

Middle and late Maastrichtian (latest Cretaceous) ammonoids from the Akkeshi Bay area, eastern Hokkaido, northern Japan and their biostratigraphic implications

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Received March 16, 2014; Revised manuscript accepted July 15, 2014

Abstract. Nine ammonoid species are reported from the Maastrichtian Senpohshi Formation exposed along the western coast of Akkeshi Bay, eastern Hokkaido, and their respective chronologic assignments are discussed on the basis of a previous magnetostratigraphic study. *Pachydiscus flexuosus* occurs in the lower and middle parts of the formation (= polarity chron C31n, i.e., middle to upper middle Maastrichtian). *Gaudryceras makarovense*, *Anagaudryceras matsumotoi* and *Diplomoceras* cf. *notabile* and *P. flexuosus* as well occur in the lower part (middle middle Maastrichtian). The uppermost part of the formation (= probably the lower part of polarity chron C30n, i.e., lower upper Maastrichtian) is fossiliferous and yields a diverse ammonoid assemblage including *Neophylloceras* sp., *Pseudophyllites* sp., *Zelandites varuna*, *A. matsumotoi*, *Gaudryceras* cf. *seymouriense*, *Gaudryceras* sp., and *D.* cf. *notabile*. Integration of bio- and magnetostratigraphy in the Senpohshi Formation makes it possible to determine precise and detailed chronologic assignment of strata containing similar faunas in the Northwest Pacific realm.

Key words: Akkeshi, ammonoid, Cretaceous, Hokkaido, Maastrichtian, Senpohshi Formation

Introduction

Maastrichtian ammonoid faunas in the Northwest Pacific realm are characterized mainly by endemic species restricted to this particular realm, and thus the lack of more cosmopolitan taxa has long made it difficult to directly correlate these local faunas with those of other regions of the globe (Toshimitsu *et al.*, 1995). One of the more effective methods for precise and detailed chronologic age assignment of the local faunas is the integration of bio- and magnetostratigraphy (Toshimitsu *et al.*, 1995).

The Northwest Pacific realm contains three continuous, well studied Maastrichtian successions as follows: the Krasnoyarsk Formation in the Makarov area, southern Sakhalin, Far East Russia (Maeda *et al.*, 2005), the Heitaro-zawa Formation in the Nakatombetsu area, northern Hokkaido, northern Japan (Ando *et al.*, 2001), and the Senpohshi Formation of the Akkeshi area, eastern Hokkaido (Nifuku *et al.*, 2009; Figure 1). Although

the first two formations yield abundant megafossils from various horizons, their magnetostratigraphy has never been studied. On the other hand, a detailed magnetostratigraphic investigation was conducted on the Senpohshi Formation, and identified magnetozones suggest that the age of the formation spans approximately two million years during middle to late Maastrichtian time (ca. 69–67 Ma).

Many ammonoid specimens collected recently from various horizons within the Senpohshi Formation in the Akkeshi area represent several taxa that are common to the Izumi Group in southwestern Japan and the Yezo Group in central Hokkaido and Sakhalin. In this paper, we document their occurrences in the formation and discuss the chronologic assignment of the faunas and their biostratigraphic implications.

Geological setting

The Nemuro Group, widely distributed in eastern Hok-

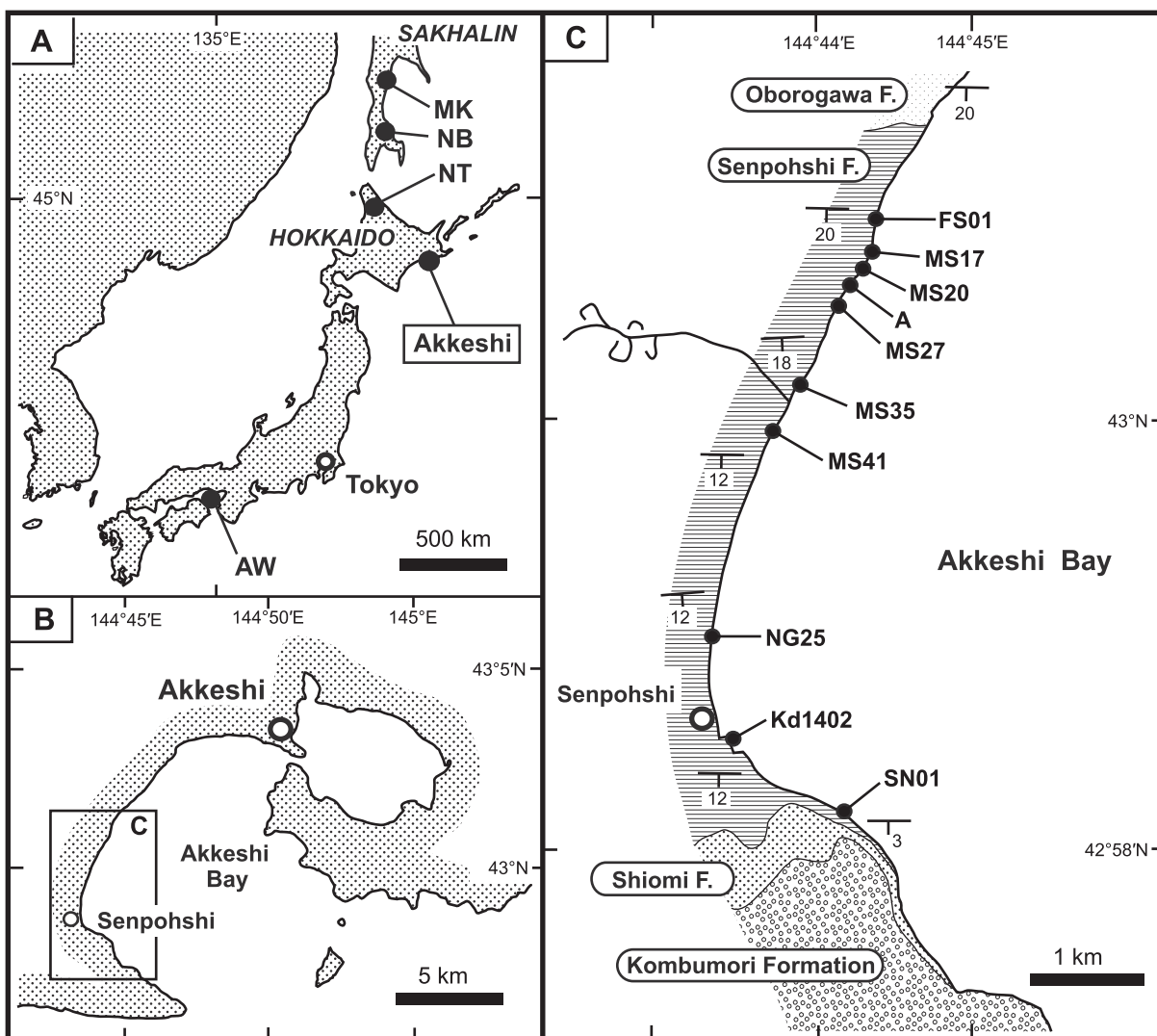


Figure 1. Index maps (A and B) and geological map (C) showing fossil localities along the western coast of Akkeshi Bay, eastern Hokkaido, as well as other localities mentioned in the text. MK, Makarov; NB, Naiba; NT, Nakatombetsu; AW, Awaji Island. For details of fossil localities with the following prefixes see the following papers. MS and FS, Nifuku *et al.* (2009); A, Naruse *et al.* (2000); NG, Okada *et al.* (1987); Kd, Kido's unpublished report of geological survey kept in the Japan Petroleum Exploration Co., Ltd. (Tokyo). Locality with the prefix SN is the original data of Shigeta and Nushimura.

kaido and some of the southern Kuril Islands (Habomai Islets and Shikotan Islands), is composed of hemipelagic mudstones and sediment gravity-flow deposits such as turbidites and submarine slump deposits (Kiminami, 1978; Naruse, 2003). It is interpreted to have been deposited in a forearc basin off the Kuril arc during the Cretaceous to Paleogene time (Kiminami, 1983).

The Senpohshi Formation of the Nemuro Group is distributed in eastern Hokkaido, and consists mainly of hemipelagic mudstone deposited in a stable sedimentary environment. The formation is well exposed along the

western coast of Akkeshi Bay, where it conformably overlies the Oborogawa Formation and is unconformably overlain by the Paleogene Shiomi Formation (Asano, 1962; Okada *et al.*, 1987; Figure 1). Its strata strike E–W and dip 10–20° southward. Nifuku *et al.* (2009) recognized four magnetozones in the formation, which are correlated with polarity chrons C31r to C30n, suggesting that the age of the Senpohshi Formation spans two million years during middle to late Maastrichtian time (*ca.* 69–67 Ma).

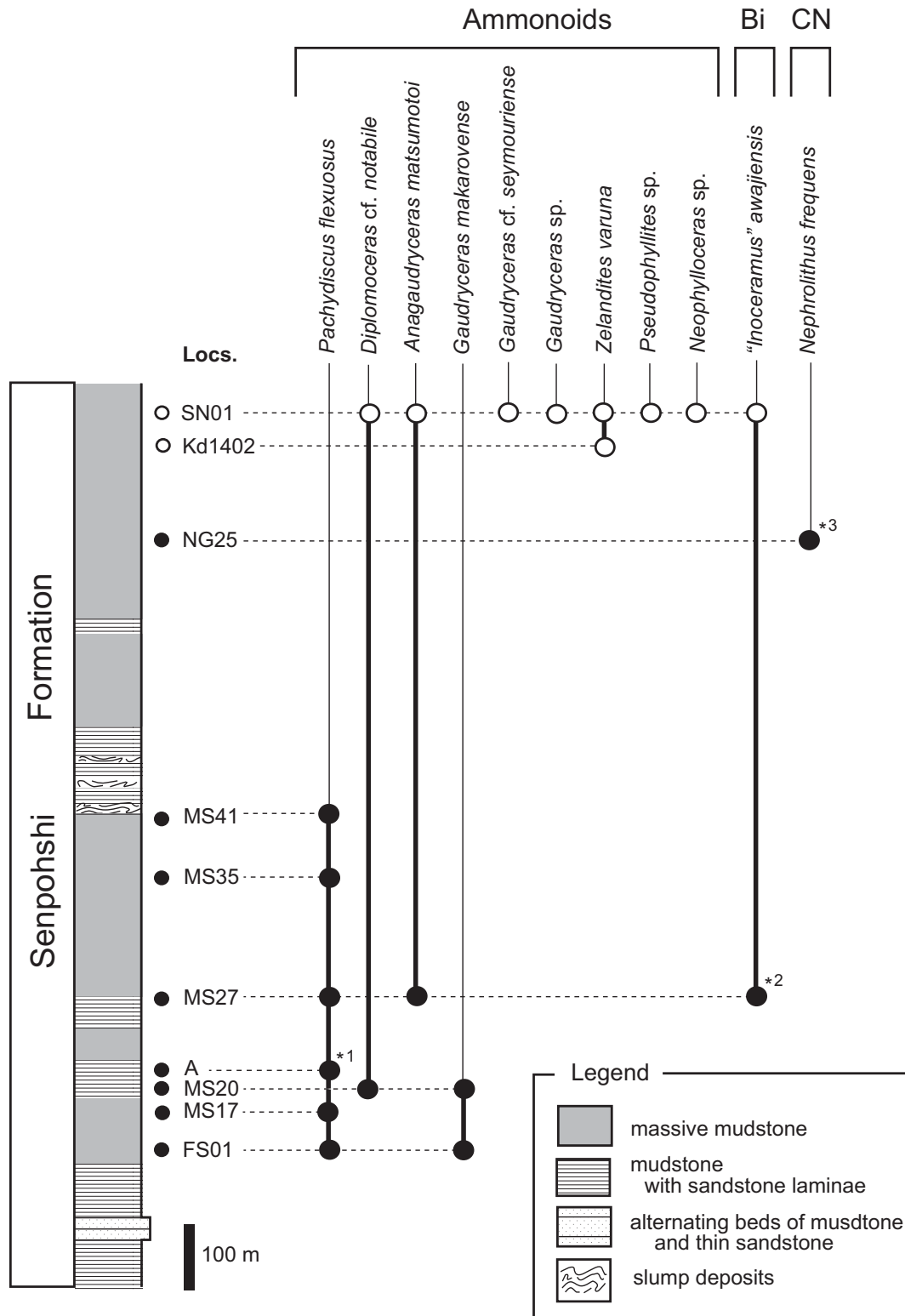


Figure 2. Lithology and stratigraphic occurrence of megafossils and microfossils in the Senpohshi Formation. Columnar section modified from Nifuku *et al.* (2009) with addition to our original data. *1, Naruse *et al.* (2000); *2, Nifuku *et al.* (2009); *3, Okada *et al.* (1987). Black circles, *in-situ* data; white circles, not *in-situ* data. Bi, bivalve; CN, calcareous nannofossil.

Fossil occurrences

A 1500 m-thick continuous succession of the Senpohshi Formation exposed along the western coast of Akkeshi Bay (Naruse *et al.*, 2000; Nifuku *et al.*, 2009) consists mainly of massive, dark gray mudstone, that is occasionally intercalated with sandstone laminae, thin sandstone beds, and thin slump deposits (Figure 2).

The following fossils were collected from the relatively fossiliferous lower part of the formation: *Gaudryceras makarovense* Shigeta and Maeda, 2005 at Locs. FS01 and MS20, *Diplomoceras* cf. *notabile* Whiteaves, 1903 at Loc. MS20, *Pachydiscus flexuosus* Matsumoto 1979, at Locs. FS01, MS17, MS27 and A of Naruse *et al.* (2000), and *Anagaudryceras matsumotoi* Morozumi, 1985 at Loc. MS27. Nifuku *et al.* (2009) also reported the occurrence of "*Inoceramus*" *awajiensis* Matsumoto, 1952 at Loc. MS27.

The middle part of the formation is not as fossiliferous and has yielded only *Pachydiscus flexuosus* from Locs. MS35 and MS41. Megafossils have not been found in most of the upper part of the formation with the exception of the very topmost part, which is very fossiliferous. In this interval, "*Inoceramus*" *awajiensis* occurs abundantly in dark gray, intensely bioturbated mudstone, and float calcareous concretions at Loc. SN01 yielded the following ammonoids: *Zelandites varuna* (Forbes, 1846), *Anagaudryceras matsumotoi*, *Gaudryceras* cf. *seymouriense* (Macellari, 1986), *Gaudryceras* sp., *Pseudophyllites* sp., *Neophylloceras* sp., and *Diplomoceras* cf. *notabile*.

Okada *et al.* (1987) reported the occurrence of calcareous nannofossils from the middle to upper parts of the formation. In particular, the upper part yields variable calcareous nannofossils, including *Nephrolithus frequens* Górká, 1957, an index fossil of calcareous nannofossil Zone CC26 of the upper Maastrichtian (Burnett, 1998). In addition, some Cretaceous planktonic foraminiferans have been reported from the upper part of the formation (Yamada, 1984).

Paleontological description

Morphological terms are those used in the *Treatise on Invertebrate Paleontology* (Moore, 1957). Quantifiers used to describe the shape of the ammonoid shell replicate those proposed by Matsumoto (1954, p. 246) and modified by Haggart (1989, table 8.1).

Abbreviations for shell dimensions.—*D* = shell diameter; *U* = umbilical diameter; *H* = whorl height; *W* = whorl width.

Institution abbreviations.—BMNH = Natural History Museum, London; GK = Department of Earth and Planetary Sciences, Kyushu University, Fukuoka; NMNS =

National Museum of Nature and Science, Tsukuba.

Suborder Phylloceratina Arkell, 1950
Superfamily Phylloceratoidea Zittel, 1884
Family Phylloceratidae Zittel, 1884
Subfamily Phylloceratinae Zittel, 1884
Genus *Neophylloceras* Shimizu, 1934

Type species.—*Ammonites* (*Scaphites*?) *ramosus* Meek, 1857.

Remarks.—*Neophylloceras*, established by Shimizu (1934, p. 61), has been regarded as either a synonym of *Hypophylloceras* Salfeld, 1924, a subgenus of *Hypophylloceras* or *Phylloceras* Suess, 1865, or as an independent genus (Murphy and Rodda, 2006). We herein follow the interpretation of Murphy and Rodda (2006).

Neophylloceras sp.

Figure 3A–3L

Material examined.—Three specimens, NMNS PM23859, from SN01-P4, NMNS PM23860, from SN01-P1, and NMNS PM23861, from SN01-P3. They were extracted from float calcareous concretions found at Loc. SN01, 1.2 km south of Senpohshi, along the western coast of Akkeshi Bay. Although the exact horizon from which the concretions came is uncertain, judging from their lithology and the locality, they almost certainly came from the bioturbated mudstone of the uppermost part of the Senpohshi Formation.

Description.—Very involute, fairly compressed shell with elliptical whorl cross section, arched venter, rounded ventral shoulders and slightly convex flanks with maximum whorl width at mid-flank. Umbilicus narrow and deep with moderately high, vertical wall and rounded shoulders. Ornamentation consists of fine, dense, feebly flexed lirae, which arise at umbilical seam, sweep gently forward across inner flank, and then strengthen and become rectiradiate at mid-flank before passing straight across venter. Broad undulations sometimes appear on inner flank. Suture line consists of numerous deeply incised elements with phylloid terminals (Figure 3K).

Measurements.—Taken at *D* = 10.6 mm of NMNS PM23859, *U* = 1.3 mm, *H* = 5.7 mm, *W* = 4.6 mm, *U/D* = 0.12, *W/H* = 0.81; at *D* = 17.6 mm of NMNS PM23860, *U* = 1.4 mm, *H* = 10.0 mm, *W* = 6.6 mm, *U/D* = 0.08, *W/H* = 0.66; and at *D* = 18.3 mm of NMNS PM23861, *U* = 1.2 mm, *H* = 10.5 mm, *W* = 7.0 mm, *U/D* = 0.07, *W/H* = 0.67.

Remarks.—The described specimens are very similar to the juvenile shells of *Neophylloceras hetonaiense* Matsumoto, 1942a and *N. nera* (Forbes, 1846), but a definitive assignment cannot be made. They are also very

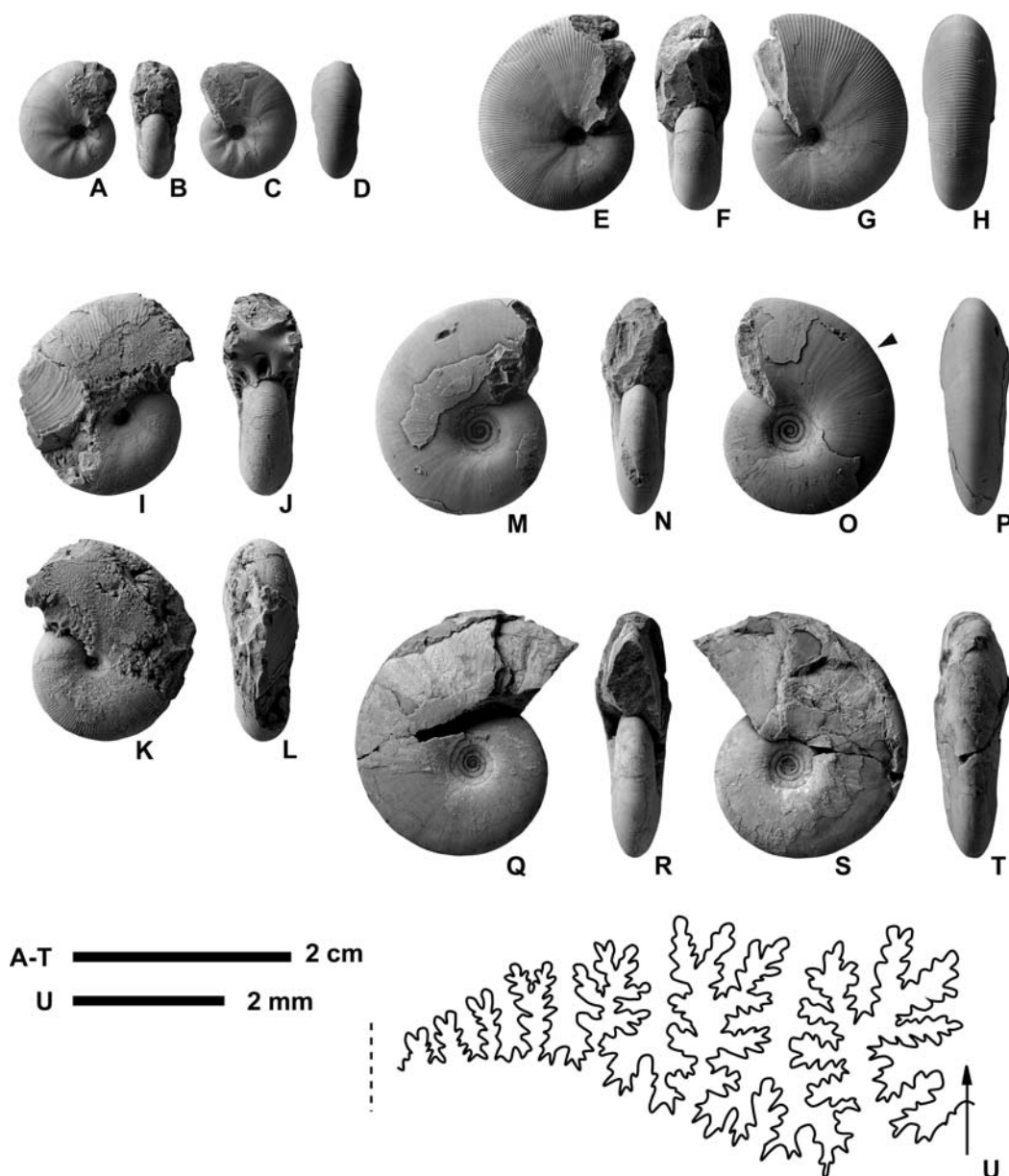


Figure 3. *Neophylloceras* and *Zelandites* from the Senpohshi Formation. A–L, *Neophylloceras* sp.; A–D, NMNS PM23859 from SN01-P4 at Loc. SN01; A, left lateral view; B, apertural view; C, right lateral view; D, ventral view; E–H, NMNS PM23860 from SN01-P1 at Loc. SN01; E, left lateral view; F, apertural view; G, right lateral view; H, ventral view; I–L, NMNS PM23861 from SN01-P3 at Loc. SN01; I, left lateral view; J, apertural view; K, right lateral view; L, ventral view; M–U, *Zelandites varuna* (Forbes, 1846); M–P, U, NMNS PM23862 from SN01-P3 at Loc. SN01, M, left lateral view; N, apertural view; O, right lateral view; P, ventral view; U, suture line at black arrow in view (O); Q–T, GK. H8473 from Loc. Ad1402; Q, left lateral view; R, apertural view; S, right lateral view; T, ventral view.

similar to specimens described as *N. cf. nera* from the Maastrichtian of southern Sakhalin by Maeda *et al.* (2005).

Suborder Lytoceratina Hyatt, 1889
Superfamily Tetragonitoidea Hyatt, 1900

Family Tetragonitidae Hyatt, 1900
Genus *Pseudophyllites* Kossmat, 1895

Type species.—*Ammonites indra* Forbes, 1846.

Pseudophyllites sp.

Figure 4

Material examined.—Seven specimens, NMNS PM23863–23869, from SN01-P3. They were extracted from float calcareous concretions found at Loc. SN01, 1.2 km south of Senpohshi. Although the exact horizon from which the concretions came is uncertain, judging from their lithology and the locality, they almost certainly came from the mudstone of the uppermost part of the Senpohshi Formation.

Description.—Very involute, fairly depressed shell with subrounded to subquadrate whorl cross section, low arched venter, rounded ventral shoulders and slightly convex flanks with maximum whorl width at mid-flank. Umbilicus fairly narrow and deep with high, vertical wall and rounded shoulders. Ornamentation consists of very fine growth lines, which are prorsiradiate on flanks but become slightly sinuous at ventral shoulders before crossing over venter with very shallow concave arch. Suture line typical tetragonitid-type with trifid major saddles (Figure 4AC).

Remarks.—The described specimens possibly represent juvenile shells of *Pseudophyllites indra* (Forbes, 1846), which is a long-ranging, cosmopolitan species known from the Santonian to upper Maastrichtian (Kennedy and Klinger, 1977; Kennedy and Henderson, 1992). They are very similar to the specimens described by Maeda *et al.* (2005) as juvenile shells of *P. indra* from the Maastrichtian of southern Sakhalin. However, the loss of the adult features precludes a definitive assignment.

Family Gaudryceratidae Spath, 1927

Genus *Zelandites* Marshall, 1926

Type species.—*Zelandites kaiparaensis* Marshall, 1926.

Zelandites varuna (Forbes, 1846)

Figure 3M–3U

Ammonites varuna Forbes, 1846, p. 107, pl. 8, fig. 5.

Lytoceras (*Gaudryceras*) *varuna* (Forbes). Kossmat, 1895, p. 161, pl. 16, fig. 4, pl. 17, fig. 8.

Lytoceras varuna (Forbes). Steinmann, 1895, p. 84, pl. 5, fig. 2, text-fig. 7.

Zelandites varuna var. *japonica* Matsumoto, 1938, p. 140, pl. 14, figs. 5–7, text-fig. 1.

Zelandites varuna (Forbes). Stinnesbeck, 1986, pl. 195, pl. 8, figs. 5–6, text-fig. 20; Macellari, 1986, p. 14, text-figs. 11.11, 11.12, 12; Matsumoto, 1988, p. 184, pl. 51, fig. 4; Kennedy and Henderson, 1992, p. 404, pl. 5, figs. 13–15, pl. 17, figs. 2–3; Ando *et al.*, 2001, pl. 1, figs. 19–21; Kodama *et al.*, 2002, fig. 8I, 8J; Maeda *et al.*, 2005, p. 84, fig. 38.1–38.4; Ifrim *et al.*, 2004, p. 1592, text-figs. 3O–3P, 6F–6G, J.

Zelandites japonicus Matsumoto. Zonova *et al.*, 1993, p. 149, pl. 90, figs. 2, 3, pl. 98, fig. 3, pl. 99, figs. 3–13, pl. 101, figs. 4–7, pl. 102, figs. 3–10; Yazykova, 1994, p. 290, pl. 1, figs. 1–4, pl. 2,

figs. 1–18; Matsumoto, 1995, p. 133; Alabushev and Wiedmann, 1997, p. 11, pl. 2, fig. 6, text-fig. 2.

Zelandites cf. *varuna* (Forbes). Morozumi, 1985, p. 32, pl. 9, fig. 2, text-fig. 8.

Zelandites aff. *varuna* (Forbes). Yazykova, 1991, pl. 2, fig. 2.

Lectotype.—Specimen designated by Matsumoto (1988, p. 184) is BMNH C51059, original of Forbes (1846, p. 107, pl. 8, fig. 5) from the upper Maastrichtian of Pondicherry, southern India.

Material examined.—GK. H8473 was extracted from a float calcareous concretion found at Loc. Ad1402, 0.6 km south of Senpohshi, along the western coast of Akkeshi Bay, by Mr. Hideo Kido. NMNS PM23862 was collected from a float calcareous concretion (SN01-P3) found at Loc. SN01, 1.2 km south of Senpohshi. Although the exact horizon from which the concretions came is uncertain, judging from their lithology and the localities, they almost without doubt came from the mudstone of the uppermost part of the Senpohshi Formation.

Description.—Very involute, fairly compressed shell with elliptical whorl-section, narrowly rounded venter, indistinct ventral shoulders and slightly convex flanks with maximum whorl width on inner flank at one third of whorl height. Umbilicus fairly narrow and shallow with low, rounded wall. Ornamentation consists of very weak constrictions and fine growth lines, which are prorsiradiate on inner flank and retriradiate on outer flank. Suture line typical gaudryceratid-type with large, incised, bifid saddle (Figure 3U).

Measurements.—Taken at $D = 22.6$ mm of GK. H8473, $U = 4.4$ mm, $H = 11.3$ mm, $W = 7.2$ mm, $U/D = 0.19$, $W/H = 0.64$; and at $D = 20.4$ mm of NMNS PM23862, $U = 4.1$ mm, $H = 9.9$ mm, $W = 6.8$ mm, $U/D = 0.20$, $W/H = 0.69$.

Remarks.—*Zelandites japonicus* was considered to be a variety of *Z. varuna* from the upper Maastrichtian in southern Sakhalin by Matsumoto (1938, p. 140), but Macellari (1986, p. 14) regarded it as a synonym of *Z. varuna*. Matsumoto (1988) subsequently agreed with Macellari's interpretation and we also concur.

Occurrence.—Upper Maastrichtian in southern India, Chile, Seymour Island in Antarctica, Awaji Island in Southwest Japan, northern Hokkaido, eastern Hokkaido and southern Sakhalin, and lower Maastrichtian in north-eastern Mexico.

Genus *Anagaudryceras* Shimizu, 1934

Type species.—*Ammonites sacya* Forbes, 1846.

Anagaudryceras matsumotoi Morozumi, 1985

Figure 5A–5P

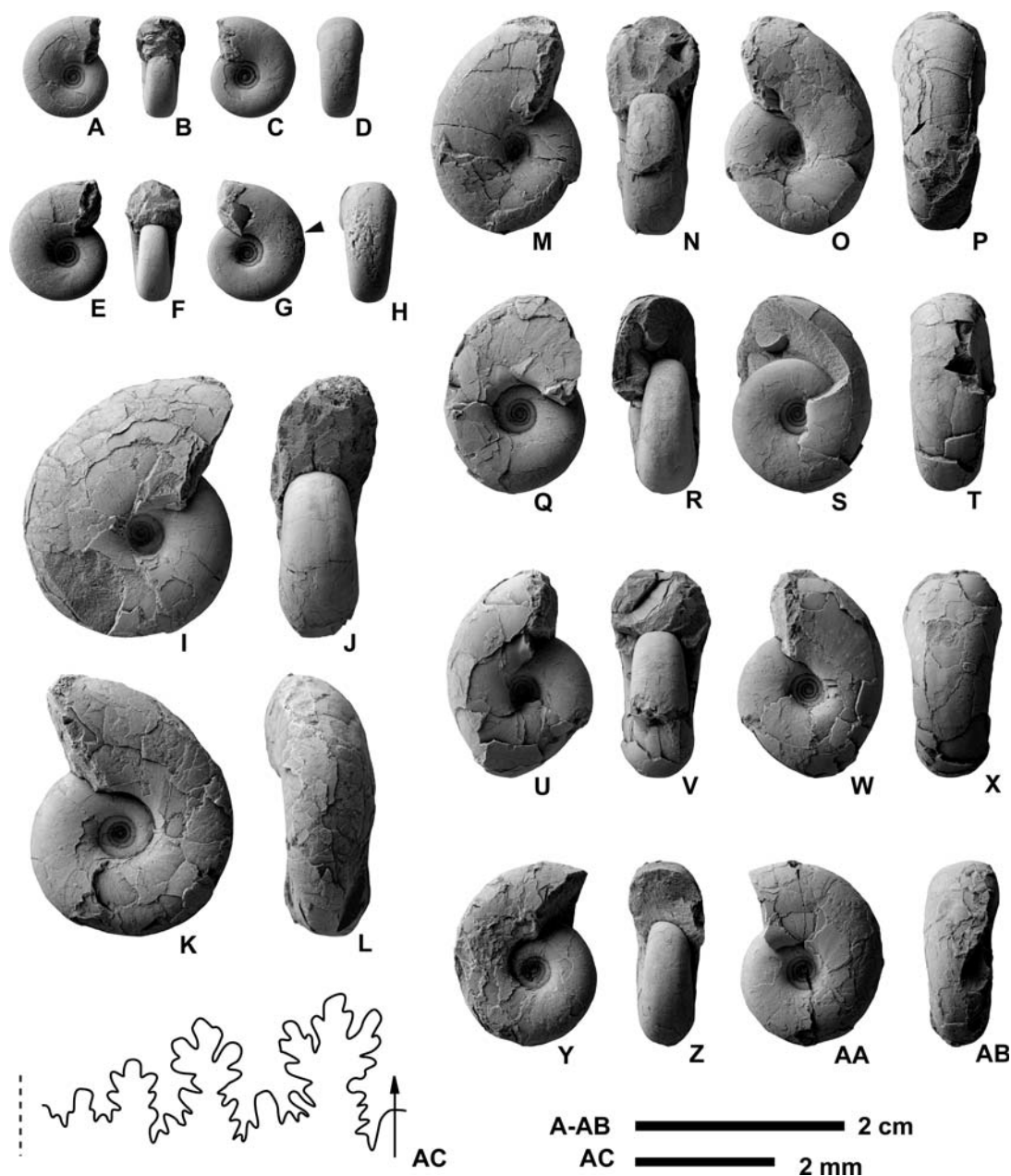


Figure 4. *Pseudophyllites* sp. from SN01-P3 at Loc. SN01 in the Senpohshi Formation. **A–D**, NMNS PM23863; A, left lateral view; B, apertural view; C, right lateral view; D, ventral view; **E–H, AC**, NMNS PM23864; E, left lateral view; F, apertural view; G, right lateral view; H, ventral view; AC, suture line at black arrow in view (G); **I–L**, NMNS PM23865; I, left lateral view; J, apertural view; K, right lateral view; L, ventral view; **M–P**, NMNS PM23866; M, left lateral view; N, apertural view; O, right lateral view; P, ventral view; **Q–T**, NMNS PM23867; Q, left lateral view; R, apertural view; S, right lateral view; T, ventral view; **U–X**, NMNS PM23868; U, left lateral view; V, apertural view; W, right lateral view; X, ventral view; **Y–AB**, NMNS PM23869; Y, left lateral view; Z, apertural view; AA, right lateral view; AB, ventral view.

Anagaudryceras matsumotoi Morozumi, 1985, p. 29, pl. 9, fig. 1, text-fig. 7; Matsumoto, 1985, p. 27, pl. 4, figs. 1–10; Matsumoto, 1988, p. 183, pl. 51, fig. 3; Ando *et al.*, 2001, pl. 1, figs. 12–14; Maeda *et al.*, 2005, p. 81, fig. 39.1–39.15.

Zelandites varuna (Forbes). Zonova *et al.*, 1993, p. 148, pl. 98, fig. 4; Yazykova, 1994, p. 289, pl. 1, fig. 8.

Holotype.—GK. H6882, figured by Morozumi (1985, p. 29, pl. 9, fig. 1, text-fig. 7), from the Maastrichtian *Pachydiscus* aff. *subcompressus* Zone in the Shimonada Formation of the Izumi Group on Awaji Island, Southwest Japan.

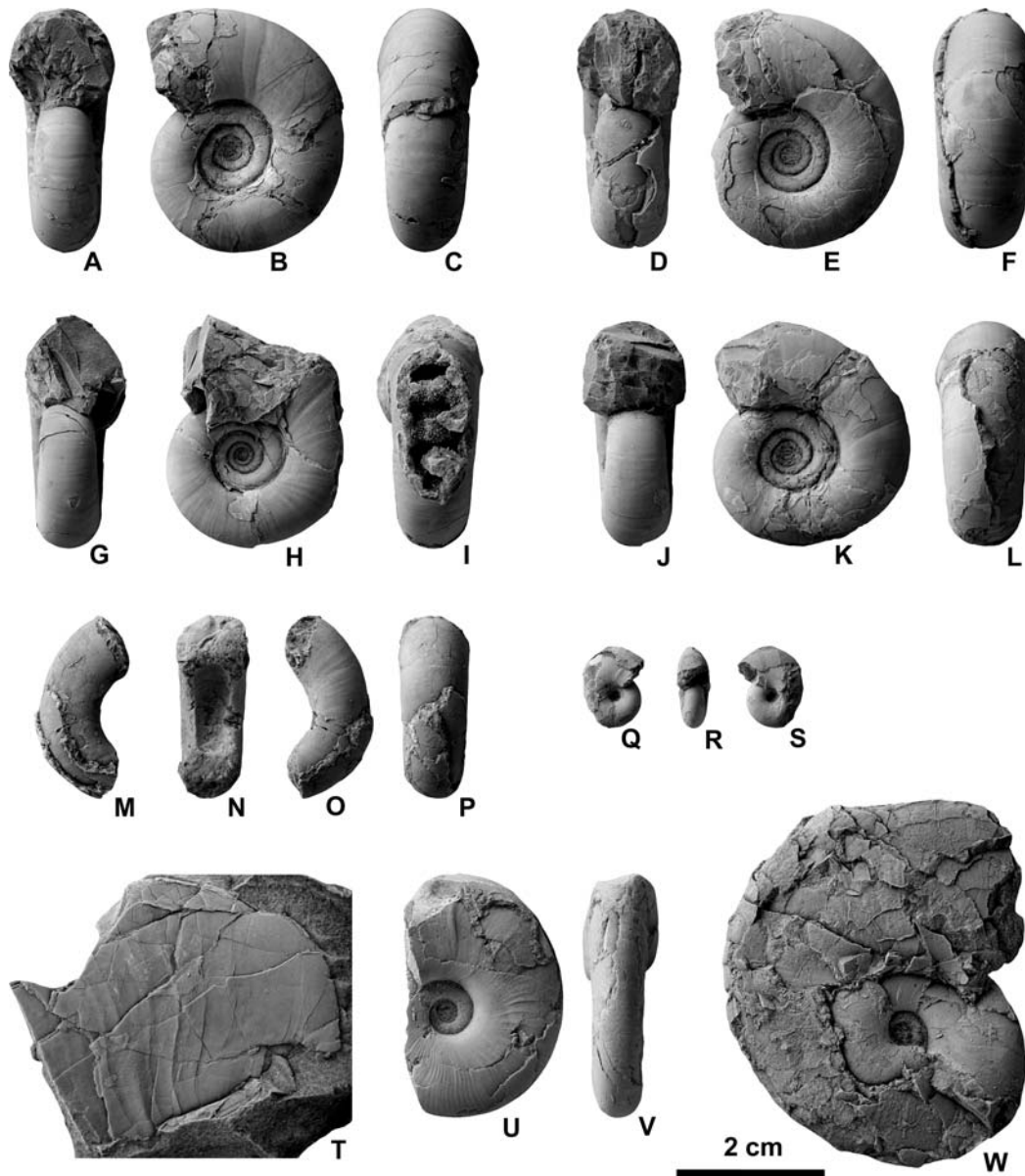


Figure 5. *Anagaudryceras* and *Pachydiscus* from the Senpohshi Formation. **A–P**, *Anagaudryceras matsumotoi* Morozumi, 1985; **A–C**, NMNS PM23870 from SN01-P9 at Loc. SN01; **A**, apertural view; **B**, right lateral view; **C**, ventral view; **D–F**, NMNS PM23871 from SN01-P9 at Loc. SN01; **D**, apertural view; **E**, right lateral view; **F**, ventral view; **G–I**, NMNS PM23872 from SN01-P9 at Loc. SN01; **G**, apertural view; **H**, right lateral view; **I**, ventral view; **J–L**, NMNS PM23873 from SN01-P9 at Loc. SN01; **J**, apertural view; **K**, right lateral view; **L**, ventral view; **M–P**, NMNS PM23874 at Loc. MS27; **M**, left lateral view; **N**, apertural view; **O**, right lateral view; **P**, ventral view; **Q–W**, *Pachydiscus flexuosus* Matsumoto, 1979; **Q–S**, NMNS PM23887 at Loc. MS41; **Q**, left lateral view; **R**, apertural view; **S**, right lateral view; **T**, NMNS PM23888 at Loc. MS17, right lateral view; **U**, **V**, NMNS PM23889 at Loc. MS27; **U**, right lateral view; **V**, ventral view; **W**, NMNS PM23890 at Loc. MS35, left lateral view.

Material examined.—NMNS PM23874 was collected from a calcareous concretion in the middle part of the Senpohshi Formation at Loc. MS27. Four specimens, NMNS PM23870–23873, were extracted from a float calcareous concretion (SN01-P9) found at Loc. SN01,

1.2 km south of Senpohshi along the western coast of Akkeshi Bay. Although the exact horizon from which the concretions came is uncertain, judging from their lithology and the locality, they almost certainly came from the mudstone of the uppermost part of the Senpohshi Formation.

Description.—Fairly evolute shell with whorl nearly as high as broad. Whorl cross section circular with arched venter, indistinct ventral shoulders and gently convex flanks. Maximum whorl width occurs slightly distance below mid-flank. Umbilicus moderately wide with moderately high, rounded umbilical wall. Ornamentation consists of very fine slightly sinuous growth lines, which pass straight across venter.

Measurements.—Taken at $D = 33.0$ mm of NMNS PM23870, $U = 12.7$ mm, $H = 12.8$ mm, $W = 13.7$ mm, $U/D = 0.38$, $W/H = 1.07$; at $D = 32.0$ mm of NMNS PM23871, $U = 11.3$ mm, $H = 13.0$ mm, $W = 13.8$ mm, $U/D = 0.35$, $W/H = 1.06$; at $D = 31.0$ mm of NMNS PM23873, $U = 11.4$ mm, $H = 12.0$ mm, $W = 12.7$ mm, $U/D = 0.37$, $W/H = 1.06$; and at $D = 27.5$ mm of NMNS PM23872, $U = 10.0$ mm, $H = 11.4$ mm, $W = 11.6$ mm, $U/D = 0.36$, $W/H = 1.02$.

Remarks.—Zonova *et al.* (1993, pl. 98, fig. 4) and Yazykova (1994, pl. 1, fig. 8) assigned a specimen from the Maastrichtian in the Pugachevo area, southern Sakhalin, to *Zelandites varuna*. However, its whorl cross section, mode of coiling and ornamentation enable us to assign it to *Anagaudryceras matsumotoi*.

Occurrence.—Maastrichtian in southern Sakhalin, northern Hokkaido, eastern Hokkaido and Awaji Island in Southwest Japan.

Genus *Gaudryceras* Grossouvre, 1894

Type species.—*Ammonites mitis* Hauer, 1866.

Gaudryceras makarovense Shigeta and Maeda, 2005

Figures 6A–6E, 7A–7C

Gaudryceras izumiense Matsumoto and Morozumi. Morozumi, 1985, p. 24, pl. 8, fig. 2.

Gaudryceras hamanakense Matsumoto and Yoshida. Yazykova, 1991, pl. 1, fig. 1; Yazykova, 1992, p. 196, pl. 110, figs. 1, 2; Zonova *et al.*, 1993, p. 154, pl. 88, fig. 1, pl. 99, fig. 2, pl. 104, fig. 2; Yazykova, 1994, p. 292, pl. 4, figs. 1–3.

Gaudryceras denmanense Whiteaves. Yazykova, 1992, p. 195, pl. 111, fig. 3; Zonova *et al.*, 1993, p. 153, pl. 102, fig. 2; Yazykova, 1994, p. 291, pl. 8, fig. 2.

Gaudryceras venustum Matsumoto. Zonova *et al.*, 1993, p. 152, pl. 87, fig. 1, pl. 102, fig. 1, pl. 103, fig. 3, pl. 104, fig. 1; Yazykova, 1994, p. 292, pl. 14, pl. 15, fig. 2.

Gaudryceras makarovense Shigeta and Maeda, 2005, p. 73, figs. 15.3, 32.4, 33–37; Maeda and Shigeta, 2005, figs. 6, 7.

Holotype.—NMNS PM17205, figured by Shigeta and Maeda (2005, p. 73, figs. 33, 34), from the Maastrichtian *Pachydiscus flexuosus* Zone in the Krasnoyarsk Formation of the Yezo Group in the Makarov area, southern Sakhalin, Russia.

Material examined.—Four specimens, NMNS

PM23875–23878, from Loc. MS14 and three specimens, NMNS PM23879–23881, from Loc. MS20 in the lower part of the Senpohshi Formation. Each specimen is a fragmentary body chamber of a large individual. All specimens are flattened by compaction.

Description.—Ornamentation consists of slightly sinuous, narrowly raised ribs and collar-like ribs, which are markedly prorsiradiate on inner flank, turn and cross to mid-flank in a gently rursiradiate arc, then turn gently forward on outer flank to cross venter in a broad convex arch. Intercalation of ribs occurs on umbilical shoulder.

Remarks.—The described specimens are fragmental, but their distinctive ornamentation enable us to identify them as *Gaudryceras makarovense*. Yazykova (1991, 1992, 1994) and Zonova *et al.* (1993) described *G. hamanakense*, *G. denmanense*, and *G. venustum* from the Maastrichtian of southern Sakhalin, but these specimens are identical to *G. makarovense* with respect to shell shape and ornamentation. A specimen described as *G. izumiense* Matsumoto and Morozumi, 1980 from the Maastrichtian on Awaji Island by Morozumi (1985) is also identical to *G. makarovense*.

Occurrence.—Maastrichtian in southern Sakhalin and Awaji Island in Southwest Japan.

Gaudryceras cf. *seymouriense* (Macellari, 1986)

Figure 8

cf. *Anagaudryceras seymouriense* Macellari, 1986, p. 10, figs. 9.1–9.6, 10.1–10.4.

cf. *Anagaudryceras* cf. *seymouriense* Macellari. Matsumoto, 1988, p. 183, pl. 51, fig. 2, pl. 53, fig. 1.

Material examined.—Two specimens, NMNS PM23883, PM23884, were extracted from float calcareous concretions (SN01-P5, SN01-P6) found at Loc. SN01, 1.2 km south of Senpohshi along the western coast of Akkeshi Bay. Although the exact horizon from which the concretions came is uncertain, judging from their lithology and the locality, they almost without doubt came from the mudstone of the uppermost part of the Senpohshi Formation. NMNS PM23883 (Figure 8A) is a body chamber fragment and NMNS PM23884 (Figure 8B, C) is part of a phragmocone.

Description.—Fairly large shell with very fine, dense lirae and collar-like ribs, which arise at umbilical seam and become slightly sigmoidal before passing over venter.

Remarks.—Macellari (1986) described a large-sized gaudryceratid ammonoid (>400 mm in diameter) as *Anagaudryceras seymouriense* from upper Maastrichtian sediments on Seymour Island, Antarctic Peninsula. The mature shell is involute with a fairly narrow umbilicus, but during early to middle growth stages, it is evolute

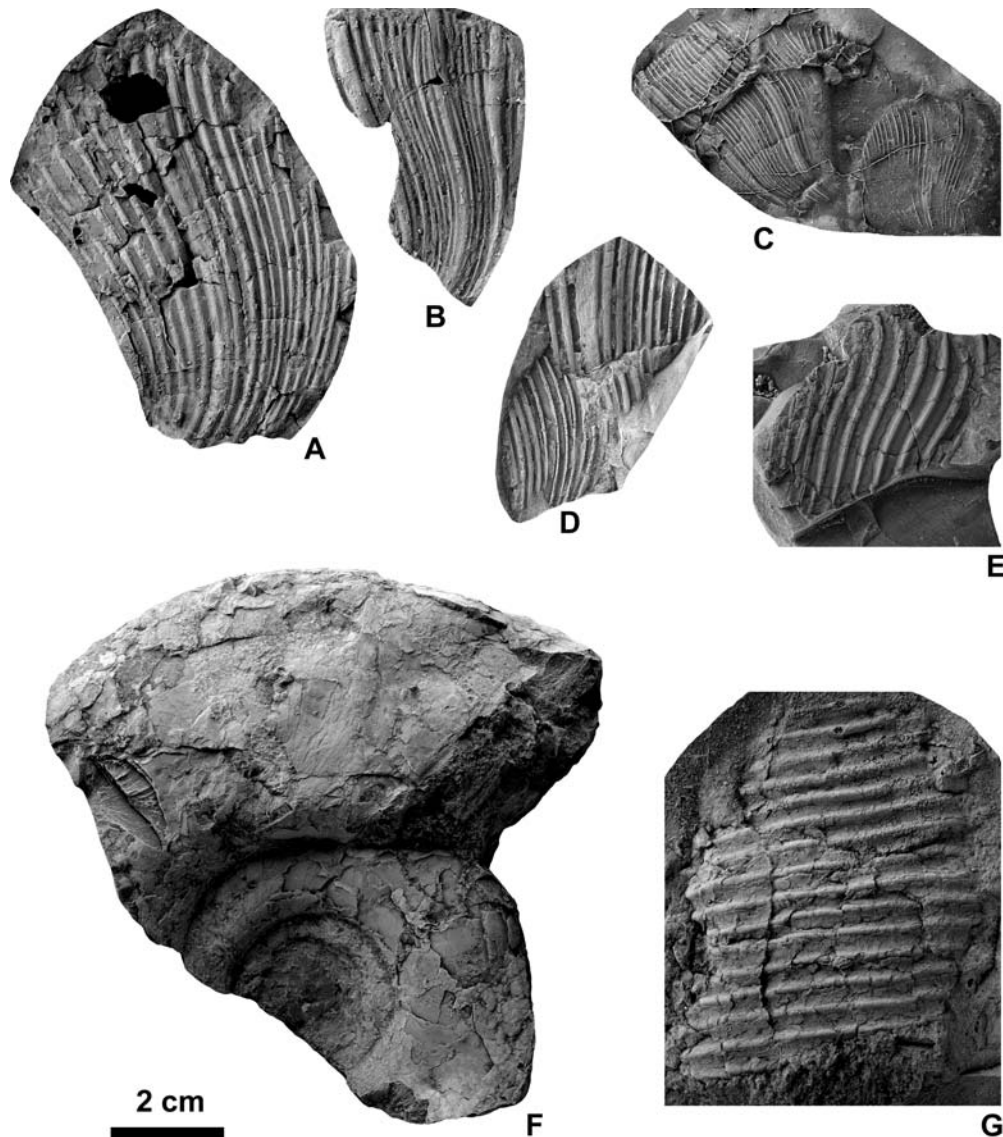


Figure 6. *Gaudryceras* and *Diplomoceras* from the Senpohshi Formation. **A–E**, *Gaudryceras makarovense* Shigeta and Maeda, 2005; **A**, NMNS PM23875 at Loc. FS01, left lateral view; **B**, NMNS PM23876 at Loc. FS01, left lateral view; **C**, NMNS PM23879 at Loc. MS20, right lateral view (rubber cast of outer mold); **D**, NMNS PM23880 at Loc. MS20, left lateral view (rubber cast of outer mold); **E**, NMNS PM23881 at Loc. MS20, left lateral view; **F**, *Gaudryceras* sp., NMNS PM23882, from SN01-P2 at Loc. SN01, left lateral view; **G**, *Diplomoceras* cf. *notabile* Whiteaves, 1903, NMNS PM23885, from SN01-P8 at Loc. SN01, lateral view (rubber cast of outer mold).

with a wide umbilicus. Its lirae, ribs and constrictions are slightly sigmoidal and projected forward onto the venter. These features are in obvious contrast with *Anagaudryceras* with its less flexuous ribs and lirae (Kennedy and Klinger, 1979; Matsumoto, 1995). Because these features are characteristic of *Gaudryceras* (see Hoffmann, 2010), this species should be assigned to *Gaudryceras*.

Although the present specimens are fragments, their distinctive features enable us to identify them with rea-

sonable confidence as *Gaudryceras seymouriense*.

Occurrence.—*Gaudryceras seymouriense* is known from the upper Maastrichtian on Seymour Island and southern Sakhalin (Matsumoto, 1988).

Gaudryceras sp.

Figure 6F

Material examined.—NMNS PM23882 was extracted

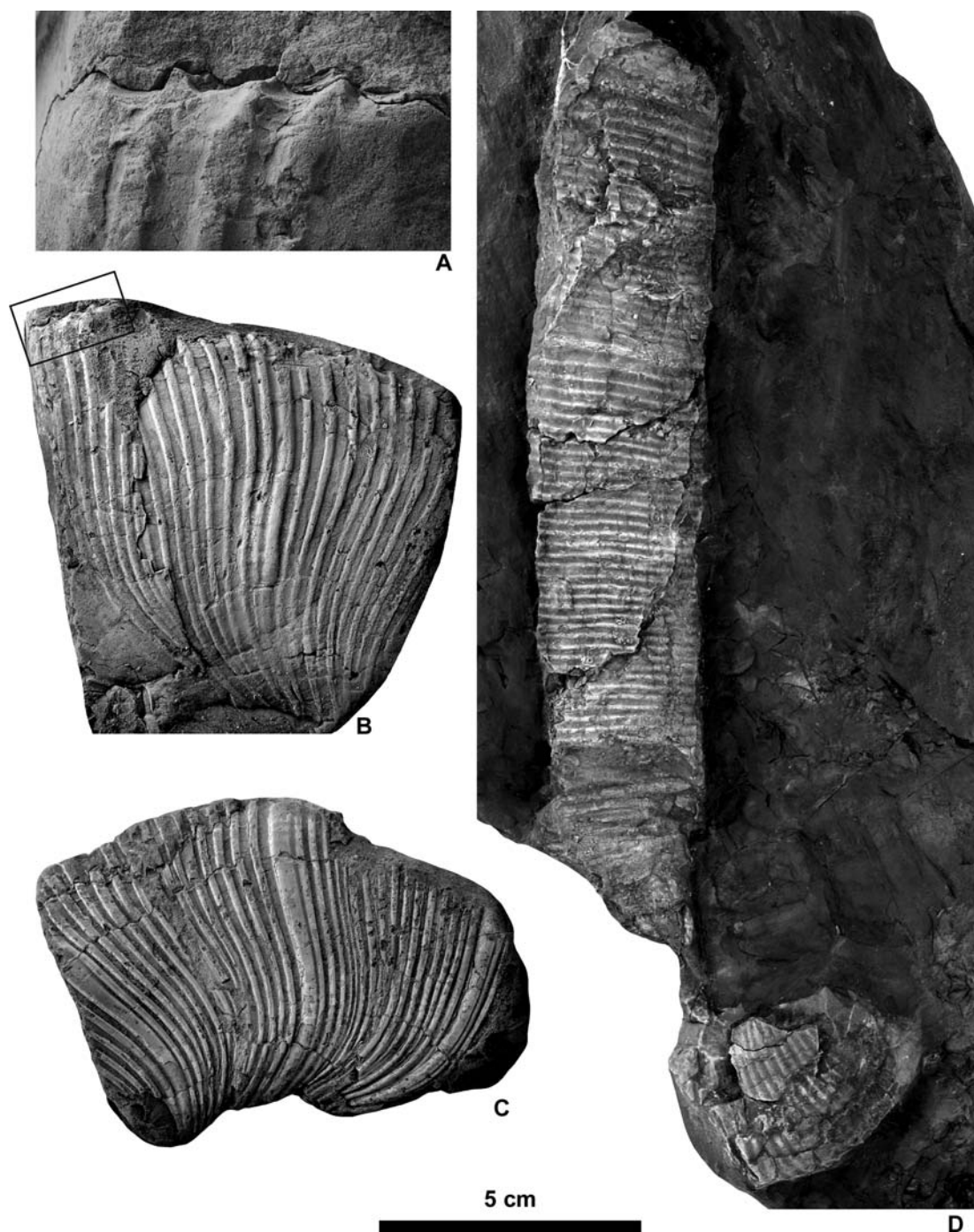


Figure 7. *Gaudryceras* and *Diplomoceras* from the Senpohshi Formation. **A–C**, *Gaudryceras makarovense* Shigeta and Maeda, 2005 at Loc. FS01; **A**, **B**, NMNS PM23877; **A**, Close-up of ribs in **B**; **B**, right lateral view; **C**, NMNS PM23878, left lateral view; **D**, *Diplomoceras* cf. *notabile* Whiteaves, 1903, NMNS PM23886, at Loc. MS20, lateral view.

from a float calcareous concretion (SN01-P2) found at Loc. SN01, 1.2 km south of Senpohshi along the western coast of Akkeshi Bay. Although the exact horizon from which the concretion came is uncertain, judging from its

lithology and the locality, it almost certainly came from the mudstone of the uppermost part of the Senpohshi Formation.

Description.—Very evolute, fairly compressed shell



Figure 8. *Gaudryceras cf. seymouriense* (Macellari, 1986) at Loc. SN01 in the Senpohshi Formation. **A**, NMNS PM23883 from SN01-P6, right lateral view; **B**, **C**, NMNS PM23884 from SN01-P5; **B**, cross-sectional view; **C**, right lateral view.

with arched venter, rounded ventral shoulders and slightly convex flanks with maximum whorl width at mid-flank. Umbilicus moderately wide with moderately high, vertical wall and round shoulders. Ornamentation consists of very fine, nearly sigmoidal, prorsiradiate growth lines, which pass over venter in a broad convex arch.

Remarks.—The described specimen is crushed laterally. Although it is somewhat similar to *Gaudryceras kayei* (Forbes, 1846), its poor preservation precludes a definitive species assignment.

Suborder Ancyloceratina Wiedmann, 1966
Superfamily Turrilitoidea Gill, 1871
Family Diplomoceratidae Spath, 1926
Genus ***Diplomoceras*** Hyatt, 1900

Type species.—*Baculites cylindracea* Defrance, 1816.

Diplomoceras* cf. *notabile Whiteaves, 1903

Figures 6G, 7D

- cf. *Diplomoceras notabile* Whiteaves, 1903, p. 335, pl. 44, fig. 4; Usher, 1952, p. 109, pl. 29, fig. 2, pl. 30, fig. 1, pl. 31, figs. 26, 27; Jones, 1963, p. 32, pl. 21, fig. 1, text-fig. 15; Matsumoto, 1984a, p. 31, pl. 8, fig. 3; Matsumoto and Miyauchi, 1984, p. 68, pl. 27, fig. 2.
cf. *Diplomoceras* cf. *notabile* Whiteaves. Matsumoto and Morozumi, 1980, p. 23, pl. 16, fig. 3; Shigeta and Maeda, 2005, p. 102, fig. 52.

Material examined.—One specimen, NMNS PM23886, was collected from massive mudstone in the lower part of the Senpohshi Formation at Loc. MS20. A second specimen, NMNS PM23885, was extracted from a float calcareous concretion (SN01-P8) at Loc. SN01, 1.2 km south of Senpohshi along the western coast of Akkeshi Bay. Although the exact horizon from which the concretion came is uncertain, judging from its lithology and the locality, it almost without doubt came from the mudstone of the uppermost part of the Senpohshi Formation.

Description.—NMNS PM23886, a large portion of phragmocone approximately 225 mm long, consists of a straight shaft and part of the U-curve portion. NMNS PM23885 is only a body chamber fragment. Ornamentation consists of numerous, regularly spaced ribs, which vary from straight to weakly oblique.

Remarks.—Although the described specimens are only phragmocone and body chamber fragments, their distinctive features enable us to identify them with reasonable confidence as *Diplomoceras notabile*.

Occurrence.—*Diplomoceras notabile* is known from the upper Campanian to Maastrichtian in Southwest Japan, northern Hokkaido, southern Sakhalin, southern Alaska, and British Columbia.

Suborder Ammonitina Hyatt, 1889
Superfamily Desmoceratoidea Zittel, 1895
Family Pachydiscidae Spath, 1922
Genus ***Pachydiscus*** Zittel, 1884

Type species.—*Ammonites neubergicus* Hauer, 1858.

Pachydiscus flexuosus Matsumoto, 1979

Figures 5Q–W, 9, 10

- Pachydiscus flexuosus* Matsumoto, 1979, p. 53, pl. 9, figs. 1–3, pl. 10, fig. 4, pl. 12, fig. 1, text-fig. 4; Matsumoto and Yoshida, 1979a, p. 67, pl. 12, figs. 3, 4; Yazykova, 1991, pl. 1, fig. 3; Yazykova, 1992, p. 197, pl. 107, fig. 1; Zonova *et al.*, 1993, p. 168, pl. 90, fig. 1, pl. 91, fig. 1, pl. 101, fig. 2; Yazykova, 1994, p. 299, pl. 8, fig. 1, pl. 9, fig. 1, pl. 10, fig. 1, pl. 12, fig. 1; Naruse *et al.*, 2000, fig. 3.1; Ando *et al.*, 2001, pl. 2, figs. 1–5; Maeda *et al.*, 2005, figs. 9.3, 14.2, 14.5, 15.1, 15.2, 15.4, 15.5; Maeda and Shigeta, 2005, figs. 5.2, 5.3, 8; Nifuku *et al.*, 2009, pl. 1, fig. 1.
Pachydiscus aff. *flexuosus* Matsumoto. Matsumoto, 1979, p. 59, pl. 9, fig. 4.
Pachydiscus gracilis Matsumoto. Yazykova, 1991, pl. 1, fig. 4; Yazykova, 1992, p. 198, pl. 108, fig. 1, pl. 109, fig. 1.
Pachydiscus japonicus Matsumoto. Yazykova, 1991, pl. 2, fig. 3; Yazykova, 1992, p. 198, pl. 112, fig. 1; Zonova *et al.*, 1993, p. 169, pl. 94, fig. 2, pl. 98, fig. 1, pl. 99, fig. 1, pl. 100; Yazykova, 1994, p. 300, pl. 7, figs. 1, 2, pl. 9, fig. 3; Alabushev and Wiedmann, 1997, pl. 9, fig. 2.
Pachydiscus neevesi Whiteaves. Zonova *et al.*, 1993, p. 167, pl. 91, fig. 2, pl. 92.
Pachydiscus subcompressus obsoletus Matsumoto. Zonova *et al.*, 1993, p. 167, pl. 97, fig. 1.
Pachydiscus ex gr. *neubergicus* Hauer. Zonova *et al.*, 1993, p. 165, pl. 105.
Pachydiscus neubergicus Hauer. Yazykova, 1994, p. 296, pl. 13, fig. 1.
Pachydiscus subcompressus Matsumoto. Yazykova, 1994, p. 298, pl. 10, fig. 3.

Holotype.—GK. H5877, figured by Matsumoto (1979, p. 53, figs. 1, 2, text-fig. 4), from the Maastrichtian in unit D2 (= upper part of the Heitaro-zawa Formation by Ando *et al.*, 2001) of the Yezo Group in the Nakatombetsu area, northern Hokkaido, Japan.

Material examined.—NMNS PM23891, from Loc. FS01, NMNS PM23888, from Loc. MS17, NMNS PM23889, from Loc. MS27, NMNS PM23890, from Loc. MS35, and NMNS PM23887, from Loc. MS41. NMNS PM23888 was found in mudstone, but the other specimens were extracted from calcareous concretions in the lower to middle parts of the Senpohshi Formation along the western coast of Akkeshi Bay.

Description.—Very involute, fairly compressed shell with elliptical whorl cross section, arched venter, rounded ventral shoulders, and slightly convex flanks. Maximum whorl width occurs at a slight distance below mid-flank. Fairly narrow umbilicus with moderately high, nearly vertical wall and rounded umbilical shoul-

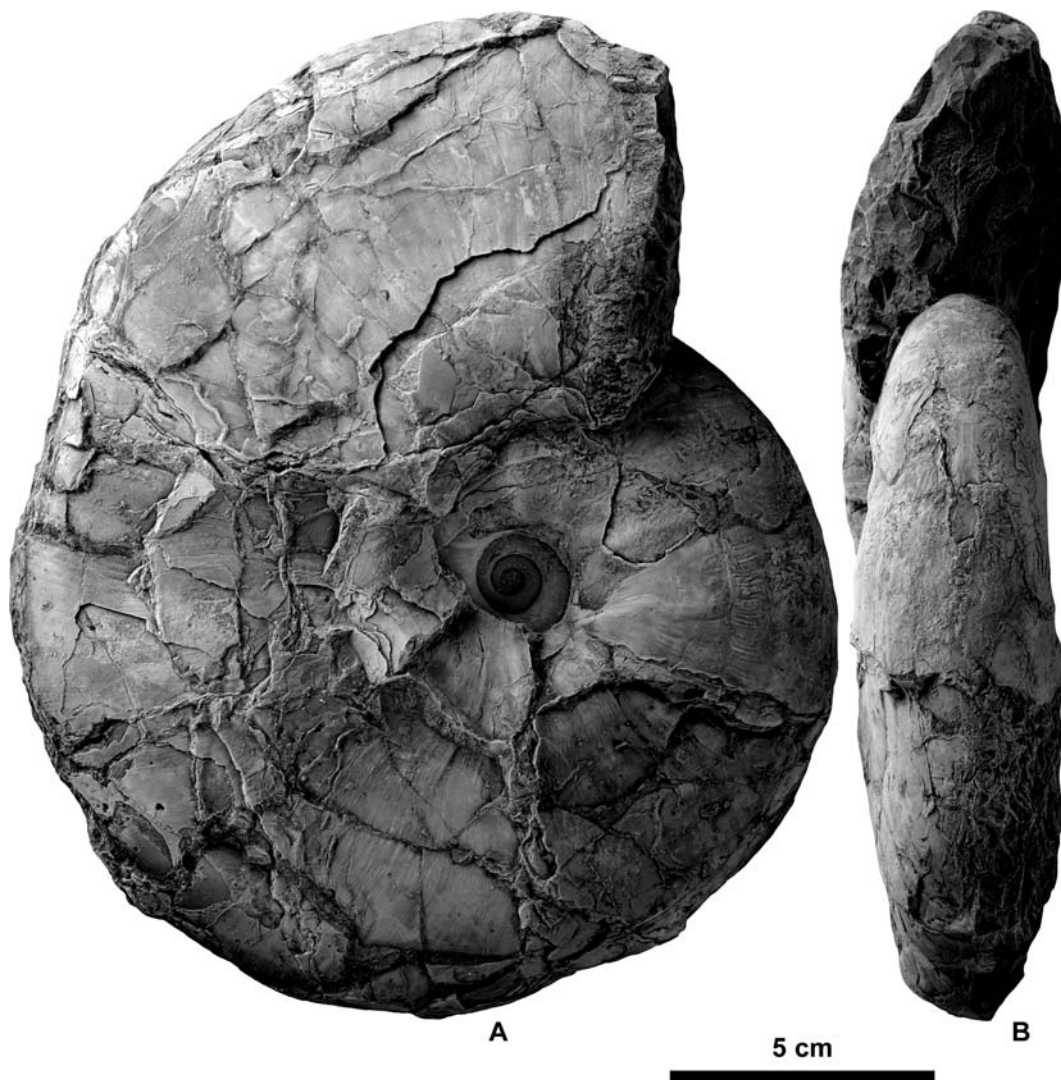


Figure 9. *Pachydiscus flexuosus* Matsumoto, 1979, NMNS PM23891, at Loc. FS01 in the Senpohshi Formation. **A**, left lateral view; **B**, apertural view.

ders. Ornamentation consists of weak radial folds and fine sinuous ribs, which are rursiradiate and concave on umbilical shoulder and rectiradiate to feebly prorsiradiate on flank. Suture line typical pachydiscid-type with deep trifid lobes.

Remarks.—Yazykova (1991, 1992, 1994) and Zonova *et al.* (1993) described several species of *Pachydiscus* from the Maastrichtian of southern Sakhalin and northern Kamchatka, and assigned them to *Pachydiscus gracilis*, *P. japonicus*, *P. neevesi*, *P. subcompressus*, *P. subcompressus obsoletus*, and *P. neubergicus*, but these specimens are identical to *P. flexuosus* with respect to shell shape and ornamentation (see Matsumoto, 1979).

Occurrence.—Maastrichtian in northern Hokkaido,

eastern Hokkaido and southern Sakhalin.

Discussion

Nifuku *et al.* (2009) recognized four magnetozones (S1–, S1+, S2–, S2+ in ascending order) in the Senpohshi Formation, and concluded that magnetozones S1– to S2+ correlate with polarity chrons C31 to C30n, based on calibration using the Maastrichtian bivalve “*Inoceramus*” *awajiensis* and the calcareous nannofossil *Nephrolithus frequens*.

According to Nifuku *et al.* (2009), the lower part of the formation including *Pachydiscus flexuosus*, *Gaudryceras makarovense*, *Anagaudryceras matsumotoi*, and *Diplo-*

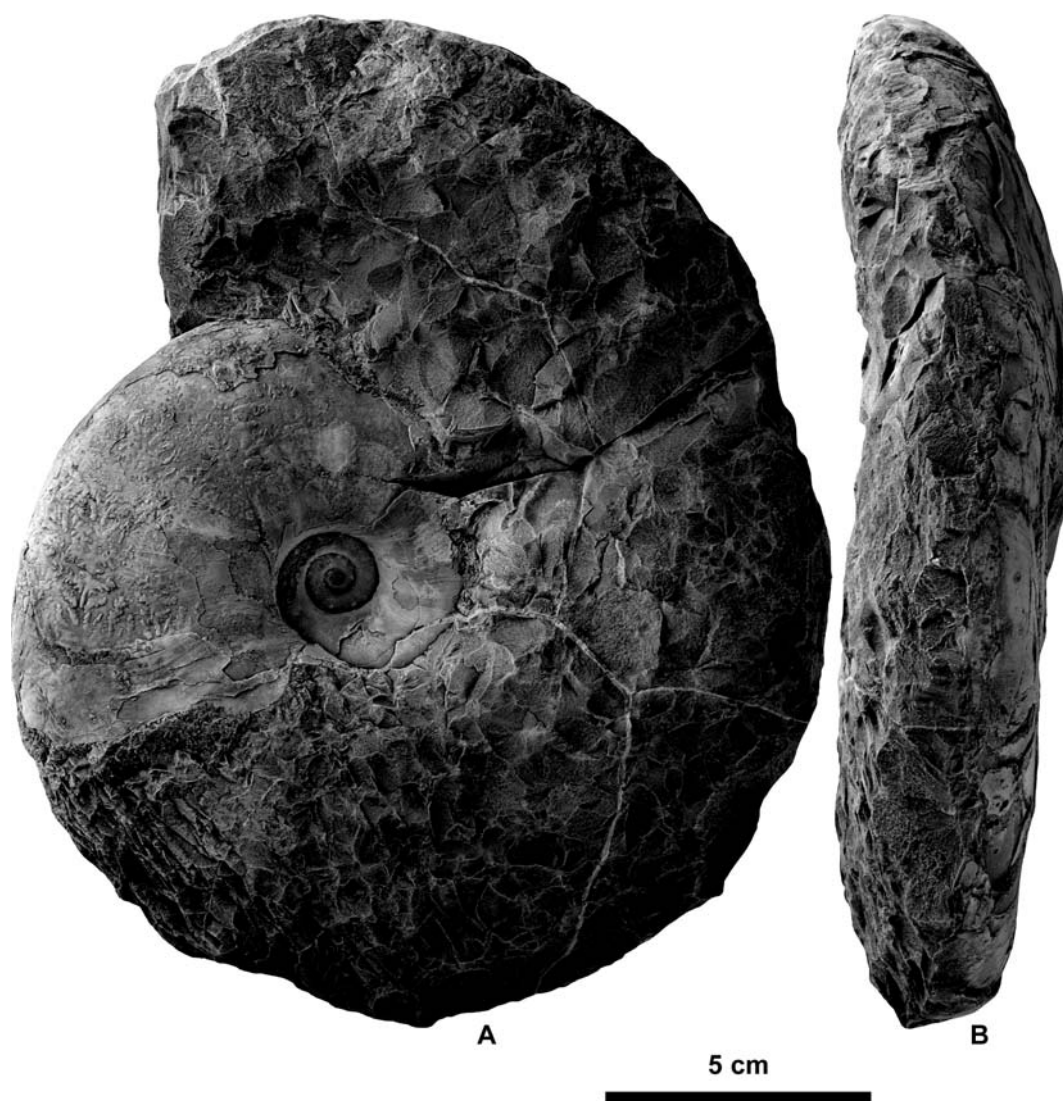


Figure 10. *Pachydiscus flexuosus* Matsumoto, 1979, NMNS PM23891, at Loc. FS01 in the Senpohshi Formation. **A**, right lateral view; **B**, ventral view.

moceras cf. *notabile*, as well as the middle part yielding *P. flexuosus*, are correlated to polarity chron C31n, i.e., the middle to upper parts of the middle Maastrichtian. The uppermost part of the formation is fossiliferous and yields a diverse ammonoid assemblage including *Neophylloceras* sp., *Pseudophyllites* sp., *Zelandites varuna*, *A. matsumotoi*, *G. cf. seymouriense*, *Gaudryceras* sp., and *D. cf. notabile*. Magnetostratigraphy has not been established for the uppermost part of the formation in the vicinity of Loc. SN01, due to poor outcrop exposures and sample conditions. Loc. NG25, which is located just below Loc. SN01, correlates with the lower part of polarity chron C30n. Considering the nearly 2 Myr duration

of polarity chron C30n (Ogg and Hinnov, 2012), and the relatively slow sedimentation rate of the uppermost part of the formation as indicated by its lithology (hemipelagic mudstone), the uppermost part of the formation also probably correlates with the lower part of polarity chron C30n, i.e., the lower part of the upper Maastrichtian (Figure 11).

The integration of bio- and magneto-stratigraphy in the Senpohshi Formation makes it possible to determine the precise and detailed chronologic assignment of similar local faunas in the Northwest Pacific realm as discussed below.

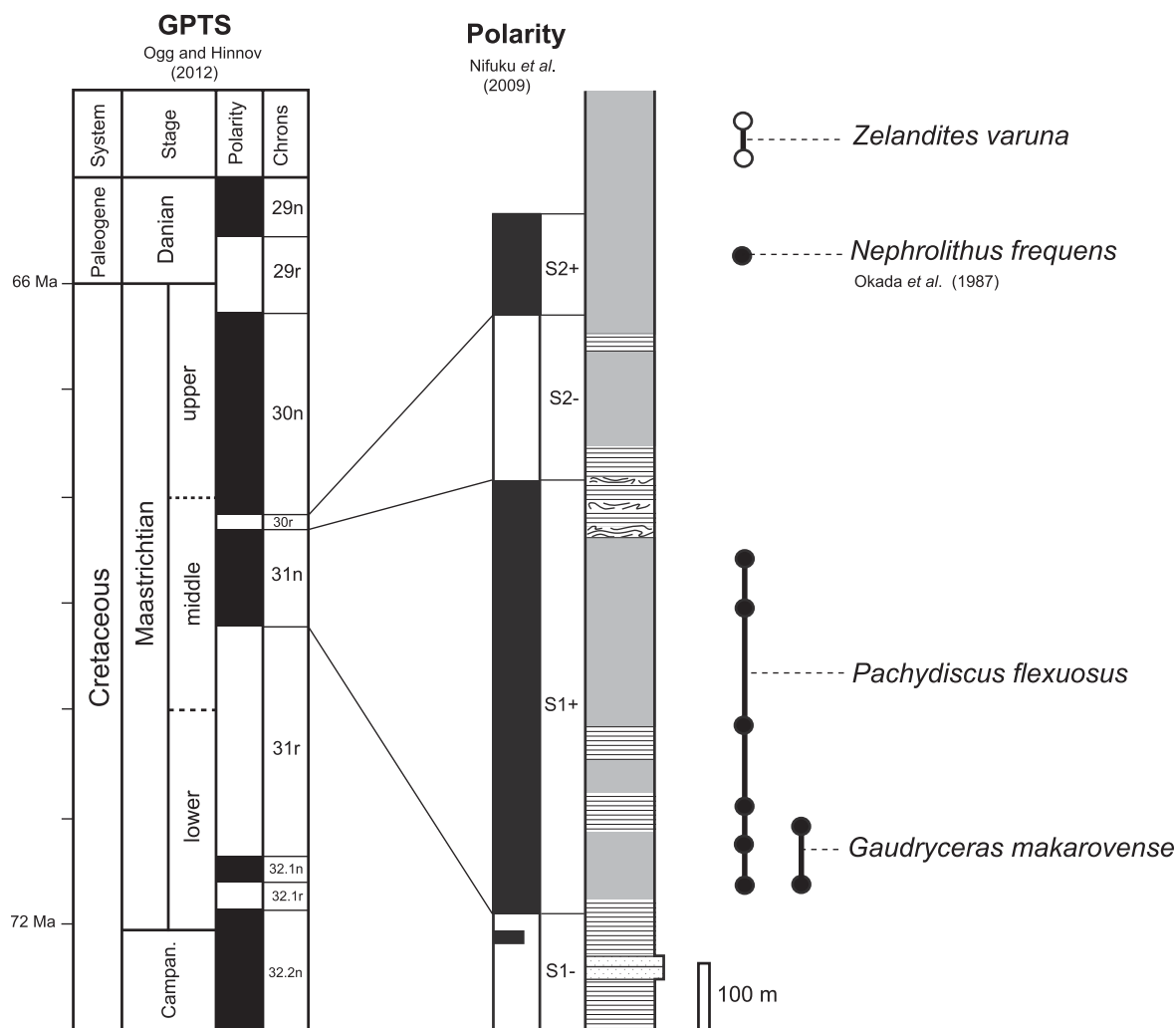


Figure 11. Lithology, magnetostratigraphy by Nifuku *et al.* (2009) and stratigraphic horizons and/or ranges of selected fossils from the Senpohshi Formation correlated with the geomagnetic polarity time scale (GPTS) by Ogg and Hinnov (2012). Legend is shown in Figure 2. Black circles, *in-situ* data; white circles, not *in-situ* data.

Awaji Island, Southwest Japan

The Shimonada Formation of the Izumi Group is distributed in a narrow band along the southwestern margin of Awaji Island, Southwest Japan. It is separated from the main part of the group by faults and its stratigraphic position is not precisely known (Morozumi, 1985). A specimen assignable to *Zelandites varuna* reported by Morozumi (1985) suggests that the formation partly correlates with the lower part of the upper Maastrichtian (Figure 12). An additional specimen, described as *Gaudryceras izumiense* by Morozumi (1985, p. 24, pl. 8, fig. 2) from a float calcareous concretion probably derived from the formation, is assignable to *Gaudryceras makarovense* (Maeda *et al.*, 2005), suggesting that the formation contains strata equivalent to the middle part of

the middle Maastrichtian (Figure 12).

Nakatombetsu area, northern Hokkaido

The Heitaro-zawa Formation, which is widely distributed in the Nakatombetsu area of northern Hokkaido, is 500 m to 1000 m thick and consists mainly of sandy mudstone and mudstone (Ando *et al.*, 2001). It occupies the uppermost part of the Yezo Group in northern Hokkaido and is unconformably overlain by the upper Paleocene Oku-utsunai Formation (Ando *et al.*, 2001). The formation yields well preserved ammonoids from various horizons (Matsumoto *et al.*, 1980; Ando *et al.*, 2001), but their taxonomy and biostratigraphy have not yet been thoroughly investigated (Matsumoto, 1979, 1984b, 1985; Shigeta and Nishimura, 2013).

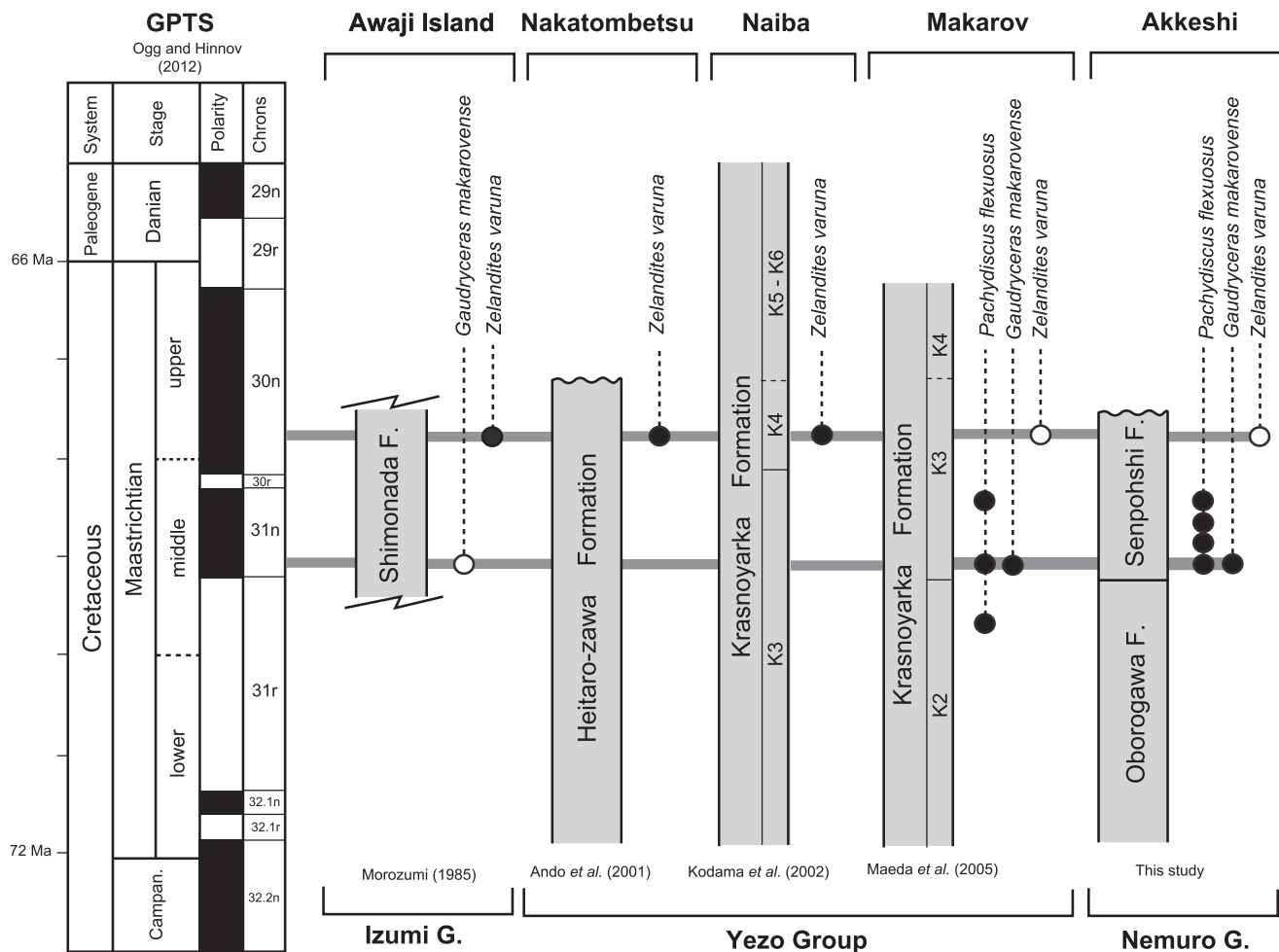


Figure 12. Diagram showing biostratigraphic correlation between Maastrichtian deposits in Southwest Japan (Awaji Island), northern Hokkaido (Nakatombetsu), southern Sakhalin (Naiba, Makarov), and eastern Hokkaido (Akkeshi). *Gaudryceras makarovense* and *Zelandites varuna* are ideal ammonoids for precise biostratigraphic correlation and age determination for the Maastrichtian in these areas of the Northwest Pacific realm. The stratigraphic range of *Pachydiscus flexuosus* probably spans the entire middle Maastrichtian. Black circles, *in-situ* data; white circles, not *in-situ* data.

Specimens assignable to *Zelandites varuna* from the Heitaro-zawa Formation (Ando *et al.*, 2001) suggest that the upper part of the formation correlates with the lower part of the upper Maastrichtian. Strata from the uppermost Maastrichtian to lower Paleocene, including the Cretaceous/Paleocene boundary, have presumably been eroded away (Figure 12).

Naiba area, southern Sakhalin

The Cretaceous Yezo Group crops out continuously in the Naiba area of southern Sakhalin, attaining over 5000 m in thickness and ranging in age from Albian to Maastrichtian (Matsumoto, 1942b; Vereshchagin and Salnikov, 1968; Pergament, 1974; Zakharov *et al.*, 1984; Poyarkova, 1987; Zonova *et al.*, 1993; Kodama *et al.*,

2000, 2002; Shigeta and Maeda, 2005). The Krasnoyarka Formation represents the uppermost part of the Cretaceous in this area and is equivalent to the Heitaro-zawa Formation of northern Hokkaido. It consists mainly of various types of sandstones as well as sandy mudstones. Kodama *et al.* (2002) divided it into six lithologic units: K1–K6.

Maastrichtian ammonoids including *Pachydiscus subcompressus* Matsumoto, 1954, *Zelandites varuna*, *Anagaudryceras matsumotoi*, and *Gaudryceras cf. seymouriense* occur in Unit K4 (Matsumoto, 1954, 1988; Kodama *et al.*, 2002). This assemblage is equivalent to that of the uppermost part of the Senpohshi Formation, thus suggesting that Unit K4 correlates with the lower part of the upper Maastrichtian.

According to Kodama *et al.* (2000), *Zelandites varuna* occurs abundantly in the normal polarity zone of Unit K4. Kodama *et al.* (2000) correlated this zone to polarity chron C32.1n, but later they (Kodama *et al.*, 2002) modified their interpretation and correlated it with an unknown normal zone in the middle part of polarity chron C31r. Because a continuous succession of fossil assemblages spanning the Campanian–Maastrichtian has not yet been observed in the Naiba section, magnetostratigraphic correlation is much more difficult. The *Zelandites varuna*-bearing beds in the Naiba area probably correlate with polarity chron C30n (Figure 12).

Makarov area, southern Sakhalin

A continuous succession of the Cretaceous Yezo Group is well exposed along several of the rivers in the Makarov area, southern Sakhalin, and any one of these exposures is worthy of consideration as a reference section for the Cretaceous stratigraphy of Sakhalin, as is the Naiba section (Maeda *et al.*, 2005). The group exceeds 2500 m in thickness, and is lithologically similar to sediments of the stratotype section in the Naiba area. Maeda *et al.* (2005) divided the Krasnoyarsk Formation into four lithologic units: K1–K4.

Gaudryceras makarovense is abundant in the lower part of Unit K3 together with *Pachydiscus flexuosus*, *Anagaudryceras matsumotoi*, and *Diplomoceras* cf. *notabile*. This ammonoid assemblage is equivalent to that in the lower part of the Senpohshi Formation, thus suggesting that Unit K3 correlates with the middle part of the middle Maastrichtian (Figure 12).

Maeda *et al.* (2005) reported a specimen of *Zelandites varuna* from a float calcareous concretion in the Makarov area and suggested that it came from the mudstone in Unit K2. However, the aragonitic preservation of its shell indicates that it almost certainly came from mudstone in the upper part of Unit K3 because in the area along the Grudzovka River, only the shells of Unit K3 are preserved in this manner (Figure 12).

The occurrence of *Pachydiscus flexuosus* in the lower and middle parts of the Senpohshi Formation demonstrates that the range of this ammonoid includes the entire polarity chron C31n, i.e., middle to upper parts of the middle Maastrichtian (Figure 11). In the Makarov area, *P. flexuosus* occurs from the middle part of Unit K2 to the middle part of Unit K3 (Maeda *et al.*, 2005). In Unit K2, it co-occurs with *Gaudryceras hamanakense* Matsumoto and Yoshida, 1979b in the upper part and *G. tombetsense* Matsumoto, 1984b and *Sphenoceras hetonaiense* (Matsumoto, 1952) in the middle part (Shigeta *et al.*, 2012). This evidence suggests that the stratigraphic range of *P. flexuosus* extends downward to the *G. makarovense*-bearing beds, i.e. the upper part of polarity

chron C31r (= the lower part of the middle Maastrichtian) (Figure 12). The stratigraphic range of *P. flexuosus* probably spans the entire middle Maastrichtian.

Concluding remarks

Our study reveals that *Gaudryceras makarovense* and *Zelandites varuna* are good index ammonoids for the interval from the middle part of the middle Maastrichtian extending up to the lower part of the upper Maastrichtian. As already indicated by Shigeta *et al.* (2010, 2012) and Shigeta and Nishimura (2013), *G. hobetsense* Shigeta and Nishimura, 2013, *G. izumiense*, and *G. tombetsense* are ideal ammonoids for precise biostratigraphic correlation of the lower to middle Maastrichtian in the Northwest Pacific realm. Although their detailed chronologic assignments have not yet been discussed, various modern methods, such as stable-isotope stratigraphy and radiometric dating as well as magnetostratigraphy, will eventually provide detailed chronologic assignments for these ammonoid-bearing beds and also contribute to the establishment of a precise biostratigraphic framework for uppermost Cretaceous strata in the Northwest Pacific realm.

Acknowledgments

We thank Akihiro Misaki (Kitakyushu Museum of Natural History and Human History, Kitakyushu) and the other reviewer for their valuable comments on the first draft. We are also grateful to the Japan Petroleum Exploration Co., Ltd. (Tokyo) and Hideo Kido (Bali, Indonesia) for providing information regarding fossil localities along the western coast of Akkeshi Bay, and staff personnel of the Akkeshi Marine Station (Akkeshi, Hokkaido) and Masataka Izukura (Sapporo, Hokkaido) for their help during our field work. We are also indebted to Kyushu University (Fukuoka) and Kyoto University (Kyoto) for kindly providing us the opportunity to examine their Cretaceous ammonoid specimens from the Senpohshi Formation. Thanks are extended to Jim Jenks (West Jordan, Utah) for his helpful suggestions and improvement of the English text. This study was supported by a Grant-in-Aid for Scientific Research of the Japan Society for Promotion of Science (No. 25400502) to Y. Shigeta and the Sasakawa Scientific Research Grant from the Japan Science Society (No. 22-234) to T. Nishimura.

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