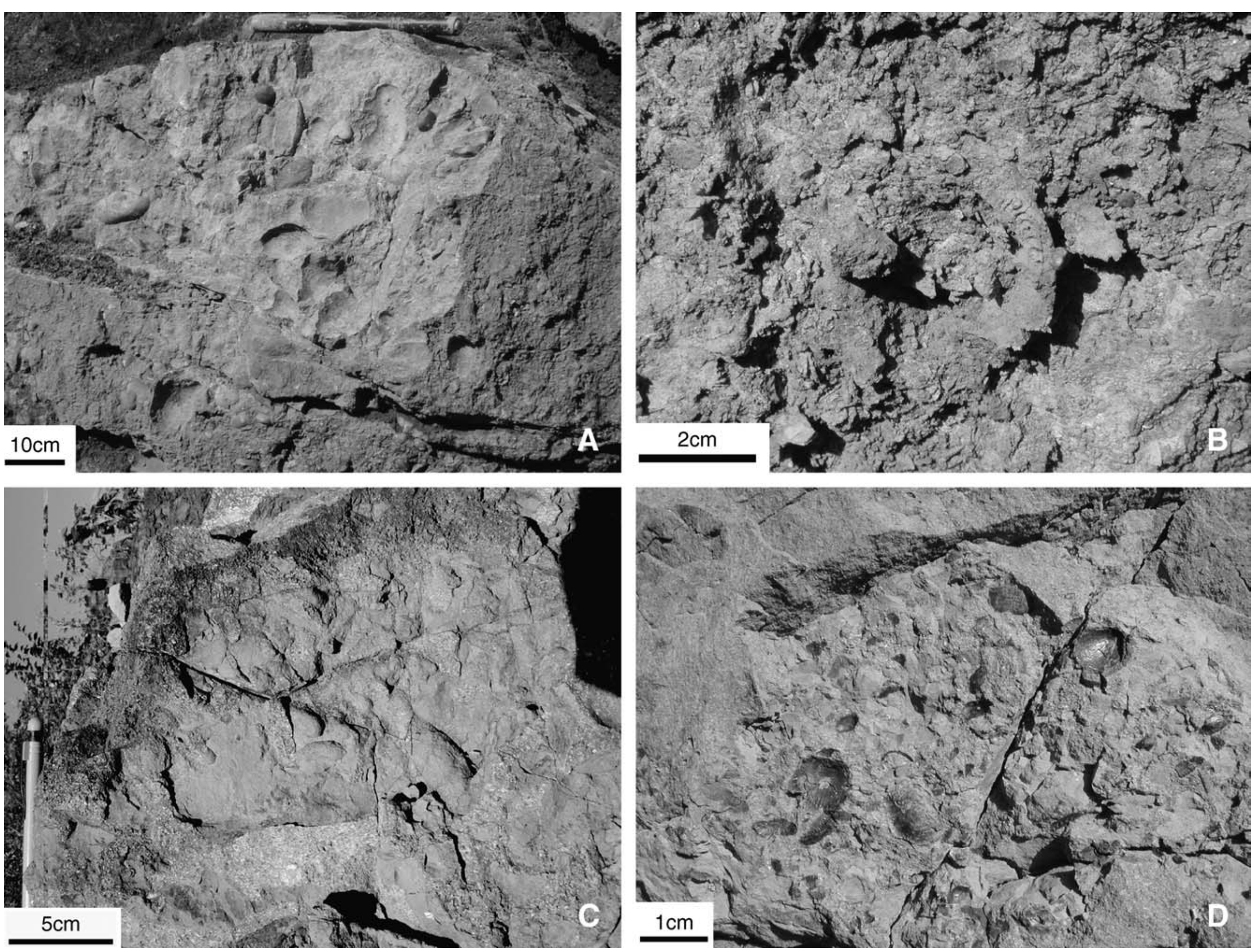

Fig. 5. A, lower surface of pebble conglomerate of unit A. B, lower surface of shell-rich sandstone (coquina) showing ligamental area of *Glycymeris* sp. C, burrowed lower surface of unit B; horizontal and vertical burrows are filled with coarse- to medium-grained sandstone. D, upper surface of a lenticular lag composed of *Glycymeris* shells and mudstone clasts in amalgamated hummocky cross-stratified (HCS) sandstone (unit C).

2001; Ando and Ando, 2002). It constitutes several repetitive upward-coarsening units of offshore sandy siltstone to shoreface sandstone, associated with fluvial sandstones, mudstones and sometimes coaly beds as lowstand sediments. Several sequence boundaries and related key features such as ravinement and marine-flooding surfaces are regionally traceable in places, but owing to limited palaeontological evidence in shallow-marine to non-marine facies, the sequence boundaries have not been well documented biostratigraphically.

The sequence boundary described above is, however, biostratigraphically well documented because the Hakobuchi Formation in the Nakatonbetsu area represents an eastern offshore facies enclosing mega- and microfossils. The absence of uppermost Maastrichtian–Lower Paleocene strata is also characteristic of the Oyubari and north Hobetsu areas (Suzuki et al., 1997) and in four drillhole successions in offshore North Honshu (Ando, 2003), and may reflect widespread subaerial erosion during a relative sea-level fall around the K/Pg boundary throughout the Yezo Basin. After this hiatus, marine to non-marine sediments were sporadically deposited during the Late Paleocene in the Nakatonbetsu, Yubari and north Hobetsu areas in Hokkaido, and parts of the offshore Kitakami and Joban subbasins in North Honshu. Lithologic and tectonic changes associated with it cannot be detected in North Honshu or Hokkaido. The lithologic similarity between the uppermost Hakobuchi Formation and the uppermost Paleocene–Lower Eocene Haboro Formation in the Haboro area (Kurita and Obuse, 1994) suggests that the latter was located in the Yezo Basin. After the early Eocene, the middle Eocene–early Oligocene Ishikari Basin was formed in central Hokkaido during widespread tectonic activity, possibly influenced by movement of the Kula and Pacific plates and their bounding oceanic ridge (Iijima, 1996; Kurita and Yokoi, 2000).

Glycymeris shell-beds occurring in the basal part of the Oku-utsunai Member are related to a Paleocene shallow-marine fauna that has not been well known hitherto (Tashiro et al., 1980; Tashiro, 1985). Except for *Glycymeris*, the faunal assemblage involves impoverished small bivalves and brachiopods. The mode of formation of these shell-beds may be inferred from comparisons with the taphonomy, ecology and palaeoecology of other *Glycymeris*-dominated shell-beds in Upper Cretaceous–Recent deposits (e.g., Matsukuma, 1986; Ando and Kodama, 1998). *Glycymeris* also occurs in the Mikasa (Ando and Kodama, 1998) and Haborogawa (Tashiro, 1985) formations. Specimens are often present as lags or laminae within the HCS sandstone of the Mikasa Formation. They are inferred to have lived on a storm-dominated lower shoreface to inner shelf (sublittoral) sandy bottom as infauna (shallow burrower).

6. Conclusions

A disconformity separates the upper Lower–lower Upper Maastrichtian offshore siltstone of the Heitaro-zawa Member from the Upper Paleocene lower shoreface to inner shelf sandstone of the Oku-utsunai Member of the Hakobuchi Formation in the Nakatonbetsu area, north Hokkaido. A Lower Campanian and two Lower Maastrichtian inoceramid zones (*Sphenoceramus schmidti*, *Inoceramus shikotanensis* and *Spehenoceramus hetonaianus* Zones, respectively) are established in the lower half of the formation, based on previous microfossil and palaeomagnetic studies in Hokkaido and Sakhalin. A lower Upper Maastrichtian ammonite fauna composed of a few smooth-flanked species occur above the inoceramid extinction horizon in the upper Heitaro-zawa Member. This fauna may be the youngest ammonite fauna present in the north-west Pacific region. *Glycymeris* shell-beds occur in the basal part of the Upper Paleocene Oku-utsunai Member. They appear to have been derived from a shoreface to inner shelf sandy bottom fauna, which may be important in analyses of evolutionary changes in Paleocene shallow-marine biota. A major time gap between Late Cretaceous and Palaeogene deposits within the Hakobuchi Formation is indicated by an erosional surface in the Oyubari and north Hobetsu areas of central Hokkaido and in four drillhole successions located offshore from northern Honshu in the Pacific Ocean. This gap indicates erosion and sea-level fall during the K/Pg transition throughout the Yezo Basin.

Acknowledgements

We thank Tadashi Oguro (JOGMEC Japan Oil, Gas and Metals National Corporation), Takao Iwata (Teikoku Oil Co. Ltd.) and Hiroshi Kurita (Niigata University) for providing much information on the exploration in the Yezo Basin. We are most grateful to Yasunari Shigeta (National Science Museum), Seiichi Toshimitsu (Geological Survey of Japan), Hisatake Okada (Hokkaido University) and Hiromichi Hirano (Waseda University) for assisting our biostratigraphical studies. Special thanks go to Dr. Luba F. Jansa and Graciano P. Yumul Jr. for helpful reviews, and to David J. Batten and Xiaoqiao Wan for editorial work. This research has been supported in part by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (nos. 10640446).

References

Ando, H., 1993. Depositional facies and sequences of the Hakobuchi Group (Upper Cretaceous) in the Sorachi Anticline. Journal of the Sedimentological Society of Japan 38, 45–52 (in Japanese, English abstract).

Ando, H., 1997. Apparent stacking patterns of depositional sequences in the Upper Cretaceous shallow-marine to fluvial successions, Northeast Japan. Memoirs of the Geological Society of Japan 48, 43–59.

Ando, H., 2003. Stratigraphic correlation of Upper Cretaceous to Paleocene forearc basin sediments in Northeast Japan: cyclic sedimentation and basin evolution. Journal of Asian Earth Sciences 21, 919–933.

Ando, H., 2004. Large-scale geologic factors controlling sedimentation of the Upper Cretaceous forearc basin sequences in Northeast Japan: eustasy, volcanism and relative plate motion. Journal of the Geological Society of Thailand, Special Issue, 35–44.

Ando, M., Ando, H., 2002. Depositional facies and megafossil biostratigraphy of the Upper Cretaceous Hakobuchi Group in the Soya Hill area, northern Hokkaido. Bulletin of the Nakagawa Museum of Natural History 6, 1–21 (in Japanese, English abstract).

Ando, H., Kodama, T., 1998. Shallow-marine bivalvian faunal change during Cenomanian to Turonian, Late Cretaceous – Ponbetsu River section in the Mikasa Formation, Middle Yezo Group, Hokkaido, Japan. Bulletin of the Mikasa City Museum 2, 1–15 (in Japanese, English abstract).

Ando, H., Tomosugi, T., Kanakubo, T., 2001. Upper Cretaceous to Paleocene Hakobuchi Group, Nakatonbetsu area, northern Hokkaido – lithostratigraphy and megafossil biostratigraphy. Journal of the Geological Society of Japan 107, 142–162 (in Japanese, English abstract).

Berggren, W.A., Kent, D.V., Swisher III, C.C., Aubry, M.P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.P., Hardenbol, J. (Eds.), Geochronology Time Scales and Global Correlation. SEPM (Society for Sedimentary Geology) Special Publication 54, 129–212.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J., Van Veen, P., Thierry, J., Huang, Z., 1995. A Triassic, Jurassic and Cretaceous time scale. In: Berggren, W.A., Kent, D.V., Aubry, M.P., Hardenbol, J. (Eds.), Geochronology Time Scales and Global Correlation. SEPM (Society for Sedimentary Geology) Special Publication 54, 95–126.

Hirano, H., Tanabe, K., Ando, H., Futakami, M., 1992. Cretaceous forearc basin of central Hokkaido: lithofacies and biofacies characteristics. In: Adachi, M., Suzuki, K. (Eds.), The 29th IGC Field Trip Guidebook, vol. 1: Paleozoic and Mesozoic Terranes: Basement of the Japanese Island Arcs. Nagoya University, pp. 45–80.

Iijima, A., 1996. Evolution of the Paleogene sedimentary basins in Hokkaido. Journal of Geography 105, 178–197 (in Japanese, English abstract).

Kaiho, K., 1984. Paleogene foraminifera from Hokkaido, Japan. Parts 1, 2. Science Reports of Tohoku University, Series 2 (Geology) 54, 95–139, 55, 1–74.

Kodama, K., Maeda, H., Shigeta, Y., Kase, T., Takeuchi, T., 2000. Magnetostratigraphy of Upper Cretaceous strata in South Sakhalin, Russian Far East. Cretaceous Research 21, 469–478.

Kodama, K., Maeda, H., Shigeta, Y., Kase, T., Takeuchi, T., 2002. Integrated biostratigraphy and magnetostratigraphy of the Upper Cretaceous System along the River Naiba in southern Sakhalin, Russia. Journal of the Geological Society of Japan 108, 366–384 (in Japanese, English abstract).

Kurita, Y., Obuse, A., 1994. Paleogene dinoflagellate cysts and pollen from the Haboro Formation, northern central Hokkaido, Japan, and their chronostratigraphic and paleoenvironmental implications. Journal of the Geological Society of Japan 100, 292–301 (in Japanese, English abstract).

Kurita, Y., Yokoi, S., 2000. Cenozoic tectonic settings and a current exploration concept in southern central Hokkaido, northern Japan. Journal of the Japanese Association for Petroleum Technology 65, 58–70 (in Japanese, English abstract).

Matsukuma, A., 1986. Cenozoic glycymeridid bivalves of Japan. Palaeontological Society of Japan, Special Paper 29, 77–91.

Matsumoto, T., 1942. Fundamentals in the Cretaceous stratigraphy of Japan. Part I. Memoirs of the Faculty of Science, Kyushu Imperial University, Series D, Geology 1, 129–280.

Matsumoto, T., 1943. Fundamentals in the Cretaceous stratigraphy of Japan. Parts II, III. Memoirs of the Faculty of Science, Kyushu Imperial University, Series D, Geology 2, 98–237.

Matsumoto, T., 1951. The Yezo Group and the Kwanmon Group. Journal of the Geological Society of Japan 57, 95–98 (in Japanese, English abstract).

Matsumoto, T., 1959. Zonation of the Upper Cretaceous in Japan. Memoirs of the Faculty of Science, Kyushu University, Series D, Geology 9, 55–93.

Matsumoto, T., Obata, I., Hirano, H., 1985. Mega-fossil zonation of the Cretaceous System in Japan and correlation with the standards in Western Europe. Memoirs of the Geological Society of Japan 26, 29–42 (in Japanese, English abstract).

Motoyama, I., Fujiwara, O., Kaiho, K., Murota, T., 1991. Lithostratigraphy and calcareous microfossil biochronolgy of the Cretaceous strata in the Oyubari area, Hokkaido, Japan. Journal of the Geological Society of Japan 97, 507–527 (in Japanese, English abstract).

Nanayama, F., Kanamatsu, T., Fujiwara, Y., 1993. Sedimentary petrology and paleotectonic analysis of the arc-arc junction: the Paleocene Nakanogawa Group in the Hidaka Belt, central Hokkaido, Japan. Palaeogeography, Palaeoclimatology, Palaeoecology 105, 53–69.

Okada, H., 1983. Collision orogenesis and sedimentation in Hokkaido, Japan. In: Hashimoto, M., Uyeda, S. (Eds.), Accretion Tectonics in the Circum-Pacific Regions. Terra Science Publishing, Tokyo, pp. 91–105.

Okada, H., Kumada, A., Suwa, T., Kurita, H., Shigeta, Y., 1998. Calcareous nannofossil assemblage from the Yezo Supergroup and its upper strata (preliminary report). Abstracts with Programs, 1998 Annual Meeting of the Palaeontological Society of Japan, p. 13 (in Japanese).

Saito, T., Yamanoi, T., Kaiho, K., 1986. End Cretaceous devastation of terrestrial flora in the boreal Far East. Nature 323, 253–255.

Salvador, A. (Ed.), 1994. International Stratigraphic Guide: A Guide to Stratigraphic Classification, Terminology, and Procedure, second ed. Geological Society of America, Boulder, 214 pp.

Shigeta, Y., Maeda, H., Uemura, K., Solov'yov, A.V., 1999. Stratigraphy of the Upper Cretaceous System in the Kril'on Peninsula, South Sakhalin, Russia. Bulletin of the National Science Museum, Tokyo, Series C 25, 1–27.

Suzuki, H., Kurita, H., Hoyanagi, K., Ando, H., Makino, A., Tsutai, S., 1997. Paleocene strata found at Yubari area and their sedimentary environments. Abstracts, 105th Annual Meeting of the Geological Society of Japan, p. 62 (in Japanese).

Takashima, R., Nishi, H., Saito, T., Hasegawa, T., 1997. Geology and planktonic foraminiferal biostratigraphy of Cretaceous strata distributed along the Shuparo River, Hokkaido, Japan. Journal of the Geological Society of Japan 103, 543–563 (in Japanese, English abstract).

Takashima, R., Kawabe, F., Nishi, H., Moriya, K., Wani, R., Ando, H., 2004. Geology and stratigraphy of forearc basin sediments in Hokkaido, Japan: Cretaceous environmental events on the northwest Pacific margin. Cretaceous Research 25, 365–390.

Tashiro, M., 1985. Bivalve faunas and their biostratigraphy of the Cretaceous in Japan. Memoirs of the Geological Society of Japan 26, 43–75 (in Japanese, English abstract).

Tashiro, M., Taira, A., Matsumoto, T., 1980. Biostratigraphy and depositional facies of the Cretaceous-Tertiary boundary strata in Amakusa-Shimojima, Kyushu, western Japan. Cretaceous Research 1, 13–26.

Toshimitsu, S., Matsumoto, T., Noda, M., Nishida, T., Maiya, S., 1995. Towards an integrated mega-, micro- and magnetostratigraphy

of the Upper Cretaceous in Japan. Journal of the Geological Society of Japan 101, 19–29 (in Japanese, English abstract).
Walker, R.G., Plint, A.G., 1992. Wave- and storm-dominated shallow marine systems. In: Walker, R.G., James, N.P. (Eds.), Facies Models: Response to Sea-level Change. Geological Association of Canada, Waterloo, Ontario, pp. 219–238.
Yasuda, N., 1986. Cretaceous and Paleocene foraminifera from northern Hokkaido, Japan. Science Reports of Tohoku University, Series 2 (Geology) 57, 1–101.