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Faunal turnover at the end of the Cretaceous in the North Pacific region: Implications from combined magnetostratigraphy and biostratigraphy of the Maastrichtian Senpohshi Formation in the eastern Hokkaido Island, northern Japan

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ABSTRACT

A combined magnetostratigraphic and biostratigraphic study has been performed on the Maastrichtian Senpohshi Formation in eastern Hokkaido Island, northern Japan, which is an approximately 1300 m thick section mainly composed of hemipelagic mudstone. The identification of magnetic polarity was possible at 51 horizons, whereby four magnetozones were recognized. These magnetozones were correlatable to geomagnetic polarity chrons C31r to C30n, suggesting that the age of the Senpohshi Formation is spanning from middle to upper part of the Maastrichtian (ca. 69–67 Ma).

The magnetostratigraphy of the Senpohshi Formation established in this study enables a direct age correlation to the Maastrichtian successions in other regions. Thus, this detailed chronology of the formation contributes to paleontological studies of the Maastrichtian in the North Pacific region. For instance, this magnetostratigraphic age assessment implies the following: (1) the stratigraphic range of the ammonite *Pachydiscus flexuosus* contains polarity chrons from the lower part of C31r to the lower part of C31n, (2) the first occurrence (FO) of the calcareous nannofossil *Nephrolithus frequens* in the North Pacific region is correlatable to polarity chron C30n or below, and (3) the FO of the bivalve "*Inoceramus*" *awajiensis* is located within polarity chrons from C31r to the upper part of C31n. This suggests that the inoceramid extinction event in the North Pacific region might have occurred during polarity chrons from C31r to the upper part of C31n (ca. 70.5–67.8 Ma), which is 2.3–5.0 Myr prior to the Cretaceous/Paleogene boundary. The trend of the Maastrichtian faunal turnover in the North Pacific is well consistent with those of other regions, brings a new evidence for understanding the global faunal turnover in the Maastrichtian, just before Cretaceous/Paleogene mass extinction.

1. Introduction

The Maastrichtian (ca. 70.6–65.5 Ma) is the geological stage that spans the last 5 Myr of the Cretaceous period (Ogg et al., 2004) just before the mass extinction event at the Cretaceous/Paleogene boundary (commonly known as K/T boundary). It has been generally believed that the K/T mass extinction event was catastrophic (e.g., D'Hondt et al., 1996; Marshall and Ward, 1996; Pospichal, 1996) and an extraterrestrial impact was the cause of the event (e.g. Alvarez et al., 1980), though controversy is still continuing about the timing of the bolide impact and its relationship with the mass extinction event (Keller et al., 2007, 2008; Schulte et al., 2008). On the other hand, it is widely known that extensive environmental changes had occurred during the Maastrichtian. For example, some second-order regressions superimposed on the long-term sea-level fall was reported (Haq et al., 1987). Many studies also reported the widespread cooling (e.g., Barrera and Savin, 1999; Frank and Arthur, 1999; Huber et al., 2002), whereas North Atlantic warmed during the Maastrichtian (MacLeod et al., 2005; Isaza-Londoño et al., 2006). Furthermore, changes in thermohaline circulation occurred in the mid-Maastrichtian, though there is disagreement on the mechanism and character of the event (MacLeod and Huber, 1996; Barrera et al., 1997; Barrera and Savin, 1999; Frank and Arthur, 1999; MacLeod et al., 2000; Frank et al., 2005).

These environmental changes seemed to cause the significant faunal turnovers. In the mid-Maastrichtian, widespread bivalve inoceramids had been extinct (Ward et al., 1991; MacLeod et al., 1996), and rudistid reef in the tropical region collapsed (Johnson and Kuffman, 1990, 1996; Johnson et al., 1996). Moreover, some calcareous plankton (calcareous nannofossil *Nephrolithus frequens* and planktonic foraminifera *Abathomphalus mayaroensis*) showed latitudinal migrations in the mid-Maastrichtian (Pospichal and Wise, 1990; Huber,

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1992; Huber and Watkins, 1992). These environmental and faunal changes were called the "mid-Maastrichtian event" (MME). An important feature of the MME is that the faunal turnovers were diachronous throughout the world; it is suggested that inoceramid extinction and first occurrences of *N. frequens* and *A. mayaroensis* are earlier in the southern high latitudes and later in equatorial and northern hemisphere (Pospichal and Wise, 1990; Huber, 1992; Huber and Watkins, 1992; MacLeod et al., 1996). It is considered that sea-level fall, climate cooling, and changes in thermohaline circulation played important roles in this faunal event (Huber and Watkins, 1992; Johnson et al., 1996; MacLeod and Huber, 1996). Therefore, the Maastrichtian faunal and environmental changes had a close relationship, and it is important to understand them because they provide background information for the K/T mass extinction event.

However, the details of the global Maastrichtian faunal and environmental changes are not understood very well, particularly as there are few data from the North Pacific region, because of the few continuous, well-dated Maastrichtian successions in this region. There are only two relatively well-studied Maastrichtian successions in the Pacific Northwest — the Hakobuchi Formation in the Nakatonbetsu area of northern Hokkaido Island, northern Japan, and the Krasnoyarka Formation in the Naiba area of southern Sakhalin, Russia (Fig. 1). Although the Hakobuchi Formation yields abundant megafossils, the strata corresponding to the uppermost part of the Maastrichtian is missing due to unconformity (Ando et al., 2001; Ando and Tomosugi, 2005). Moreover, precise age determination of the Hakobuchi Formation is difficult because most of the index fossils show provinciality. On the other hand, a magnetostratigraphic study of the Krasnoyarka Formation has revealed that it includes the uppermost part of the Maastrichtian, even though the K/T boundary was not recognized (Kodama et al., 2000, 2002). The stable carbon isotope stratigraphy of the Krasnoyarka Formation was also proposed (Hasegawa et al., 2003). However, due to the absence of megafossils in the Upper Maastrichtian of the Krasnoyarka Formation (Kodama et al., 2002), one can obtain less information of the faunal turnover in the Upper Maastrichtian from the formation. Therefore, in order to improve the database about the Maastrichtian faunal turnover, it is important to give attention to other good sections in the North Pacific region. We thus focused on the Maastrichtian Senpohshi Formation in eastern Hokkaido Island, northern Japan, which exhibits excellent exposure of hemipelagic mudstone deposited under a stable sedimentary environment. The Senpohshi Formation yields Maastrichtian megafossils and microfossils, though most of them are endemic (Toshimitsu et al., 1995). Therefore, in order to make a global stratigraphic correlation possible, we performed a magnetostratigraphic study to assess the precise and detailed chronologic assignment of the formation. On the basis of our magnetostratigraphic correlation, we reconsider the biostratigraphic zonation of the Upper Maastrichtian in the North Pacific region and estimate the chronostratigraphic timing of the first occurrence of the calcareous nannofossil *Nephrolithus frequens* and the inoceramid extinction event.

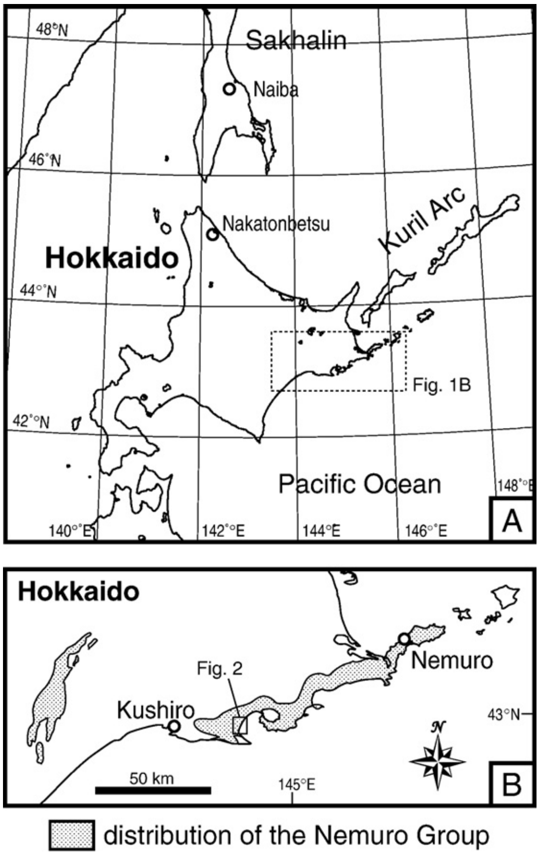

Fig. 1. Index maps showing location of Hokkaido Island (A), and distribution of the Nemuro Group (B). The square in B indicates the study area (refer to Fig. 2).

2. Geological setting

The Senpohshi Formation belongs to the Cretaceous–Paleogene Nemuro Group distributed in eastern Hokkaido Island, northern Japan (Fig. 1). The Nemuro Group is mainly composed of hemipelagic mudstones and sediment gravity flow deposits such as turbidites and submarine slump deposits (Kiminami, 1978; Naruse, 2003), and the Nemuro Group is interpreted as deposits in the forearc basin off the Kuril arc (Kiminami, 1983).

The Senpohshi Formation is extensively exposed along the western coast of Akkeshi Bay in eastern Hokkaido Island (Fig. 2), conformably overlying the Oborogawa Formation and unconformably overlain by the Shiomi Formation (Asano, 1962; Okada et al., 1987). Structurally, the Senpohshi Formation exhibits homoclinal bedding in the E–W direction and gently dips 10–20° southward. The thickness of the formation is greater than 1270 m, although its upper boundary is not exposed. No large-scale fault and tectonic folding are recognized. The formation mainly consists of weakly bioturbated, dark gray mudstone (Fig. 3). The mudstone layers are occasionally intercalated with sandstone laminae or thin beds (~1.0 cm) that can be interpreted as sediment gravity flow deposits. Thin slump deposits occur in some horizons.

3. Fossil occurrence and biostratigraphy

Megafossils and microfossils reported in the Senpohshi Formation, though not abundant, indicate Maastrichtian (Fig. 3). Naruse et al. (2000) have reported the occurrence of the ammonite *Pachydiscus flexuosus* in the lower part of the formation, which is widely distributed in Maastrichtian successions throughout southern Sakhalin and Hokkaido Island (Maeda and Shigeta, 2005; Maeda et al., 2005). Okada et al. (1987) have reported the occurrence of the calcareous nannofossil *Nephrolithus frequens*, an index fossil of the Upper Maastrichtian (Burnett, 1998), in the upper part of the formation. Moreover, planktonic foraminifera *Globotruncanella petaloidea*, which indicates the Maastrichtian (Caron, 1985), was reported to occur in the upper part of the formation (Yamada, 1984).

In this study, the following megafossils were newly discovered (Fig. 3, Plate I): the ammonite *Pachydiscus flexuosus* (Loc. FS01) and the bivalve "*Inoceramus*" *awajiensis* (Loc. FS02). Both megafossils occur in the lower to middle part of the formation, and they are preserved in calcareous concretions. *P. flexuosus* occurs in the Maastrichtian sections in the Pacific Northwest (Toshimitsu et al., 1995; Maeda and Shigeta, 2005; Maeda et al., 2005). "*I.*" *awajiensis*, which may be

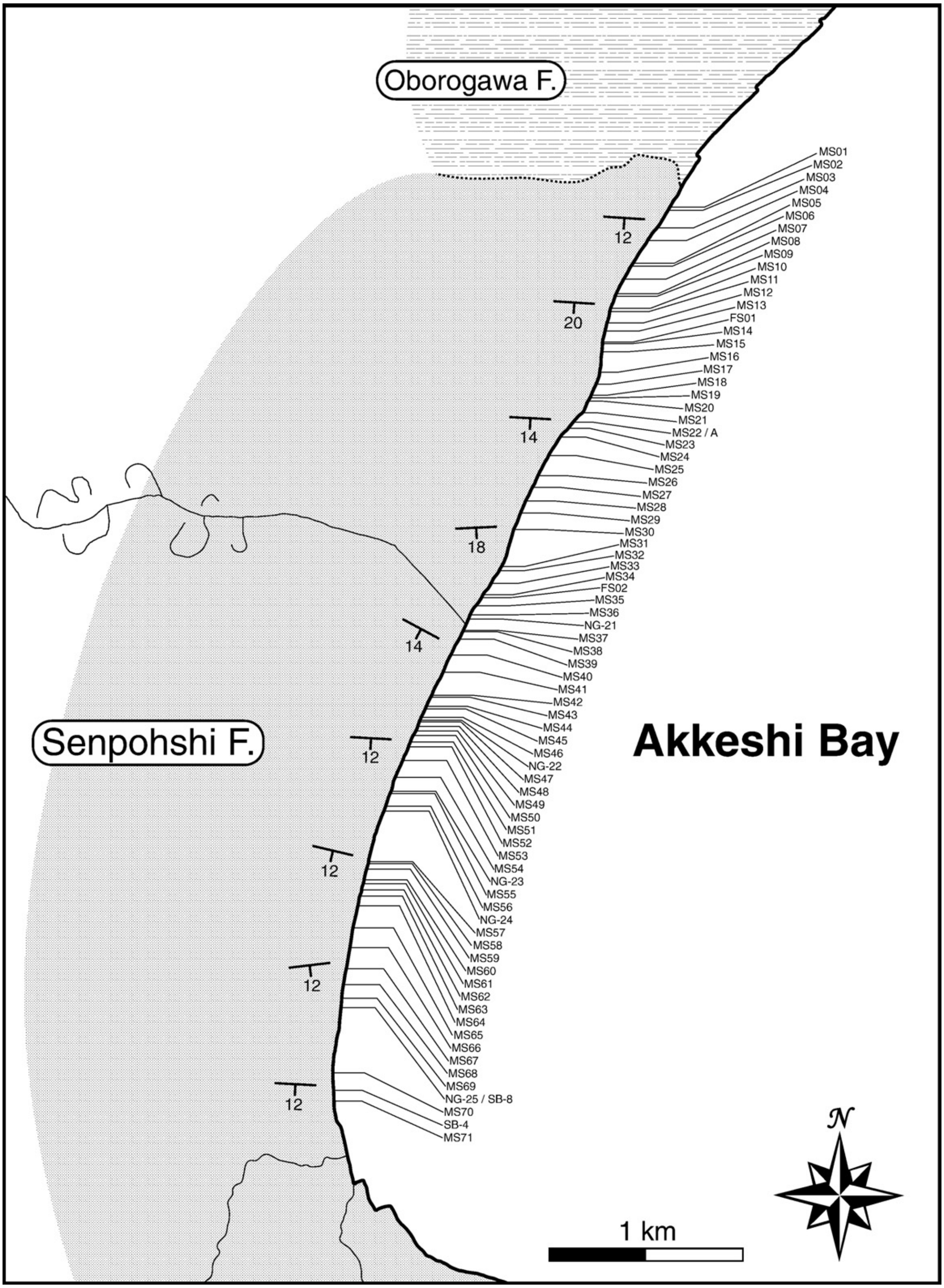

Fig. 2. Sampling sites for magnetostratigraphy and fossil localities. The sources of the fossil localities are as follows. Locs. FS01 and FS02: this study; Loc. A: Naruse et al. (2000); Locs. NG-21, NG-22, NG-23, NG-24, and NG-25: Okada et al. (1987); and Locs. SB-4 and SB-8: Yamada (1984).

better classified into the genus *Tenuipteria,* is an index fossil of the Maastrichtian (Toshimitsu et al., 1995).

4. Paleomagnetic analysis

Samples for magnetostratigraphy were collected at 71 sites at stratigraphic intervals ranging from 2 m to 81 m with an average of 18 m, depending on the availability of suitable exposures (Fig. 2). A gasoline-powered drill was mainly used for sampling (55 out of 71 sites), and the remaining sites were sampled as oriented slabs. All the samples were cut into specimens 25 mm in diameter and 22 mm in length, and 401 specimens were obtained in total.

Natural remanent magnetizations (NRMs) were measured with a 2G cryogenic magnetometer. Progressive alternating-field (AF)

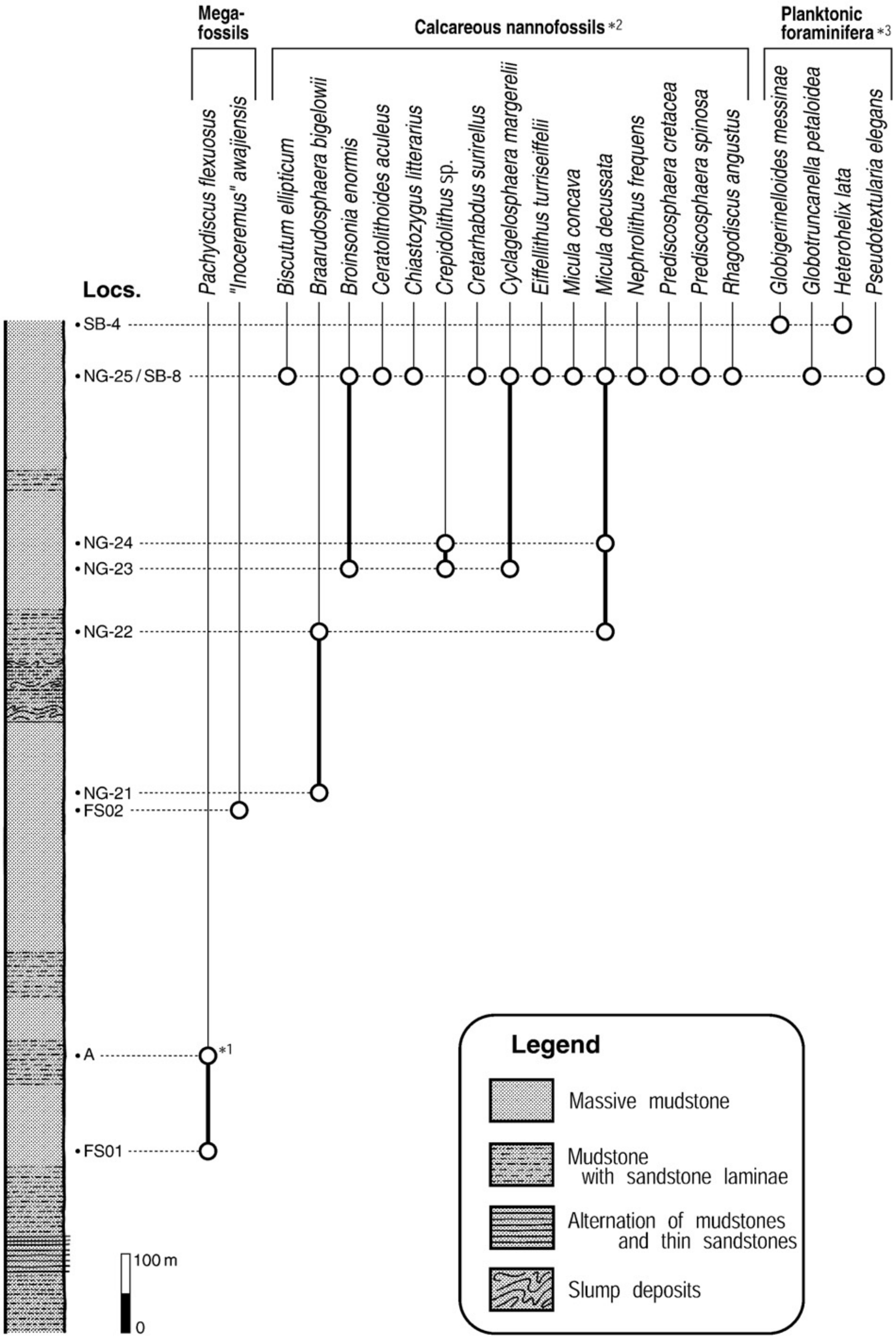

Fig. 3. Lithology and stratigraphic occurrence of megafossils and microfossils of the Senpohshi Formation. *1: Naruse et al. (2000), *2: Okada et al. (1987), and *3: Yamada (1984).

demagnetizations were primarily applied, and additional thermal demagnetization was carried out, if necessary, from 120 °C in steps of 40 °C until the magnetization intensity dropped below the noise level or until the direction became erratic. All the measurements and demagnetizations were performed in a magnetically shielded room at the Center for Advanced Marine Core Research, Kochi University.

The magnetic stabilities of the specimens were classified into three groups—A, B, and C. Typical examples of the demagnetization behaviors of each group are shown in Fig. 4, and their definitions are as follows:

Group A: The polarity is clearly recognized, and the characteristic remanent magnetization (ChRM) direction can be isolated. These directions were estimated by the principal component analysis (Kirschvink, 1980), with the maximum angular deviation (MAD) less than 15°. Group B: The polarity is identifiable but less stable, with MAD > 15°. Group C: Too unstable to recognize polarity.

The specimens of groups A and B were employed for the identification of the magnetic polarity, and site mean directions were calculated only from group A.

5. Magnetostratigraphy of the Senpohshi Formation

Finally, the magnetic polarity was identified at 51 out of the total 71 sites, comprising 29 sites of normal polarity and 22 sites of reversed polarity. The site mean directions were estimated by Fisher's (1953) method from a total of 35 sites comprising 22 sites of normal polarity and 13 of reversed polarity. Table 1 lists the polarities and mean directions of these sites, and Fig. 5 illustrates their plots on stratigraphic coordinates.

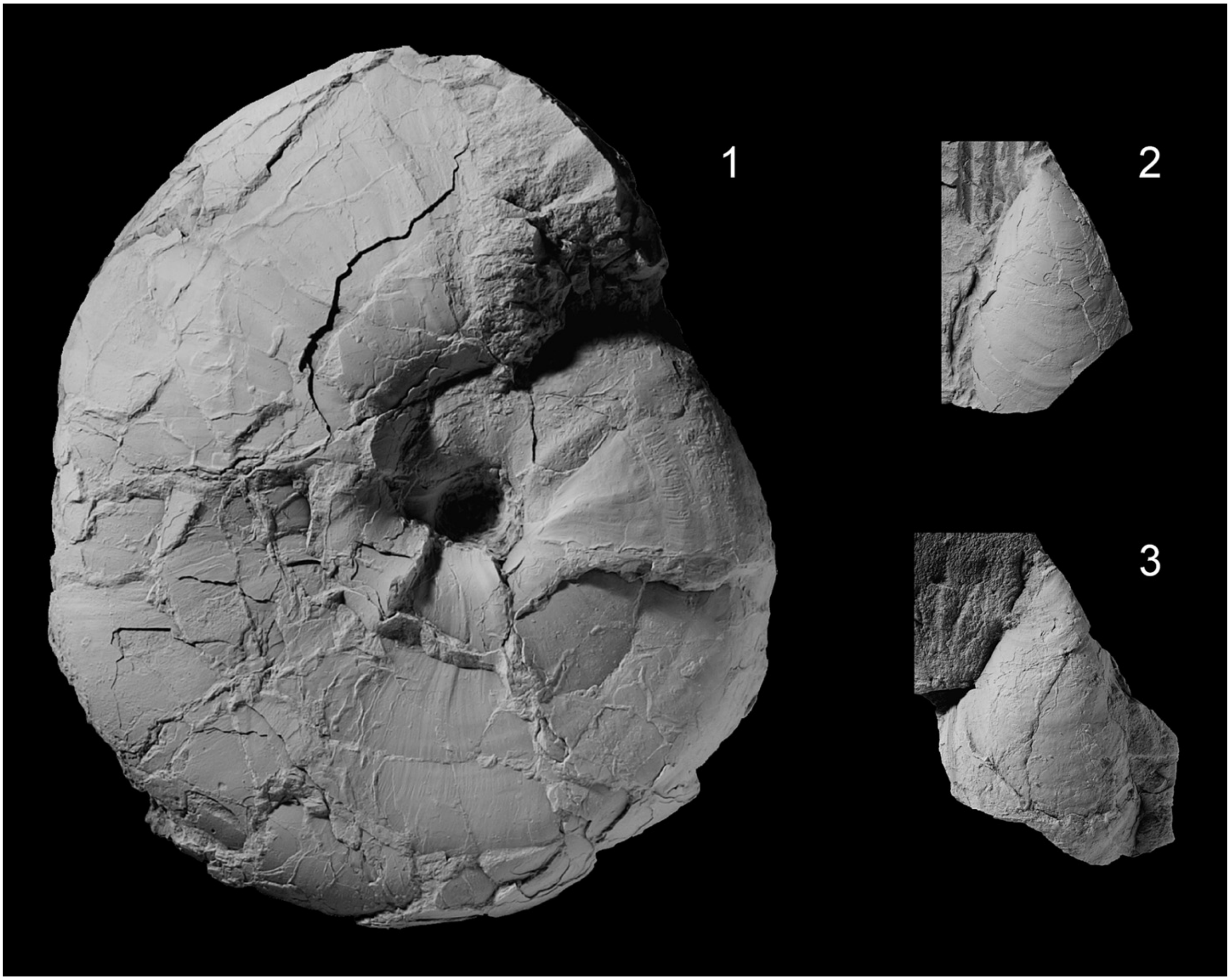

Plate I. Megafossils from the lower part of the Senpohshi Formation.

1. *Pachydiscus flexuosus* Matsumoto, Loc. FS01, ×0.5.
2–3. "*Inoceramus*" *awajiensis* Matsumoto, Loc. MS27, ×1.0.

Fig. 6 shows the site mean directions before and after applying bedding tilt corrections to the 35 sites. The grouping of the overall directions barely changed before ($\alpha_{95}=7.6°$) and after ($\alpha_{95}=7.5°$) these corrections (Table 1) because the study area generally exhibits a homoclinal structure. The mean direction of the normal and reversal polarity groups are antipodal. We carried out a reversal test after McFadden and McElhinny (1990). The angle between the mean directions of the two polarity groups was 9.0°, which is smaller than the critical angle (15.6°). Therefore, The ChRM data of the Senpohshi Formation passed the reversal test. The antipodal mean directions of each polarity groups indicate the preservation of the primary magnetizations. The declinations do not appear to be deviated from the N–S direction, which is consistent with the previous works of the Nemuro Group (Tanaka and Uchimura, 1989; Fujiwara and Kanamatsu, 1990). The mean inclination appears to be slightly shallower than that expected at the present latitude of the basin. The shallower inclination seems to be consistent with the Maastrichtian paleomagnetic result from the nearby Nemuro–Shikotan terrane (Bazhenov and Burtman, 1994). However, considering the relatively large statistical error for the present study, it might be premature to draw definite conclusion on the latitudinal drift of the terrane.

We recognize four magnetozones in the Senpohshi Formation, hereafter referred to as S1−, S1+, S2−, and S2+ in ascending order (Fig. 5). The normal polarity magnetozone S1+ yields the ammonite *Pachydiscus flexuosus* and the bivalve "*Inoceramus*" *awajiensis* (Fig. 7), and the normal polarity magnetozone S2+ yields the calcareous nannofossil *Nephrolithus frequens*.

We conclude that magnetozones S1− to S2+ are correlatable to polarity chrons C31r to C30n, respectively (Fig. 7). Since "*I.*" *awajiensis* is the index fossil of the Maastrichtian (Toshimitsu et al., 1995), S1+ can be correlated to polarity chron C32n or above. In southern Sakhalin, ammonites *Phyllopachyceras ezoense*, *Tetragonites popetensis*, and *Desmophyllites diphylloides* occur within the polarity chron C32n of the Krasnoyarka Formation (Kodama et al., 2002). In the Hakobuchi Formation in the Nakatonbetsu area, northern Hokkaido Island, these ammonites occur below the range zone of "*I.*" *awajiensis* (Ando and Tomosugi, 2005). Thus, the range zone of "*I.*" *awajiensis* is inferred to be above polarity chron C32n; therefore, S1+ can be correlated to polarity chron C31n or above because magnetozone S1+ yields "*I.*" *awajiensis*. In addition, the occurrence of the calcareous nannofossil *Nephrolithus frequens*, one of the Upper Maastrichtian index fossils, in S2+ suggests that S2+ could be correlated to polarity chron C30n or

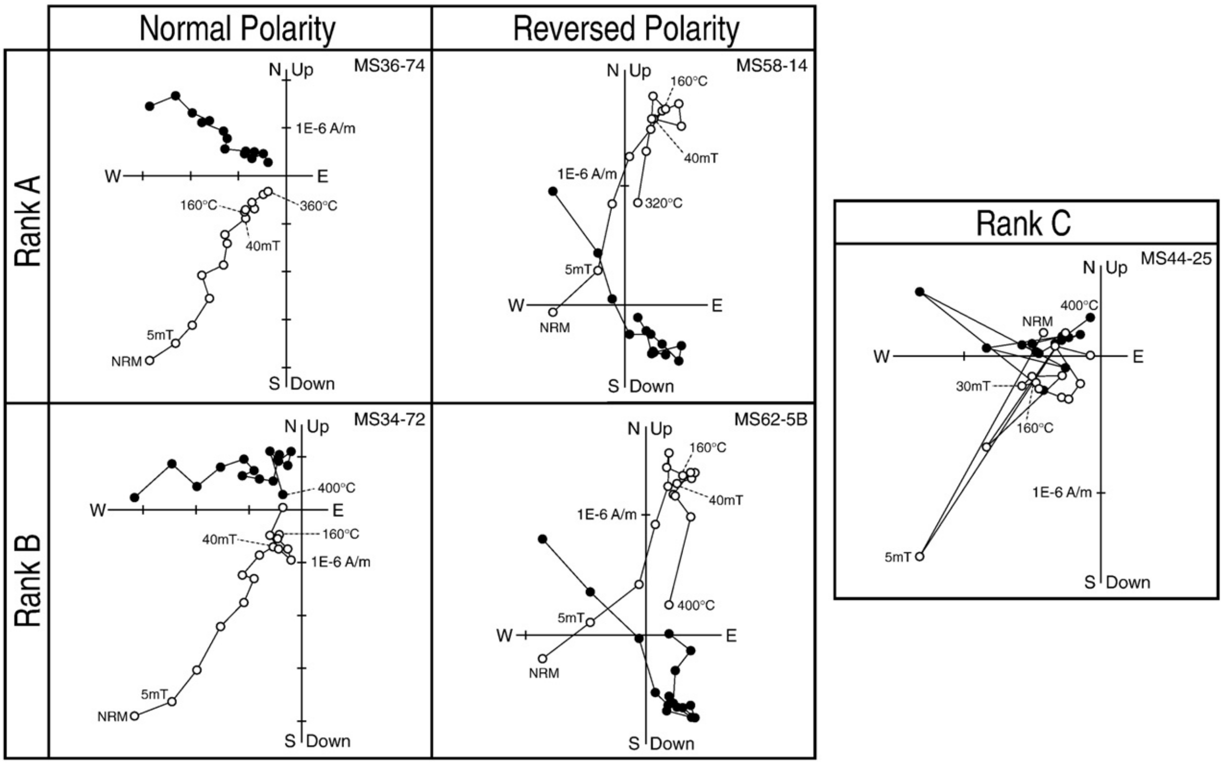

Fig. 4. Examples of orthogonal vector diagrams of progressive demagnetizations. Solid and open circles are projections on horizontal and east–west vertical planes, respectively, in coordinates after bedding tilt correction. The definitions of groups A, B, and C are described in the text.

below. Considering the continuous succession of the Senpohshi Formation, the magnetozones S1− to S2+ could be correlatable to polarity chrons C31r to C30n, respectively. These results suggest that the Senpohshi Formation corresponds to the Upper Maastrichtian and that the age of the formation approximately spans from 69 to 67 Ma.

6. Implications of biostratigraphy and inoceramid extinction event

The correlation of the Maastrichtian biostratigraphy of the North Pacific region to that of other regions has been difficult because most of the fossils in this period exhibit provinciality (Toshimitsu et al., 1995); therefore, the precise age determination of the Maastrichtian strata in the North Pacific region was impossible. However, this study established the magnetostratigraphy of the Maastrichtian Senpohshi Formation, which made it possible to correlate the occurrence of the horizons of certain index fossils or biotic events to other regions. Here, we discuss the biostratigraphic correlation of three fossil species occurring in the Senpohshi Formation and their significance for understanding the Maastrichtian faunal turnover in the North Pacific region.

6.1. *Pachydiscus flexuosus*

The ammonite *Pachydiscus flexuosus* is widely distributed in the Maastrichtian successions throughout southern Sakhalin and Hokkaido Island (Maeda and Shigeta, 2005; Maeda et al., 2005). Maeda et al. (2005) have suggested that it might be an indigenous species in the North Pacific region. The occurrence of *P. flexuosus* is so common that the confirmation of its stratigraphic range is quite significant for biostratigraphic correlation in the North Pacific region.

However, despite the frequent occurrence of *P. flexuosus*, its stratigraphic range is controversial (Toshimitsu et al., 1995; Maeda et al., 2005). *P. flexuosus* has been believed to be an indicator of the Upper Maastrichtian (Matsumoto et al., 1979; Toshimitsu et al., 1995); however, its stratigraphic range is probably considerably greater than that anticipated formerly (Kodama et al., 2002; Maeda et al., 2005).

In the Senpohshi Formation, *P. flexuosus* occurred at the lower part of polarity chron C31n (Fig. 7). *P. flexuosus* was also reported to occur at the bottom of the lithologic unit K4 corresponding to the lower part of polarity chron C31r at the Krasnoyarka Formation in southern Sakhalin (Kodama et al., 2002, Table 3, Figs. 4, 9). Therefore, the stratigraphic range of *P. flexuosus* certainly spans from the lower part of C31r to the lower part of C31n, i.e., from the Lower Maastrichtian to the lower part of the Upper Maastrichtian.

6.2. *Nephrolithus frequens*

The calcareous nannofossil *Nephrolithus frequens* is the index fossil of the Upper Maastrichtian and was extinct at the K/T boundary (e.g. Burnett, 1998). *N. frequens* mainly occurs at the high latitudes of both the Northern and Southern Hemispheres (Thierstein, 1981). It has been reported that *N. frequens* showed northward migration in the mid-Maastrichtian and it might be caused by the global climatic cooling (Worsley and Martini, 1970; Wind, 1979; Wise, 1988; Pospichal and Wise, 1990; Huber and Watkins, 1992). The FO of *N. frequens* in southern high latitudes is considered to be the earliest (Fig. 8), and it is correlated to the middle of polarity chron C31r at Antarctic ODP Sites 689 and 690 (Pospichal and Wise, 1990). On the other hand, the FO of *N. frequens* in other regions is later than that in the southern high latitudes (Fig. 8). For example, in northern mid-latitudes, the FO of *N. frequens* at the North Atlantic DSDP Site 384 was correlated to the uppermost part of polarity chron C31n (Larson and Opdyke, 1979; Okada and Thierstein, 1979). Moreover, the FO of *N. frequens* at the North Atlantic DSDP Site 605 was correlated to the C30r/C30n boundary or above (this is because two different interpretations of the magnetostratigraphy of this site are possible due to poor recovery and the possible existence of an unconformity, Bruins et al., 1987), which is also later than that in the southern high

Table 1
Paleomagnetic data from the Senpohshi Formation

Site	Height (m)	N_A /N	D_{is}	I_{is}	D_{tc}	I_{tc}	k	α_{95}	Polarity
MS71	1272	0/5	–	–	–	–	–	–	?
MS70	1251	3/3	314.8	19.6	312.3	27.7	26.7	24.3	N
MS69	1195	4/4	353.7	53.3	351.3	59.1	78.9	10.4	N
MS68	1187	8/8	10.6	29.7	358.5	43.6	2.1	51.6	N
MS67	1172	0/5	–	–	–	–	–	–	?
MS66	1149	6/7	10.3	45.2	353.2	54.8	3.2	45.1	N
MS65	1134	5/5	2.9	24.5	354	31.5	2.4	63.6	N
MS64	1117	0/4	–	–	–	–	–	–	?
MS63	1108	0/4	–	–	–	–	–	–	?
MS62	1101	3/6	175.9	−48.7	170.5	−64.3	10.5	40	R
MS61	1091	0/3	–	–	–	–	–	–	?
MS60	1086	2/7	200.1	−42.8	199.9	−54.8	–	–	R
MS59	1070	0/4	–	–	–	–	–	–	?
MS58	1062	6/7	168.5	−46.8	164.5	−57.3	20.9	15	R
MS57	1060	7/9	165.6	−40.5	162.2	−58.3	17.1	15	R
MS56	979	0/2	–	–	–	–	–	–	R
MS55	960	1/3	208.6	−68.3	221.8	−75	–	–	R
MS54	937	0/6	–	–	–	–	–	–	R
MS53	918	1/5	159.9	−13.6	155.3	−14.7	–	–	R
MS52	906	0/3	–	–	–	–	–	–	R
MS51	903	2/9	194.6	−24.6	196.3	−35.2	–	–	R
MS50	895	1/13	199.6	−67.1	228.5	−81.4	–	–	R
MS49	887	5/11	175.3	−44.3	171.8	−59.1	30.7	14	R
MS48	882	0/4	–	–	–	–	–	–	R
MS47	876	0/9	–	–	–	–	–	–	R
MS46	869	0/13	–	–	–	–	–	–	R
MS45	854	1/12	202.9	−33.3	207.1	−47.5	–	–	R
MS44	851	0/4	–	–	–	–	–	–	?
MS43	831	0/6	–	–	–	–	–	–	?
MS42	828	0/6	–	–	–	–	–	–	N
MS41	769	1/5	358.2	47.0	336.6	59.5	–	–	N
MS40	744	0/6	–	–	–	–	–	–	N
MS39	717	1/4	324.2	29.2	314.4	27.7	–	–	N
MS38	705	8/9	19.9	48.5	25.1	66.2	4.4	29.9	N
MS37	703	1/2	25.7	37.1	30.9	54.4	–	–	N
MS36	679	8/8	325.5	53.6	314.9	62.5	23.2	11.7	N
MS35	665	3/7	335.2	57.9	300.3	69	63.3	15.6	N
MS34	655	2/5	333.8	37.2	324.3	48.2	–	–	N
MS33	643	4/7	341.1	44.5	320.4	44	91.6	9.7	N
MS32	631	0/4	–	–	–	–	–	–	N
MS31	625	0/13	–	–	–	–	–	–	?
MS30	558	1/4	8.9	12.7	4.5	33.4	–	–	N
MS29	522	1/4	332.8	15.0	327.9	26.1	–	–	N
MS28	499	0/1	–	–	–	–	–	–	?
MS27	471	0/2	–	–	–	–	–	–	N
MS26	454	0/0	–	–	–	–	–	–	?
MS25	410	0/2	–	–	–	–	–	–	N
MS24	378	0/1	–	–	–	–	–	–	N
MS23	361	1/1	32.5	0.4	33.9	18.5	–	–	N
MS22	349	0/4	–	–	–	–	–	–	?
MS21	328	2/5	19.8	44.5	14.9	61.1	–	–	N
MS20	311	0/4	–	–	–	–	–	–	?
MS19	307	2/2	5.1	50.6	354.1	61.4	–	–	N
MS18	305	1/5	350.7	58.5	321.9	71.1	–	–	N
MS17	291	0/2	–	–	–	–	–	–	?
MS16	277	0/2	–	–	–	–	–	–	?
MS15	233	5/5	40.8	38.9	48	58	4.7	39.4	N
MS14	231	1/1	355.5	18.2	348.2	38.2	–	–	N
MS13	208	0/3	–	–	–	–	–	–	N
MS12	192	0/3	–	–	–	–	–	–	?
MS11	171	0/3	–	–	–	–	–	–	R
MS10	163	2/3	201.4	−33.5	197.1	−44.3	–	–	R
MS09	141	4/4	0.7	2.5	356.6	23.6	4.5	48.9	N
MS08	135	1/8	138.5	−37.3	124.9	−52.3	–	–	R
MS07	106	1/8	159.9	−59.8	142.1	−71.4	–	–	R
MS06	91	0/3	–	–	–	–	–	–	?
MS05	88	0/7	–	–	–	–	–	–	R
MS04	63	0/4	–	–	–	–	–	–	?
MS03	47	0/3	–	–	–	–	–	–	?
MS02	17	0/4	–	–	–	–	–	–	?
MS01	11	0/6	–	–	–	–	–	–	R
			N	D_{is}	I_{is}	D_{tc}	I_{tc}	k	α_{95}
			35	358.5	40.3	–	–	11.2	7.6
			35	–	–	351.2	53.6	11.4	7.5

Height: height of the horizon from the bottom of the Senpohshi Formation.
N_A: number of specimens used in calculation.
N: number of selected samples (specimens classified into groups A and B).
D_{is}, I_{is}: in-situ declination and inclination, respectively.
D_{tc}, I_{tc}: declination and inclination, respectively, after bedding correction.
K: Fisher's precision parameter.
α_{95}: angle of the 95% confidence cone.
Polarity: interpretation of the site polarity.
(N: normal polarity, R: reversed polarity, ?: site polarity cannot be interpreted)

latitudes. In summary, the FO of *N. frequens* is correlated to polarity chron C31n or upper chrons in the northern mid-latitudes, at least in the North Atlantic. However, data regarding the FO of *N. frequens* in the North Pacific region was unavailable.

Our magnetostratigraphic correlation reveals that *N. frequens* occurs at the bottom of polarity chron C30n in the Senpohshi Formation (Figs. 7, 8). This implies that the FO of *N. frequens* in the North Pacific region is correlatable to the bottom of polarity chron C30n or below. This suggests that the FO of *N. frequens* in the North Pacific region can be as early as that in the northern mid-latitudes of the Atlantic. Thus, this result is still conformable with the general trend in the latitudinal variation of the FO of *N. frequens*.

Our correlation of the horizon yielding *N. frequens* with the geomagnetic polarity time scale is the first report in the North Pacific region, although it should be noted that the only one horizon yielded *N.frequens* from this succession (Okada et al., 1987). Okada et al. (1987) described that calcareous nannofossils from the Senpohshi Formation were extremely scarce, as they examine more than one hundred samples, only ten samples yielded rare nannofossils. Although it is difficult to demonstrate the cause of the scarcity, it might be because of the diagenetic dissolution. In addition, as the Senpohshi Formation was deposited at the active margin settings off the Kuril arc (Kiminami, 1983), very high sedimentation rate and its effect of dilution might be another possible cause. Further examination in other successions in the North Pacific region would provide more information about FO of *N. frequens* in this region.

6.3. "*Inoceramus*" *awajiensis* and inoceramid extinction event

Inoceramid bivalves first appeared in the Early Permian, and they flourished during the Mesozoic (Dhondt, 1983a). It is suggested that all Inoceramidae with the exception of *Tenuipteria* disappeared in the mid-Maastrichtian (Dhondt, 1983a; MacLeod and Ward, 1990; MacLeod and Orr, 1993; MacLeod, 1994; Chauris et al., 1998). The enigmatic genus *Tenuipteria* is the only inoceramid taxon known to have survived through most of the Late Maastrichtian (Jeletzki and Clemens, 1965; Spenden, 1970; Dhondt, 1983b; Ward et al., 1991). It is supposed that inoceramid extinction event would be caused by the changes in the thermohaline circulation and consequent supply of the cool and oxygenized intermediate water (MacLeod et al., 1996). However, it has not fully revealed the process and cause of the inoceramid extinction event because there is not enough data yet; data is still poor especially in the North Pacific region.

In the North Pacific region, "*Inoceramus*" *awajiensis* is the only species that survived the inoceramid extinction event (Toshimitsu et al., 1995; Ando et al., 2001; Ando and Tomosugi, 2005). "*I.*" *awajiensis* is suggested to probably belong to the genus *Tenuipteria* (Toshimitsu et al., 1995). The FO of "*I.*" *awajiensis* approximately corresponds to the horizon where other inoceramids were extinct

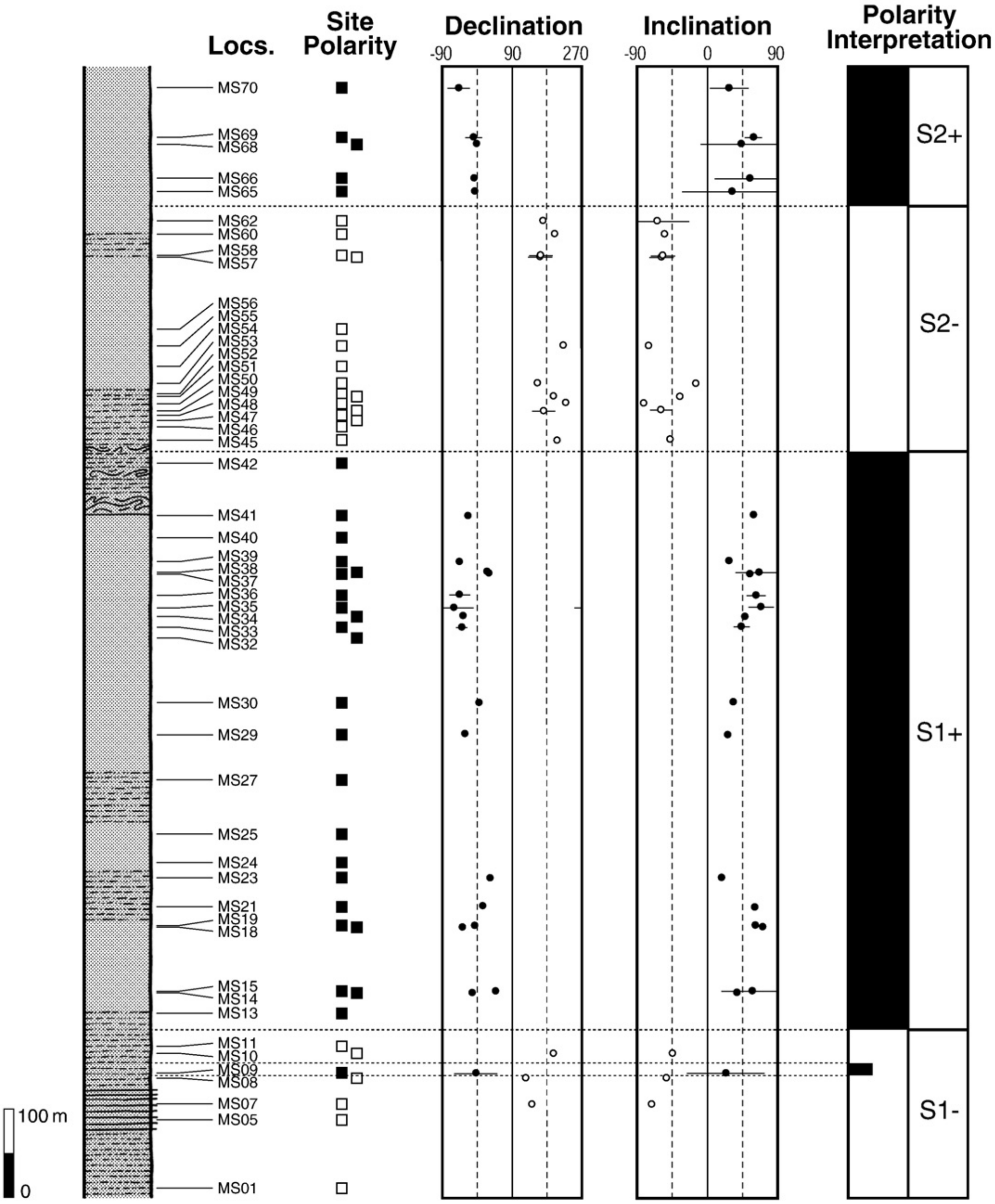

Fig. 5. Magnetostratigraphy of the Senpohshi Formation. Sites where the polarity cannot be interpreted are omitted. The solid (open) squares represent normal (reversed) polarity sites. The solid (open) circles represent the inclinations and declinations of the normal (reversed) polarity along with 95% confidence error bars if they can be computed from more than two individual directions. Polarity zones represented by a single site are denoted by half bars. The boundaries between the magnetozones are placed at midway between adjacent horizons of opposite magnetic polarity.

(Ando et al., 2001; Ando and Tomosugi, 2005). Thus, the first appearance datum of "*I.*" *awajiensis* indicates the approximate timing of the inoceramid extinction event in the North Pacific region. Our magnetostratigraphic correlation revealed that the FO of "*I.*" *awajiensis* is correlatable to the upper part of polarity chron C31n or below (Fig. 7). It has already been suggested that the FO of "*I.*" *awajiensis* is above the polarity chron 32r (refer to the discussion in Section 5, *Magnetostratigraphy of the Senpohshi Formation*). Thus, if the FO of "*I.*" *awajiensis* indicates the inoceramid extinction event in the North Pacific region, it could have occurred between polarity chrons C31r and the upper part of C31n (ca. 70.4–67.8 Ma), which corresponds to the Lower-lower part of the Upper Maastrichtian.

It has been suggested that the inoceramid extinction event was asynchronous throughout the world; the event occurred in different basins in different ages (Fig. 9). MacLeod et al. (1996) have reported that there appears to be a general Antarctic-to-Equator progression in the timing of the pulse of extinction among inoceramids. For example, in the southern high latitudes, the event occurred at the C33n/C32r boundary (or at the bottom of polarity chron C32n) at Antarctic DSDP Site 700 (Fig. 9). On the other hand, in the northern mid-latitudes, the inoceramid extinction event occurred at the upper part of polarity chron C31r (Gubbio) or above (Basque region, DSDP Site 605 and ODP Site 1052). They are still considerably younger than that in the southern high latitudes. However, this hypothesis was led from data from Atlantic Ocean, Indian Ocean, and Europe (MacLeod et al., 1996), and data regarding the timing of the event in Pacific was scarcely available.

This study suggests the possibility that the inoceramid extinction event in the North Pacific region could have occurred between polarity chrons C31r and the upper part of C31n, which is still considerably younger than that in the southern high latitudes. If our estimation is correct, the timing of the event in the North Pacific

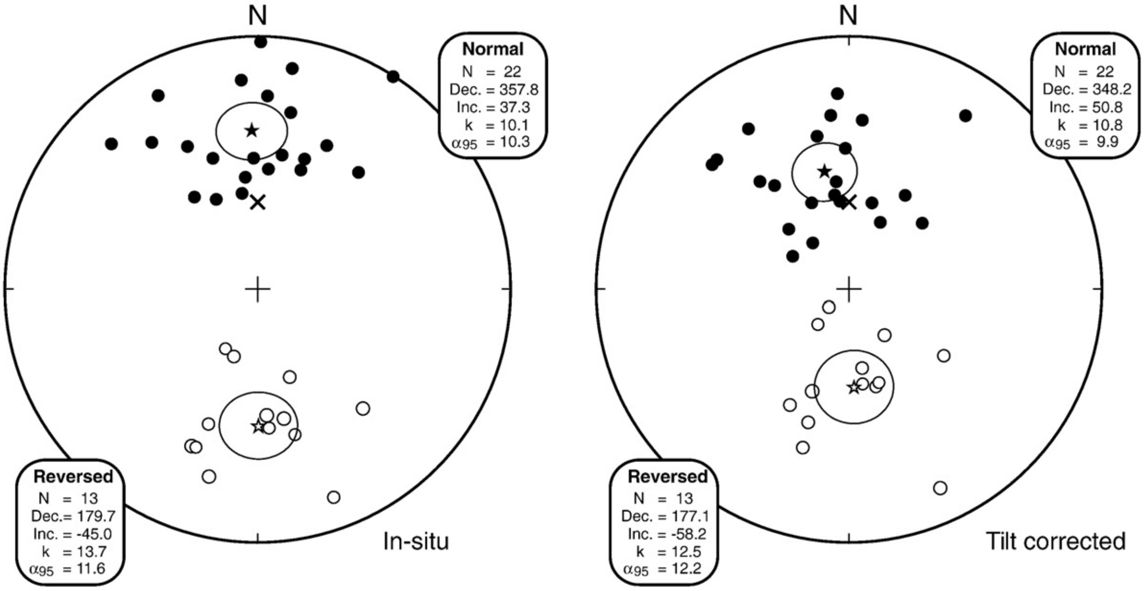

Fig. 6. Equal-area projections of magnetization directions of 22 normal and 13 reversed polarity sites before (left) and after (right) bedding tilt correction. The solid (open) circles correspond to the Lower (Upper) Hemisphere. The overall mean directions and their 95% error limits are provided in boxes and plotted using stars and ovals. The oblique cross shows the present dipole field direction.

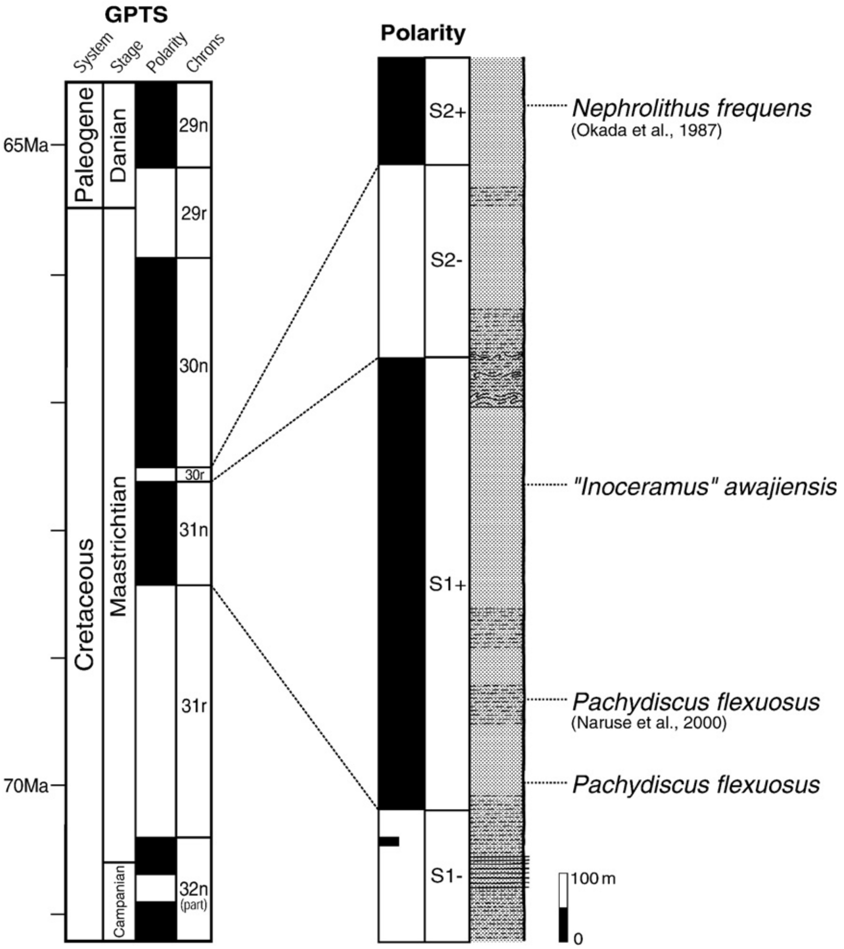

Fig. 7. Lithology, magnetostratigraphy, and occurrence horizons of selected index fossils of the Senpohshi Formation correlated to the geomagnetic polarity time scale (GPTS), which is obtained from Ogg et al. (2004).

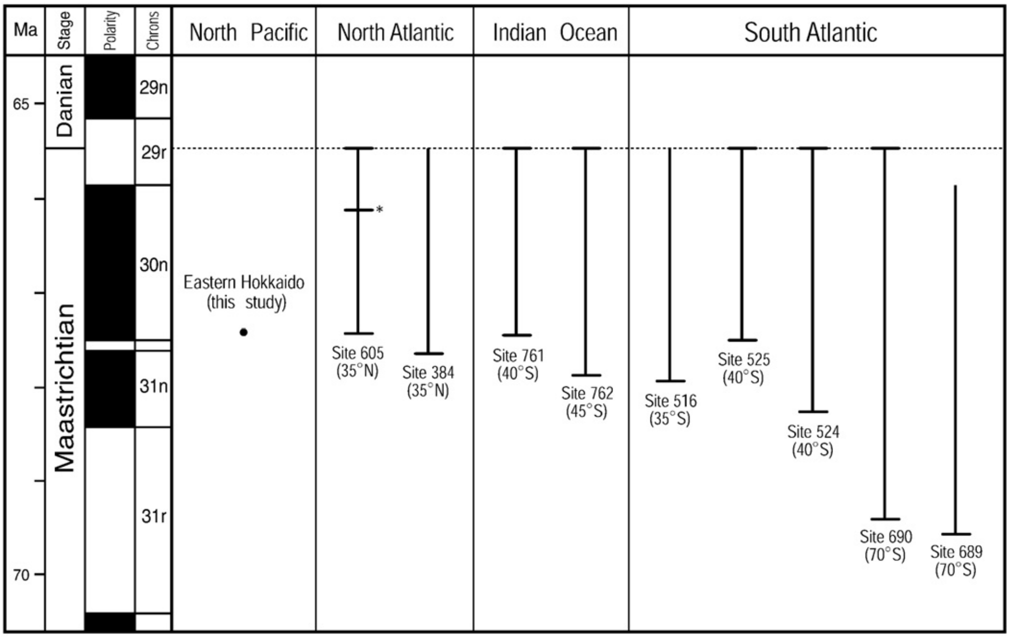

Fig. 8. Stratigraphic range of *Nephrolithus frequens* obtained from various successions where magnetostratigraphy has been established. The occurrence horizon of *N. frequens* in the Senpohshi Formation is also plotted. The GPTS is obtained from Ogg et al. (2004). The Paleolatitudes of the ODP/DSDP sites, obtained from the ODSN Plate Tectonic Reconstruction Service (http://www.odsn.de/odsn/services/paleomap/paleomap.html), are shown in this figure. *: alternative to the FO of *N. frequens* at site 605 (refer to text for further explanation). The last occurrences of *N. frequens* at sites 384, 516, and 689 are unclear; therefore, they are not represented by horizontal bars. The references are as follows. Site 605: Bruins et al. (1987); Lang and Wise (1987). Site 384: Larson and Opdyke (1979); Okada and Thierstein (1979). Sites 761 and 762: Bralower and Siesser (1992); Galbrun (1992). Site 516: Hamilton and Suzyumov (1983). Site 525: Sugarman et al. (1995). Site 524: Poore et al. (1983). Sites 689 and 690: Pospichal and Wise (1990).

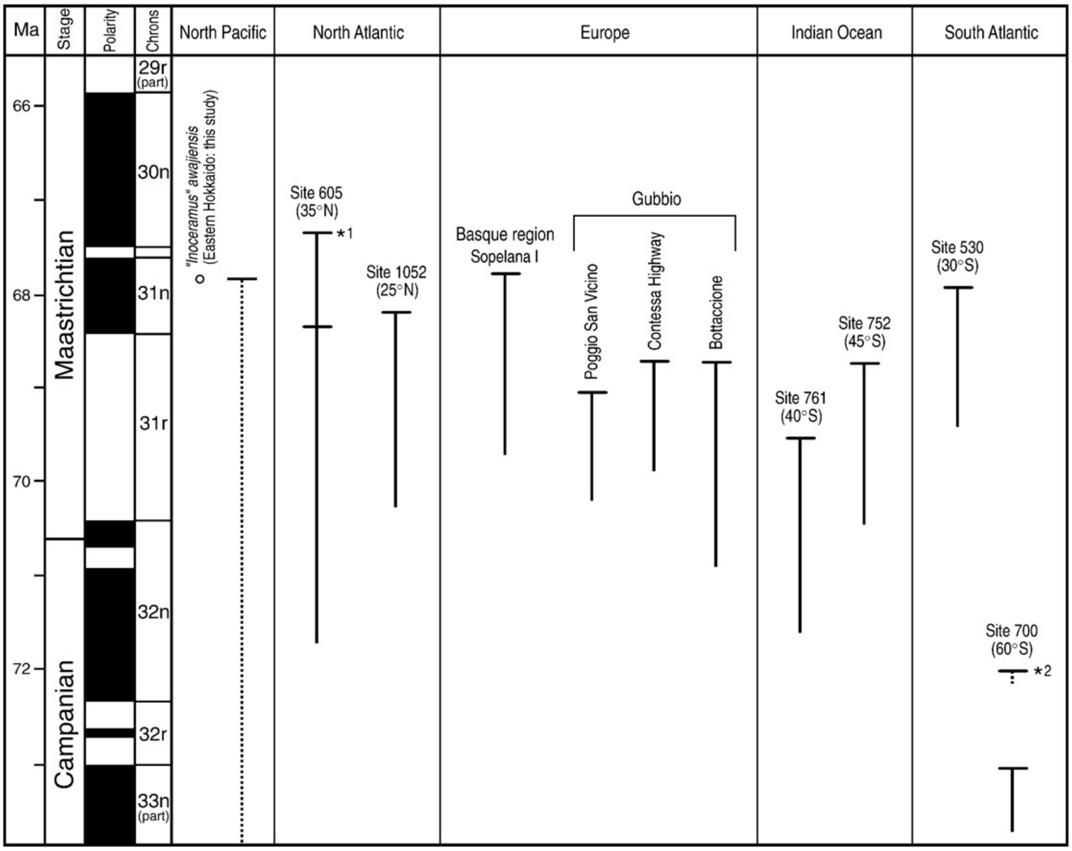

Fig. 9. Last occurrence of inoceramids (except genus *Tenuipteria*) obtained from various successions where magnetostratigraphy has been established. The occurrence horizon of "*Inoceramus*" *awajiensis* in the Senpohshi Formation is also plotted, and the possible stratigraphic range of inoceramids (except *Tenuipteria*) in the North Pacific region is represented with the dashed line. Inoceramid prisms were used for evidence at the following successions: Sopelana I, Contessa Highway, Bottacione, ODP/DSDP Sites 530, 605, 700, 752, 761, and 1052. The GPTS is obtained from Ogg et al. (2004). The paleolatitudes of the ODP/DSDP sites, obtained from the ODSN Plate Tectonic Reconstruction Service (http://www.odsn.de/odsn/services/paleomap/paleomap.html), are shown in this figure. *1: alternative to the last occurrence of inoceramids at site 605 (for further explanation, refer to discussion in Section 6.2, *Nephrolithus frequens*). *2: alternative to the last occurrence of inoceramids at site 700 (refer to MacLeod et al., 1996). The references are as follows. Site 605: Bruins et al. (1987), MacLeod et al. (1996). Site 1052: MacLeod and Huber (2001), Ogg and Bardot (2001). Basque region: MacLeod and Orr (1993). Gubbio: Chauris et al. (1998). Site 761: Galbrun (1992), MacLeod et al. (1996). Site 752: Gee et al. (1991), MacLeod et al. (1996). Site 530: Keating and Herrero-Bervera (1984), MacLeod et al. (1996). Site 700: Hailwood and Clement (1991), MacLeod et al. (1996).

region is approximately identical to that in other sections in the northern mid-latitudes of Europe and North Atlantic (Fig. 9). Therefore, the result of this study is currently conformable to the hypothesis of the northward progression of the inoceramid extinction (MacLeod et al., 1996).

Further examination in other basins appears to be necessary to reveal the process and cause of the inoceramid extinction event. In addition to latitude of the basins, other factors seem to concern the timing of the event; for example, MacLeod et al. (1996) have also reported that “Inoceramids also disappear earlier in onshore sites than they do in offshore sites.” The collection of data from many different basins will clarify the detailed process of the event and aid in distinguishing the global trend of this event from regional/local ones. To understand the detailed process of the event helps to reveal the cause of the event. Furthermore, the taxonomic study of “*I.*” *awajiensis* is also important for considering the problem in the North Pacific region. If “*I.*” *awajiensis* is truly classified to *Inoceramus* and not to *Tenuipteria*, we should accept the fact that the inoceramid extinction in the North Pacific region occurred considerably later than that in other areas. Therefore, further studies on the taxonomy of “*I.*” *awajiensis* are also necessary in order to reveal the complete picture of the inoceramid extinction event in this region.

7. Conclusions

From the magnetostratigraphic and biostratigraphic studies of the Maastrichtian Senpohshi Formation in eastern Hokkaido Island, northern Japan, we can conclude the following:

1) Four magnetozones were recognized from the Senpohshi Formation. They are correlatable to polarity chrons C31r to C30n, suggesting that the Senpohshi Formation spans from the middle to the upper part of the Maastrichtian (ca. 69–67 Ma).

2) The stratigraphic range of the ammonite *Pachydiscus flexuosus* spans from the lower part of C31r to the lower part of C31n, i.e., from the Lower Maastrichtian to the lower part of the Upper Maastrichtian.

3) The calcareous nannofossil *Nephrolithus frequens* occurring in polarity chron C30n suggests that the first occurrence of *N. frequens* in the North Pacific region is correlatable to polarity chron C30n or below.

4) The first occurrence of the bivalve “*Inoceramus*” *awajiensis* is correlatable to polarity chrons from C31r to the upper part of C31n. This suggests that the inoceramid extinction in the North Pacific region may have occurred in polarity chrons from C31r to the upper part of C31n (ca. 70.4–67.8 Ma).

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