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Magnetostratigraphy of Upper Cretaceous strata in South Sakhalin, Russian Far East

***Kazuto Kodama, †Haruyoshi Maeda, ‡Yasunari Shigeta, ‡Tomoki Kase and §Tohru Takeuchi**

**Marine Core Research Center, Kochi University, Kochi, Japan 780-8072*
†*Department of Geology and Mineralogy, Kyoto University, Kyoto, Japan 606-8224*
‡*Department of Geology and Palaeontology, National Science Museum, Tokyo, Japan 169-0073*
§*Department of Earth and Planetary Sciences, Nagoya University, Nagoya, Japan 464-0814*

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A stratigraphic sequence of magnetic polarity reversals consisting of 13 magnetozones is recognized in Upper Cretaceous sedimentary strata in the Naiba area of South Sakhalin, Russian Far East. Combined with local biostratigraphic age assignments using ammonites and other molluscs that apparently range from Coniacian to Maastrichtian, the geomagnetic polarity sequence can be correlated with polarity chrons from C34n, the Cretaceous long normal interval, through C30n in the upper Maastrichtian. The recognition of these polarity chrons and their correlation with regional faunal assemblages that commonly occur in Japan and other areas in the Far East provide an integrated reference that should be of value for linking local biostratigraphic zonations in the North Pacific and serve as another basis for calibration in the quest to establish a global definition of Upper Cretaceous stage boundaries.

KEY WORDS: Upper Cretaceous; magnetostratigraphy; ammonite biostratigraphy; Sakhalin; Russia; North Pacific.

1. Introduction

Cretaceous strata in South Sakhalin have been known to comprise slope and basin marine deposits that are correlatable in both lithology and macrofossil assemblages with the Cretaceous Yezo Group in central Hokkaido (Matsumoto, 1942, 1954). Unlike Cretaceous strata in Hokkaido, however, which generally occur as disrupted sequences at a single locality, those in South Sakhalin crop out continuously in the Naiba area (Figure 1), attaining over 4500 m in thickness and ranging in age from Aptian to Maastrichtian, and possibly Danian (Vereshchagin, 1970, 1977; Kalishevitch *et al.*, 1981; Salnikov & Tikhomolov, 1987). In spite of the stratigraphic continuity and an age-range spanning most of the Late Cretaceous, the provinciality of macrofossils, as also seen in the Yezo Group, has made precise global correlation difficult. This led us to conduct a field survey of the Naiba area in 1990, focusing on both magnetostratigraphy and biostratigraphy in conjunction with detailed field mapping. Additional work followed in 1996 in the form of supplementary palaeomagnetic sampling of the Krasnoyarka River section to cover sampling gaps remaining from the previous work, but later found to be critical to establishing a complete magnetostratigraphy. This paper provides the results of the successful magnetostratigraphic study.

2. Lithology and biostratigraphy

The Cretaceous strata in the Naiba area consist of the Ai, Naiba, Bykov, and Krasnoyarka Formations (Salnikov & Tikhomolov, 1987). Numerous ammonites and inoceramids occur throughout, except in the uppermost part of the Krasnoyarka Formation (Matsumoto, 1942; Pergament, 1974; Zakharov *et al.*, 1981, 1984; Zonova *et al.*, 1993; Yazykova, 1994; Alabushev & Wiedmann, 1997). Although cosmopolitan marker species are few, the lithological and faunal successions can be correlated with those in Hokkaido and other Far Eastern areas that have been dated within the range Coniacian–late Maastrichtian (Matsumoto, 1942, 1954). Our study has focused on the upper part of the Bykov Formation and the Krasnoyarka Formation, which are well exposed along the Naiba River and its two tributaries, the Krasnoyarka and Seim Rivers (Figure 1). We attempted to carry out a micropalaeontological study using

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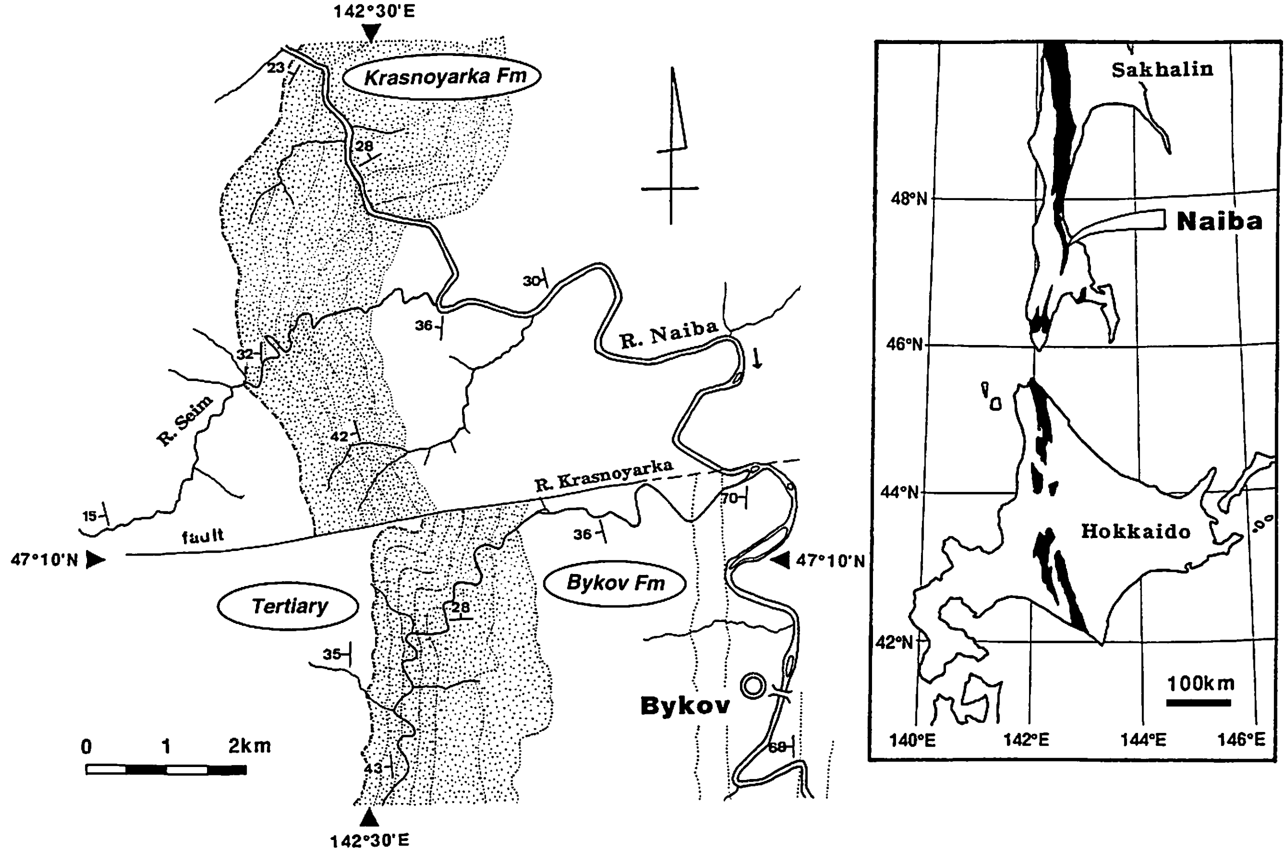
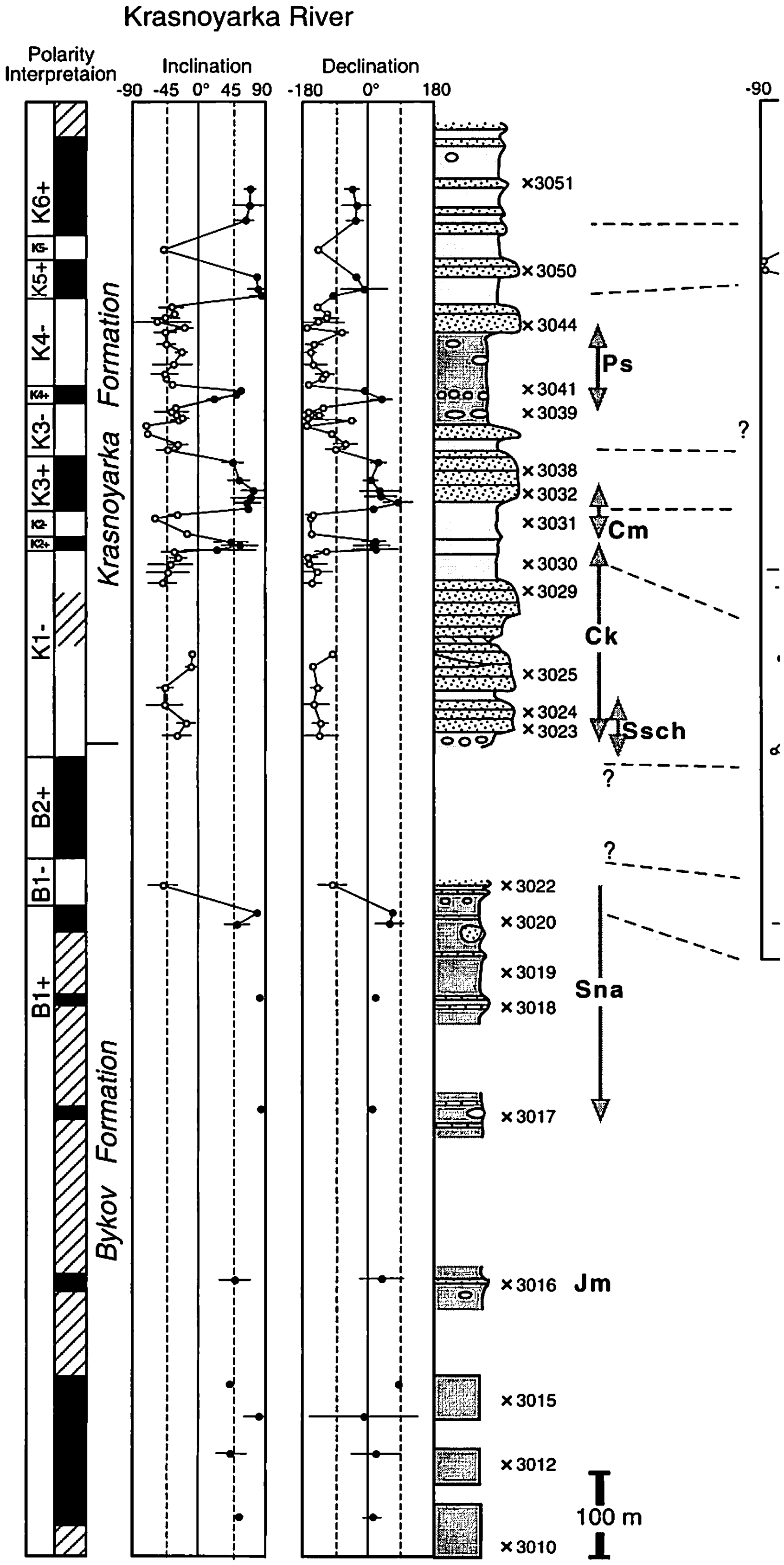


Figure 1. Right: map showing distribution of Cretaceous rocks (black areas) in South Sakhalin, Russia, and Hokkaido, northern Japan. Left: simplified geological map showing distribution of Upper Cretaceous strata (stippled) in the Naiba area of South Sakhalin.

foraminifera and nannoplankton, but unfortunately no productive samples were obtained, although a few late Cretaceous benthic foraminifera have been reported from the upper portion of the Krasnoyarka Formation (Turenko, 1987). A brief description of the lithology and molluscan biostratigraphy for the Krasnoyarka section is given below on the basis of the biostratigraphic schemes of Matsumoto (1942, 1954), Salnikov & Tikhomolov (1987), Zonova *et al.* (1993), Yazykova (1994), Yazykova & Zonova (1994) and Toshimitsu *et al.* (1995). Correlation with the other two sections is shown schematically in Figure 2.

The upper part of the Bykov Formation consists of monotonous, dark grey, intensely bioturbated, massive or mottled mudstone intercalated with thin turbiditic sandstone and acidic tuff layers. Calcareous concretions tens of centimetres in diameter, in which many ammonites and inoceramids are concentrated, are abundant in the mudstone. A rich Coniacian ammonoid assemblage including *Anagaudryceras limatum*, *Nipponites* sp. and *Scalarites mihoensis*, occurs at Localities 3012 and 3015 (Figure 2). *Jimboiceras mihoense*, which is indicative of the upper Coniacian in Hokkaido, occurs at Loc. 3016. These records indicate that the strata from Locs 3010–3016 can be correlated with the Coniacian. The first appearance datum (FAD) of *Gaudryceras tenuiliratum*, *Sphenoceramus naumanni*, and *Yokoyamaoceras ishikawai*, which are indicative of the Santonian (Maeda, 1993), occur at Locs 3017–3020.

The Krasnoyarka Formation comprises mainly dark, greenish grey, poorly-sorted, bedded sandstone and mottled sandy mudstone. A dark grey, massive mudstone member occurs in the middle part of the formation. Fossiliferous calcareous concretions are abundant except in the uppermost part. A basal sandy mudstone at Loc. 3023 yielded numerous *Eupachydiscus haradai*, which is abundant in the Campanian in Hokkaido. The overlying bedded sandstone at Locs 3023 and 3024 is rich in *Sphenoceramus schmidti*, a late Cretaceous inoceramid that is common in Hokkaido and California (Haggart, 1984). *Canadoceras kossmati* at Locs 3023–3030 suggests the early–mid Campanian, based on its range in the Far East. A late


Krasnoyarka River
Polarity Interpretaion
Inclination
-90 -45 0° 45 90
Declination
-180 0° 180
-90
K6+
K5-
K5+
K4-
K4+
K3-
K3+
K3-
K2+
K1-
B2+
B1-
B1+
Krasnoyarka Formation
Bykov Formation
×3051
×3050
×3044
×3041
×3039
×3038
×3032
×3031
×3030
×3029
×3025
×3024
×3023
×3022
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×3019
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Ps
Cm
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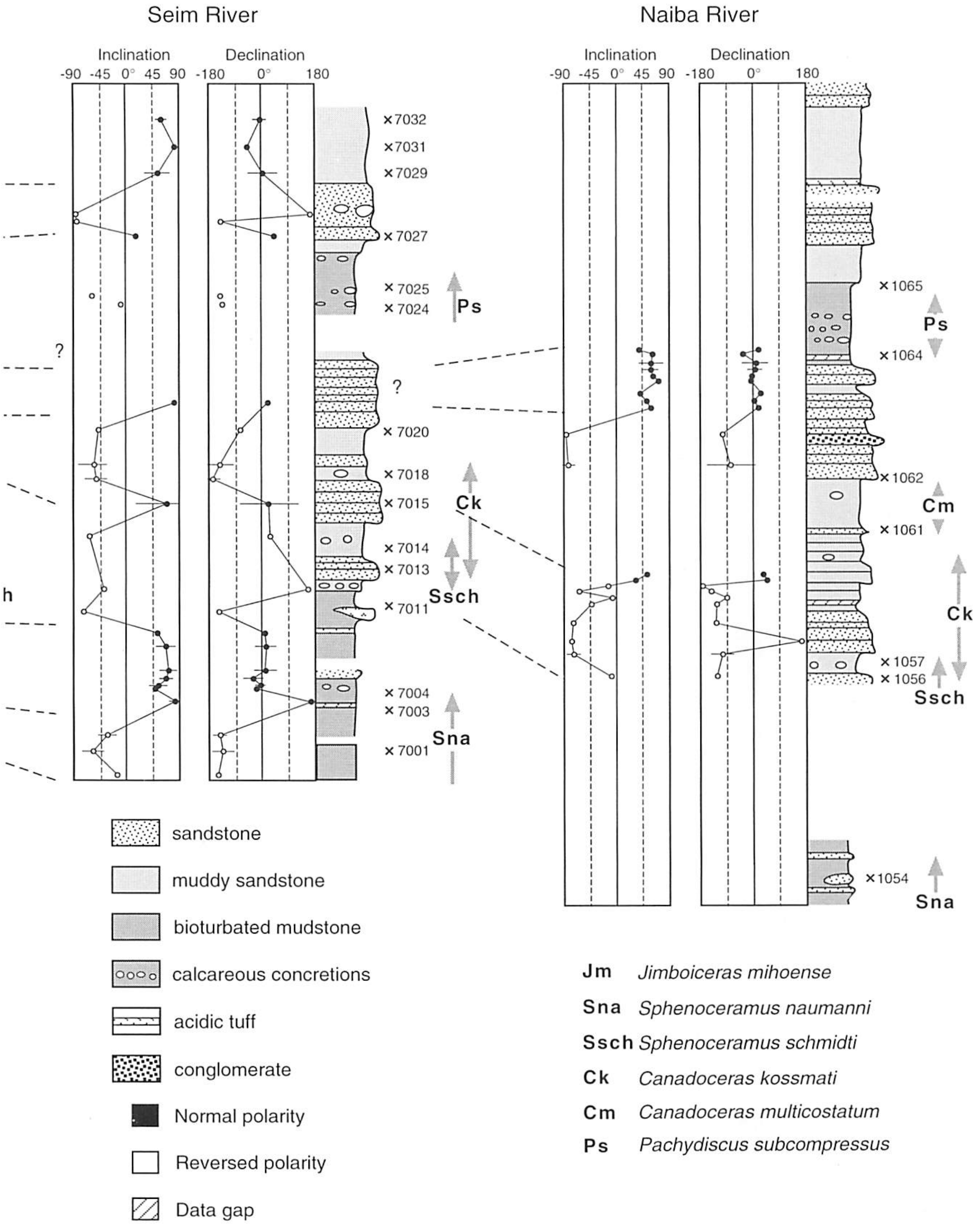

Figure 2. Lithology, magnetostratigraphy and ranges of selected zone fossils of the Krasnoyarka River, Seim River, and Naiba River sections. The boundaries between the magnetozones are placed at a midpoint between adjacent horizons of opposite magnetic polarity. Solid (open) circles show inclinations and declinations of normal (reversed) polarity, along with 95% confidence error bars if they can be computed from more than three individual sample directions. Broken lines indicate possible correlation of the magnetozone boundaries between sections.

Campanian age is indicated for strata including Locs 3031 and 3032 on the basis of the occurrence of *Canadoceras multicostatum*, '*Pachydiscus*' *soyaensis*, and associated ammonoid assemblages (Matsumoto, 1984). A Maastrichtian ammonoid assemblage, characterized by *Anagaudryceras matsumotoi*, *Pachydiscus subcompressus*, and *Zelandites varuna*, is dominant in the mudstone member at Locs 3039–3041. The last appearance datum of ammonoids lies at Loc. 3044 in the uppermost part of the mudstone member.

3. Palaeomagnetic analysis

Samples were drilled and oriented in field, and at least three cores were taken at each horizon (site) separated by a few metres to tens of metres in stratigraphic thickness, depending upon availability of suitable exposures. Where possible, denser sampling with a spacing of tens of centimetres was attempted, in which case a set of closely sampled layers was regarded as a single site. One thousand and sixty-two samples were collected from the three sections, including 664 from the Krasnoyarka, 237 from the Seim and 161 from the Naiba River sections.

All the measurements were carried out using a cryogenic magnetometer, combined with stepwise thermal or alternating-field (AF) demagnetization, in a magnetically shielded room with an ambient field intensity smaller than 200 nT. Thermal demagnetization was made in air with a laboratory-made electric furnace with an internal field less than 5 nT. Progressive thermal demagnetization was carried out, in steps of 40°C from 120°C, until the magnetization intensity fell below noise level or the direction became erratic, or the low-field bulk magnetic susceptibility, which was measured each time after a cooling run, increased by more than one order of magnitude, indicating alteration of magnetic minerals. AF demagnetization was made in 5 mT steps from 5 to 40 mT and in 10 mT steps from 50 mT. Initially, a pair of samples was taken from each site, one being subjected to thermal and the other to AF demagnetization, to determine proper demagnetization of the rest. According to this pilot study, which showed more erratic behaviours of AF demagnetization, most of the remaining specimens were subjected to moderate thermal demagnetization below 500°C. Characteristic magnetization components were isolated by applying the method of Kirschvink (1980) to vector segments composed of at least four points with a maximum angular deviation smaller than 15°.

Examples of typical demagnetization behaviours are shown in Figure 3. Magnetic polarity identification was possible at 112 of 184 horizons in total, comprising 65 from the Krasnoyarka, 26 from the Seim and 21 from the Naiba River sections. Figure 2 shows their stratigraphic levels, inclination and declination in stratigraphic coordinates, as well as ranges of selected zone fossils that commonly occur in the three sections. A composite magnetostratigraphy and macrofossil biostratigraphy is illustrated in Figure 4.

4. Magnetostratigraphy

The stratigraphically lowest zones of reversed polarity are recognizable at Loc. 3022 of the Krasnoyarka River section and around Loc. 7001 of the Seim section. We interpret these intervals as one magnetozone (B1 −), which is most likely to be correlated with polarity chron C33r in the early Campanian, because no interval of reversed polarity is recognizable in underlying horizons, in which late Coniacian–Santonian index fossils, such as *Jimboiceras mihoense* and *Sphenoceramus naumanni*, occur. Therefore, in spite of a large data gap, we regard the underlying zones of normal polarity as a single, thick magnetozone (B1+) corresponding to polarity chron C34n, the Cretaceous long normal interval. There is no exposure from just above Loc. 3022 to *c.* 10 m below Loc. 3023 in the Krasnoyarka section, but the corresponding strata lie in the lower portion of the Seim section, in which seven horizons were sampled between Locs 7003 and 7011. All of these horizons are of normal polarity, which we consider to be within one normal polarity magnetozone (B2+) and correlatable with polarity chron C33n in the late Campanian.

There is a distinctive change in lithology from mudstone- to sandstone-rich facies, marking the boundary between the Bykov and the Krasnoyarka Formations (Salnikov & Tikhomolov, 1987), at Loc. 3023 in the Krasnoyarka section as well as between Locs 7011 and 7013 in the Seim section. The basal part of the Krasnoyarka Formation is characterized by the FAD of *Sphenoceramus schmidti*. Intervals of reversed polarity containing the *S. schmidti* Zone at the base are recognized in all three sections, and we interpret this interval as one reversed polarity magnetozone (K1 −). This zone is overlain by a short interval of normal polarity (K2+) just above Loc. 3030 in the Krasnoyarka section. This short interval can be correlated with two horizons of normal polarity; one at Loc. 7015 in the Seim section and the other below Loc. 1061 in the Naiba section. The short magnetozone K2+ is overlain by another reversed polarity zone (K2 −), which comprises three horizons containing Loc. 3031 in the Krasnoyarka section and may correspond to horizons around Loc. 7018 in the Seim section. We interpret the two reversed (K1 −,

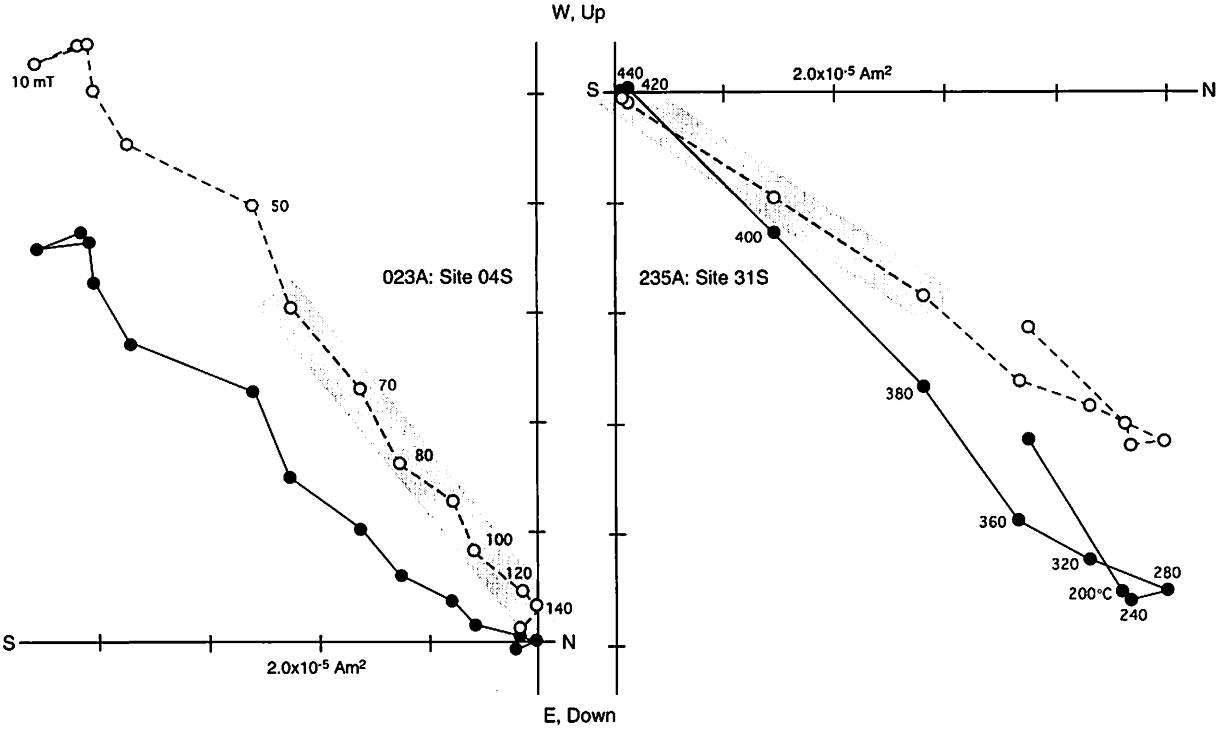

Figure 3. Examples of orthogonal vector diagrams of progressive alternating-field (left) and thermal (right) demagnetizations. Solid and open circles are projections on horizontal and east-west vertical planes, respectively, in coordinates after correction for bedding tilt. Shaded areas indicate vector endpoints used for least-squares computation; reversed polarity (left) with characteristic direction: D (declination), 215°; I (inclination), −48°; MAD (maximum angular deviation of Kirschvink, 1980), 5.6°; normal polarity (right) with D, 45°; I, 25°; MAD, 1.2°.

K2 −) and one normal (K2+) zones, as one composite magnetozone correlatable with polarity chron C32r, which means that the K2+ zone is correlated with a normal-polarity subchron within polarity chron C32r, denoted as C32r.1n in chron terminology. Likewise, we recognize one normal magnetozone (K3+) from Locs 3032–3038, one reversed zone (K3 −) around Loc. 3039, and one normal zone (K4+) containing Loc. 3041, each of which we temporarily correlate with three subchrons in C32n. There is a remarkable difference between the relative thickness of the magnetozones and the corresponding pattern of polarity time scale from polarity chron C33n to C32r. We assume that this inconsistency is derived from the marked lithological change starting at the base of the Krasnoyarka Formation. The repeated layers of basal sandstone indicate that the K1- magnetozone probably spans a relatively brief time interval.

The age of the Campanian/Maastrichtian boundary is controversial; Cande & Kent (1992) placed the boundary near the top of polarity chron C33n (74.5 Ma), whereas Gradstein *et al.* (1995) assigned it to the bottom of polarity chron C32n.1n (71.3 Ma), a normal polarity subchron in C32n. We adopt the latter definition, which is based principally upon macrofossil stratigraphy, whereby the Campanian/Maastrichtian boundary can be placed at the bottom of the K4+ magnetozone, immediately above Loc. 3039 in the Krasnoyarka section. Successive polarity chron interpretation above the boundary is possible only for the Krasnoyarka section. There is a reversed polarity magnetozone approximately 100 m thick from Locs 3041 to above 3044 that is correlatable with polarity chron C31r. This is overlain by a pair of normal and reversed polarity zones (K5+, K5 −), each being assignable to polarity chrons C31n and C31r. Finally, we regard the three top horizons as a single normal polarity magnetozone (K6+) correlatable with polarity chron C30n, which apparently corresponds to the top horizons of normal polarity at Locs 7029–7032 in the Seim section. We assume, therefore, that the K/T boundary, which is known to be placed within polarity chron C29r, is unlikely to occur in the sections studied.

Figure 5 shows magnetization directions before and after bedding tilt corrections for all of the 112 horizons, including 52 of normal and 60 of reversed polarity. The corrected directions cluster slightly better than the *in situ* directions. The change in grouping,

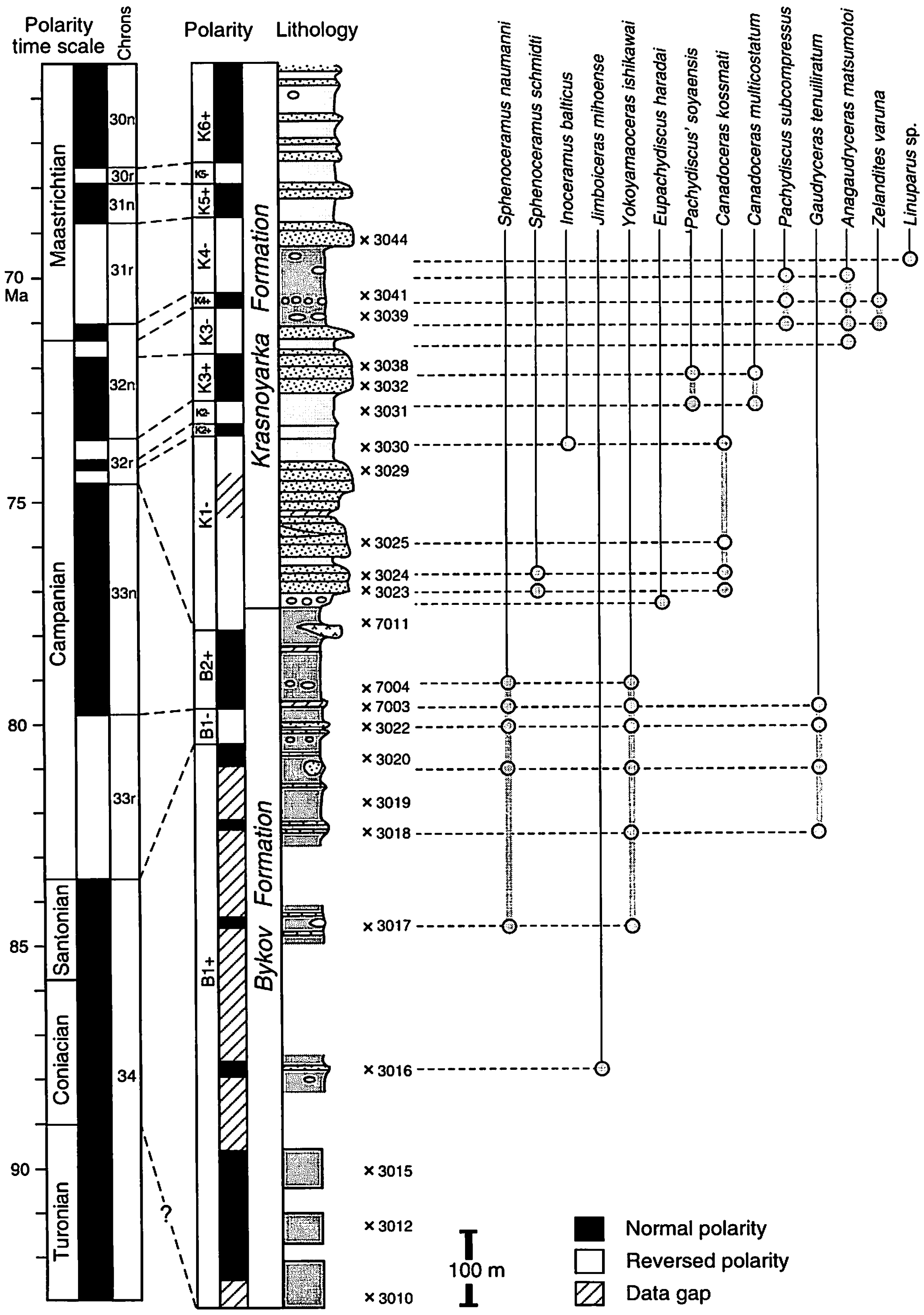

Figure 4. Composite sequence based on the Krasnoyarka River, Seim River, and Naiba River sections, showing lithology, magnetostratigraphy, and occurrence ranges of 14 representative macrofossils. Broken lines indicate correlation of the magnetozones to polarity chrons for the Upper Cretaceous. Polarity time scale after Gradstein *et al.* (1995).

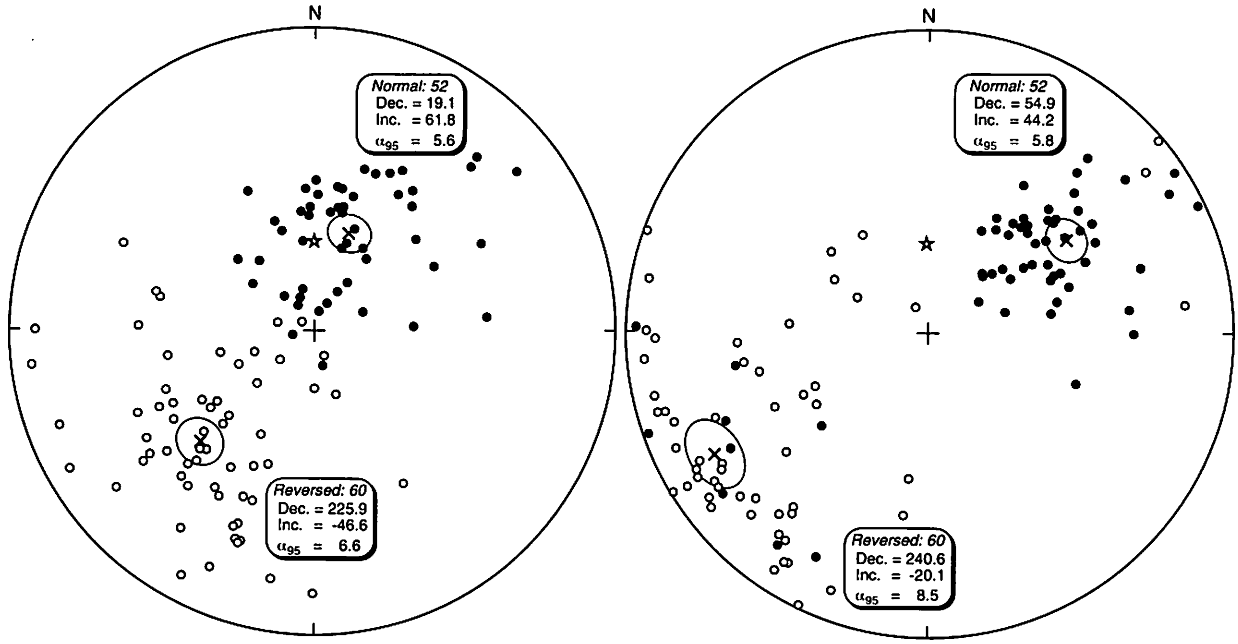

Figure 5. Equal-area projections of magnetization directions of 52 horizons of normal and 60 of reversed, after (left) and before (right) correction for bedding tilt. Solid circles are plotted on the lower hemisphere and open circles on the upper hemisphere. Overall mean directions and their 95% error limits are given in boxes, and plotted by crosses and ovals. The star shows the present dipole field direction.

although not large enough to be statistically significant, is a positive result, suggesting that the magnetizations were acquired prior to folding. The mean directions of the normal and reversed polarity groups are not exactly antipodal, which may indicate some bias towards the present normal field that was not completely removed by demagnetization. The eastward deviation in declinations, which becomes less significant upon tilt corrections, is consistent with those reported from Tertiary deposits in South Sakhalin (Takeuchi *et al.*, 1999) and Hokkaido (Kodama *et al.*, 1993). This consistency implies regional rather than local tectonic rotation for the South Sakhalin–Hokkaido area, which seems to have taken place in the Neogene (Kodama *et al.*, 1993).

5. Discussion

There has been controversy concerning the global definition of the Late Cretaceous stage boundaries, which leads to significant discrepancies in their numerical age and stratigraphic position (e.g., Gale *et al.*, 1995). Therefore, we should note that correlation of Cretaceous stage boundaries to polarity chrons is rather vaguely defined even in the latest geomagnetic polarity time scale (e.g., Gradstein *et al.*, 1995). A few attempts at more precise correlation have been carried out; for instance, Gale *et al.* (1995) have shown that the base of polarity chron C33r, generally considered to coincide with the base of the Campanian, lies within the Upper Santonian. The current lack of a global standard for calibration of geological stage boundaries may mean that the polarity chron interpretation of this study is rather ambiguous or premature. However, we believe that in current circumstances temporary magnetostratigraphy based on the working definitions serves as a versatile basis for linking local biostratigraphic zonations from diverse provinces in the North Pacific. We therefore discuss below factors that could be important for integrating the regional palaeontological assemblages, none of which includes a characteristic ammonite fauna, unlike Europe.

According to our polarity chron interpretation (Figure 4), *S. schmidti* occurs at the bottom of polarity chron C32r. This assignment, however, disagrees with results from the Great Valley Sequence in northern California (Verosub *et al.*, 1989), where the *S. schmidti* Zone has been placed near the top of polarity chron C34n, in the Upper Santonian. This interpretation comes from the presence of only one interval of reversed polarity above the *S. schmidti* Zone in the Great Valley Sequence, which was regarded as representing polarity chron C33r. Given that the zone is time-transgressive to some degree, the age gap between polarity chron C32r.2r and the top of C34n is so substantial that we think there might be an unrecognized reversed interval below the *S. schmidti* Zone in California that can be correlated with polarity chron C33r. In fact, Verosub *et al.* (1989) noted the presence of a short interval of reversed polarity below the *S. schmidti* Zone in some of the sections studied. Although they paid little attention to the interval, only mentioning the possibility of a geomagnetic excursion, we consider it may actually represent polarity chron C33r, and that the normal interval containing the *S. schmidti* Zone at the top may correspond to polarity chron C33n. If this is the case, then the *S. schmidti* Zone in the entire North Pacific province could range from late C33n to C32r.2r, in the middle–upper Campanian. This interpretation appears to be consistent with a proposal by Matsumoto (1976), who placed the *S. schmidti* Zone of the western Pacific in the middle Campanian.

A more cosmopolitan species found in Sakhalin is *Zelandites varuna* (Figure 4), an ammonite that occurs in the upper Maastrichtian of areas remote from Sakhalin such as India, Chile, and Antarctica (Ward, 1990; Kennedy & Henderson, 1992). In Chile, for instance, the *Z. varuna* Zone ranges from the top of polarity chron C30r, or C31r, to the bottom of polarity chron C29r (Ward, 1990). This chron assignment disagrees with our interpretation that places the zone at the top of polarity chron C32n. The discrepancy may be resolved by another chron interpretation, namely that both K3– and K4– magnetozones correspond to a single reversed-polarity chron of C31r, the underlying K3+ magnetozone representing normal-polarity chron C32n. This would imply that the K4+ magnetozone equates with an unknown subchron within polarity chron C31r. The horizons corresponding to polarity chron C32r may be condensed or eroded out to some degree, or an unrecognized hiatus could be present. This interpretation may be more likely because the *Canadoceras multicostatum* Zone just below the *Z. varuna* Zone in the Naiba area is more than 50% thinner than that in the Kril'on Peninsula about 120 km south of the Naiba area (Shigeta *et al.*, 1999).

Endemism of many of the Cretaceous molluscan fossils in Sakhalin and Hokkaido has long made it difficult to correlate the local zonations directly with the Cretaceous stages established for other remote sections in the Pacific. However, the magnetostratigraphy of Upper Cretaceous strata in South Sakhalin now makes possible a preliminary correlation, as demonstrated in Figure 4. More importantly, provided that more detailed magnetostratigraphic work is carried out in the eastern Pacific, combined palaeomagnetic and fossil stratigraphy should be of value for comparative studies of Cretaceous successions and the development of the endemic fauna in the North Pacific, and could eventually contribute to the establishment of a global definition of Cretaceous stage boundaries.

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