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Polarity reversals of remanent magnetization in a sedimentary core from Northwind Ridge, western Arctic Ocean

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Abstract: We studied the remanent magnetization of a sedimentary core PC2 (6.48 m length) drilled during the MR99-K05 cruise of JAMSTEC in the western Arctic Ocean. Discrete specimens and u-channel samples were used in the study. In the discrete specimens, the change of remanent magnetization with depth show many clear polarity reversals in both inclination and declination. Furthermore, most reversals in discrete specimens correlated well with those in the u-channel samples.

Core PC2 is characterized by distinct alternations of dark gray and brownish layers. Through comparison of lithostratigraphic cycles with glacial-interglacial cycles (referring to R.L. Phillips and A. Grantz, Geol. Soc. Am. Bull., 109, 1101, 1997), sedimentary cycles of core PC2 are correlated to marine isotope stages up to MIS-8. This indicates that polarity reversals of remanent magnetization in core PC2 are geomagnetic excursions in the Brunhes epoch. Comparison with the previously known geomagnetic excursions shows that the polarity reversals are clear and have long duration in core PC2. This feature may be related to characteristic geomagnetism around the western Arctic Ocean.

key words: magnetization of sedimentary core, polarity reversals, western Arctic Ocean, glacial-interglacial cycles

1. Introduction

During cruise MR99-K05 of the vessel Mirai of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), a piston core, PC2, 6.48 m in length was recovered from the Northwind Ridge of the Chukchi Sea, in the western Arctic Ocean (74°25′N, 160°02′W, water depth 530 m, Fig. 1).

The Arctic Ocean is a key component of the Earth's climate system; however, the

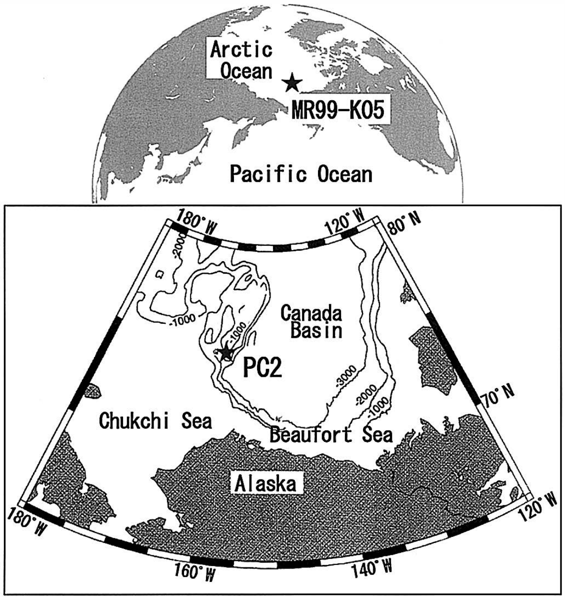

Fig. 1. Sampling location of core PC2 at Northwind Ridge in the Chukchi Sea during cruise MR99-K05 of JAMSTEC.

paleoceanographic studies of the Arctic are still inadequate and the results are controversial (Itaki *et al.*, 2003). Core PC2 is expected to elucidate the paleoceanographic and paleoclimate record of the past few hundred thousand years around the western Arctic Ocean (Itaki, in prep).

Remanent magnetization of a marine/lake sediment is preserved over a long period as a "fossil" of the geomagnetic field, so that the sedimentary sequence is useful to study the history of polarity change and/or the secular variation of the geomagnetic field. The paleomagnetism of sediments at high latitude, especially in the Antarctic (Sakai *et al.*, 1998) and the Arctic Ocean is important for the understanding of geomagnetism. In the Arctic Ocean, paleomagnetic studies of sedimentary cores have been limited, and most of them (Clark, 1970; Lovlie *et al.*, 1986; Witte and Kent, 1988; Schneider *et al.*, 1996; etc.) have been done in the eastern Arctic Ocean. Core PC2 drilled in the Chukchi Sea may be valuable to study the poorly known paleomagnetism of the western Arctic Ocean.

In this paper, the paleomagnetic study of core PC2 examines geomagnetic excursions during the Brunhes epoch. Geomagnetic excursions during the Brunhes epoch have been reported mostly from low and middle latitudes. Recently, Lund *et al.* (2001) showed 14 excursions in the Brunhes epoch from ODP Leg172 cores in the western North Atlantic Ocean. Based on investigation of these excursions and former studies, they suggested that an "excursional state" of the Earth's magnetic field may have both a strongly multipolar spatial pattern of variability and a complicated temporal pattern of variability. Also, they emphasize the necessity of other global records to understand the exact space-time pattern of geomagnetic field behavior during excursional states and the relationships among individual excursions worldwide. It is important to find areas (especially at high latitude) where reliable plural geomagnetic excursions can be reconstructed, and to investigate them from a sedimentary core in detail.

We studied the remanent magnetization of the sedimentary sequence in core PC2. On discrete specimens and u-channel samples, the polarity change of the remanent magnetization is investigated.

2. Sample description and experiments

The PC2 piston core 6.48 m in length is characterized by distinct alternations of dark gray and brownish layers (Fig. 2). The dark layer is composed of laminated silty clay, the brownish layer of bioturbated gravel-bearing sandy mud.

The core was cut into sub-cores 0.7 to 1.0 m in length. In the magnetic study, we used discrete specimens collected in 7 cc cubic plastic cases at intervals of 2 cm, and u-channel samples. Figure 3 illustrates the sampling. A total of 326 discrete specimens and seven u-channel samples were utilized in the study.

The remanent magnetization was measured by a 2G-760R cryogenic magnetometer of Toyama University. The u-channel sample was measured at 2 cm intervals. The

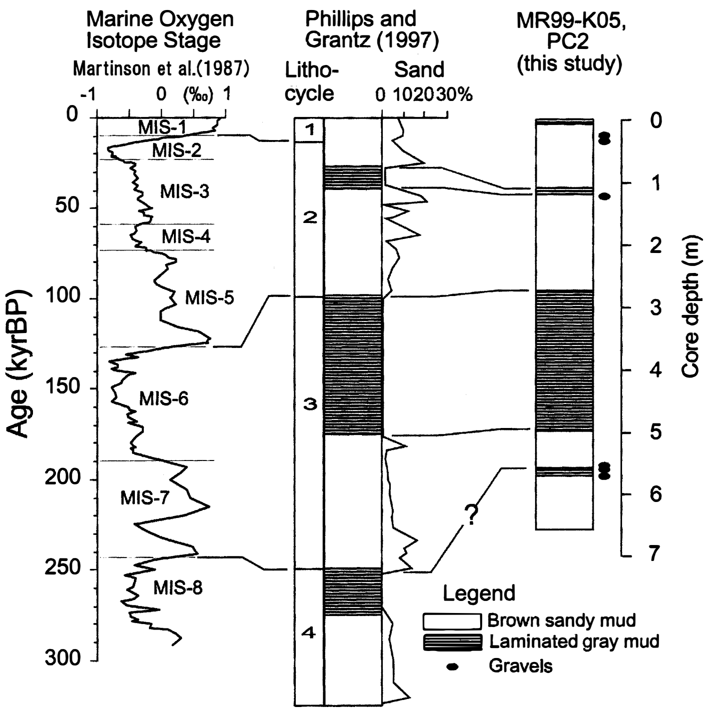

Fig. 2. Lithology of core PC2 and its correlation to the standard litho-cycle of Northwind Ridge proposed by Phillips and Grantz (1997).

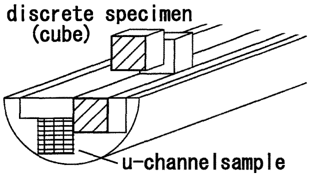

Fig. 3. Sampling.

magnetometer has an automatic alternating field (af) demagnetization system which is used for af demagnetization experiments of discrete specimens and u-channel samples.

Magnetic susceptibility was studied by a KLY-3S susceptibility measurement system. By this system, the anisotropy of magnetic susceptibility (AMS) of discrete specimens and also the thermal dependence of susceptibility was measured. A heating experiment was done in an Ar atmosphere. The results are shown in Section 4.

3. Results of the experiment on remanent magnetization

3.1. Alternating field (af) demagnetization

The intensity of remanent magnetization in most of the discrete specimens ranged from 10^{-5} to 10^{-7} Am^2/kg. First, an af demagnetization experiment was conducted on pilot discrete specimens selected at 50 cm intervals from the core. Demagnetization was done stepwise up to 80–85 mT increment of 5 mT steps.

Examples of af demagnetization are shown in Fig. 4, by Schmidt's equal area projection net and Zijderveld (1967) diagrams. We can identify, in each Zijderveld diagram, the straight line crossing the plots to the origin suggesting stable remanent magnetization.

As secondary magnetization in most pilot specimens can be eliminated by a demagnetization field less than 20 mT, the residual specimens are demagnetized in 6 steps up to 40 mT. By examining the demagnetization results through fitting analysis, the characteristic direction of magnetization was selected. When a reliable magnetization vector was not obtained, we did not use the data in further discussion.

Af demagnetization on u-channel samples was conducted stepwise up to 50 mT at the 6 af level. In Fig. 4, examples of results are shown. Similar to discrete specimens, in most of the measured points, the secondary magnetization was eliminated by demagnetization treatment.

3.2. Variation of the remanent magnetization vector of core PC2 with depth

In Fig. 5, variations of declination, inclination and intensity of remanent magnetization with depth in discrete specimens are shown. The direction of the magnetization is the characteristic direction obtained from the fitting analysis of the stepwise demagnetization data of each specimen. The intensity of the magnetization is that of the natural remanent magnetization (NRM). Several clear and well correlated polarity changes are identified in both inclination and declination. Stable inclination in the core is almost concordant with the inclination calculated from the axial centric geomagnetic dipole.

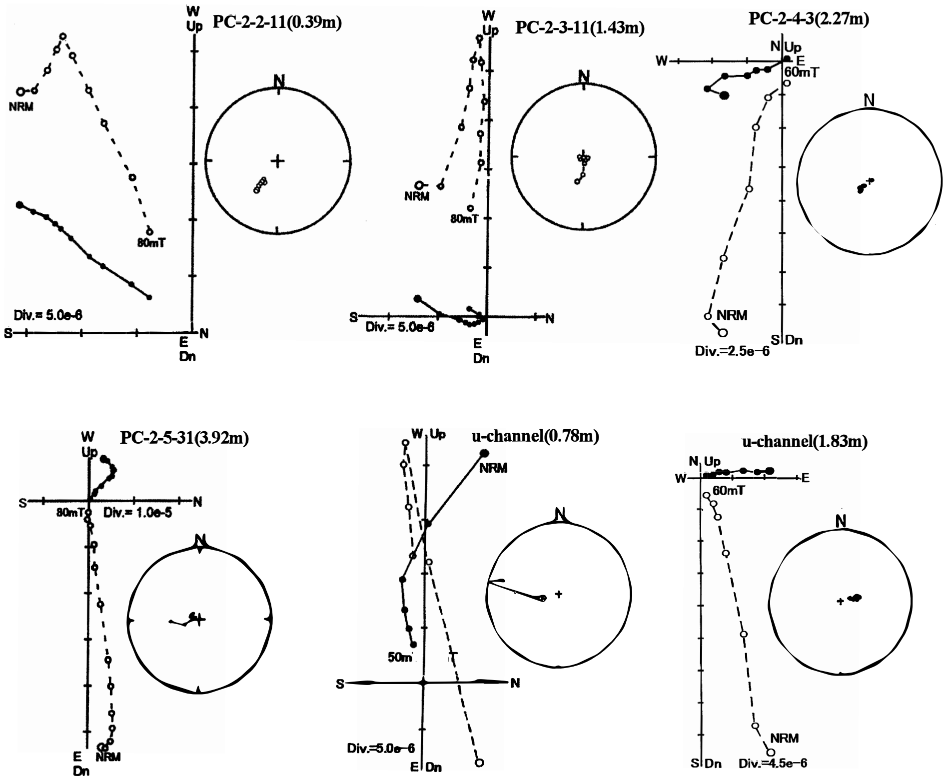

Fig. 4. Af demagnetization results are represented in Schmidt's net and Zijderveld (1967) diagram. Examples of discrete specimens, PC2-2-11, PC2-3-11, PC2-4-3, PC2-5-31 and examples at two measured points in the u-channel sample are shown.

The changes of inclination in u-channel samples (after 20 mT demagnetization) with depth were compared with those of discrete specimens (Fig. 6). On the whole, we can identify concordant polarity changes among these data. In the polarity columns, black (normal polarity) and white (reversed polarity) indicate our interpretation of the assigned polarities from the discrete specimens. Reversed polarity is inferred when the following criteria are satisfied.

(1) The characteristic direction (both inclination and declination) of relevant specimens is antipodal to the direction of the specimens around them.

(2) The reversed magnetization occurs in than two adjacent specimens.

At several depths of the core, the magnetization direction of discrete specimens is different from the magnetization of the u-channel sample. We consider the following reasons for this difference.

(3) The u-channel measurement is conducted on successive cores, so that each point datum of the core consists of integrated magnetization of sediment over a rather broad area (over *ca*. 10 cm).

(4) U-channel samples, in some cases, might include disturbed or cracked areas in the

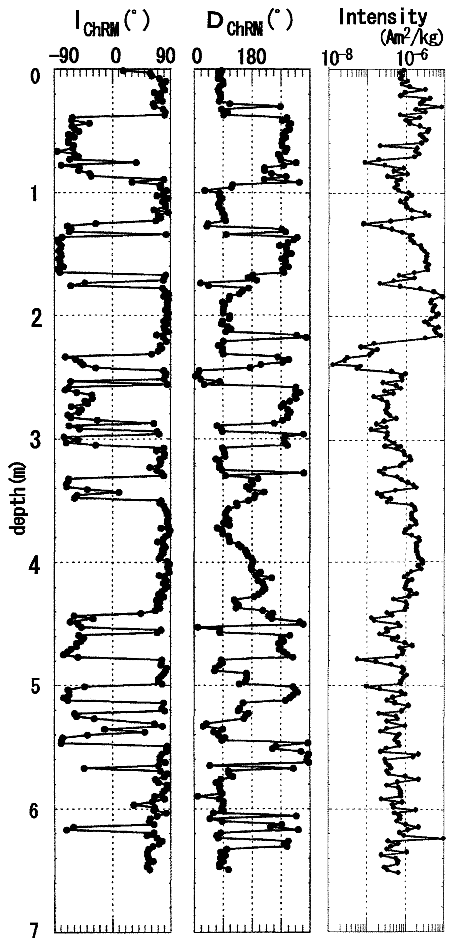

Fig. 5. Variations of declination, inclination and intensity of remanent magnetization with depth in discrete specimens.

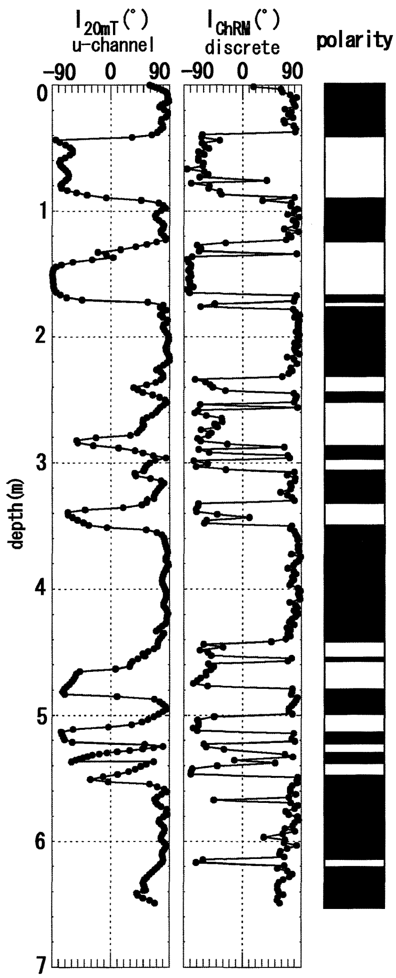

Fig. 6. Variation of inclination in u-channel samples (after 20 mT demagnetization) and inclination of characteristic magnetization of discrete specimens with depth. At right, assigned polarity reversals are shown by the white column (reversed polarity) and black column (normal polarity).

inner region.

(5) Generally, the demagnetization property (coercive force distribution) is not uniform in the core, so that the demagnetized data set for the u-channel in a certain af field may be different from the characteristic direction (it is not easy to obtain the characteristic magnetization at each data point in the u-channel by the fitting analysis of stepwise demagnetization data).

In this study, we use data from discrete specimens mainly for the discussion of magnetic polarity. U-channel data were used to examine the mis-orientation of discrete specimens, and broken or twisted areas in the core.

4. Rock magnetic experiments

The areas of reversed polarity magnetization are clear and have long range in the core. Before discussing the polarities of magnetization in relation to geomagnetism, we conducted the several rockmagnetic experiments.

4.1. Acquisition of thermal remanent magnetization

The reversed polarity specimens were submitted to an artificial thermal remanent magnetization (TRM) acquisition experiment. The purpose is to examine the possibility that the reversed polarity in core PC2 is caused by some mechanism such as self-reversal of the magnetic mineral.

Specimens in cube cases after 100 mT af demagnetization were prepared for the experiment. The block sediments were carefully removed from the cube cases, then coated and firmed with a non-magnetic ceramic bond. In the TRM acquisition experiment, these specimens were set in a silica glass tube and heated by an electric furnace. The experiment was done in an Ar atmosphere in a magnetic shielded space. During the cooling process, an artificial magnetic field of 50 μT was imposed, and the acquired partial TRM (pTRM) was measured. The above process was conducted in several temperature ranges up to 600°C.

Figure 7 shows the intensity distribution of pTRM. All of the pTRMs point to the imposed artificial magnetic field. Generally, the self-reversal occurs at the blocking temperature of 200–300°C (Uyeda, 1958). Around this temperature range, we could not identify either a directional change or an abrupt intensity change of magnetization. Similar results were obtained from the eight specimens with reversed polarity magnetization. Figure 7 shows that the pTRM was mostly acquired at 500–600°C, which suggests the possibility of secondary formed magnetite during heating experiment. However, pTRM acquired below 400°C is weak, so we consider that secondary magnetite if formed during heating may have not seriously contributed to the pTRM around

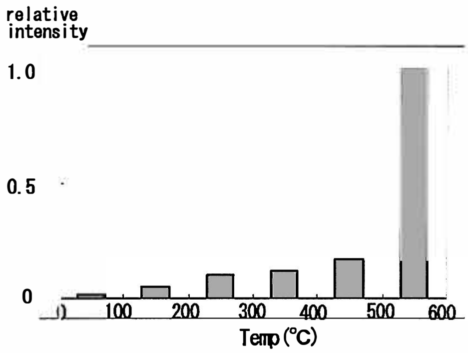

Fig. 7. Intensity distribution of acquired pTRM in several temperature ranges. Specimen PC2-2-14 (0.46 m depth) with reversed polarity after 100 mT af demagnetization was used in the experiment.

200–300°C. That is, if the specimens include hemoilmenite, its acquired reversed magnetization around 200–300°C may be larger than the pTRM of secondary formed magnetite. As the abnormal change (direction, intensity) of magnetization was not identified, we consider that a self-reversing magnetic mineral such as hemoilmenite is probably not included in the PC2 core sediment.

4.2. Anisotropy of magnetic susceptibility

The anisotropy of magnetic susceptibility (AMS) was studied on the discrete specimens. The shape anisotropy represented by the Flinn diagram (Flinn, 1962) in Fig. 8 indicates the dominant of foliation anisotropy. The AMS directions in Schmidt's projection net (Fig. 9) show that the minimum axes concentrate in the vertical direction and the other axes are scattered in the horizontal plane. Such AMS properties indicate that the sedimentation progressed in a quiet condition at the PC2 site, and that the sediment layer was not inclined much.

4.3. Other rock magnetic properties

We studied, the magnetic susceptibility (χ), the anhysteretic remanent magnetization (ARM), the saturation isothermal remanent magnetization (SIRM), the S-ratio, the ratio of ARM susceptibility and susceptibility (χ_a/χ), the median destructive af field of ARM (ARM-MDF) and the thermal dependence of susceptibility.

ARM was acquired in an alternating magnetic field of 0.1 T and a direct field of 0.05 mT and, in the af demagnetization experiment, ARM-MDF was studied. SIRM was imparted at a direct magnetic field of 1.0 T. These magnetic parameters should reflect the concentration, grain size and mineralogy of the magnetic minerals in the sediments (Robinson, 1986; Bloemendal *et al.*, 1988). Also, IRM-0.1T was imparted at 0.1 T in the opposite direction to SIRM, and the S-ratio (-IRM-0.1T/SIRM) was used

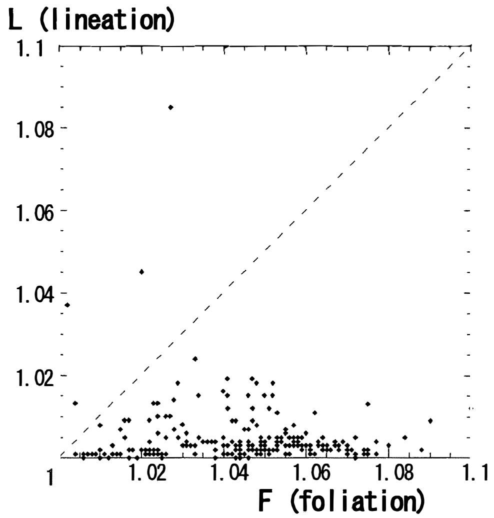

Fig. 8. The shape anisotropy of AMS is shown in the Flinn diagram.

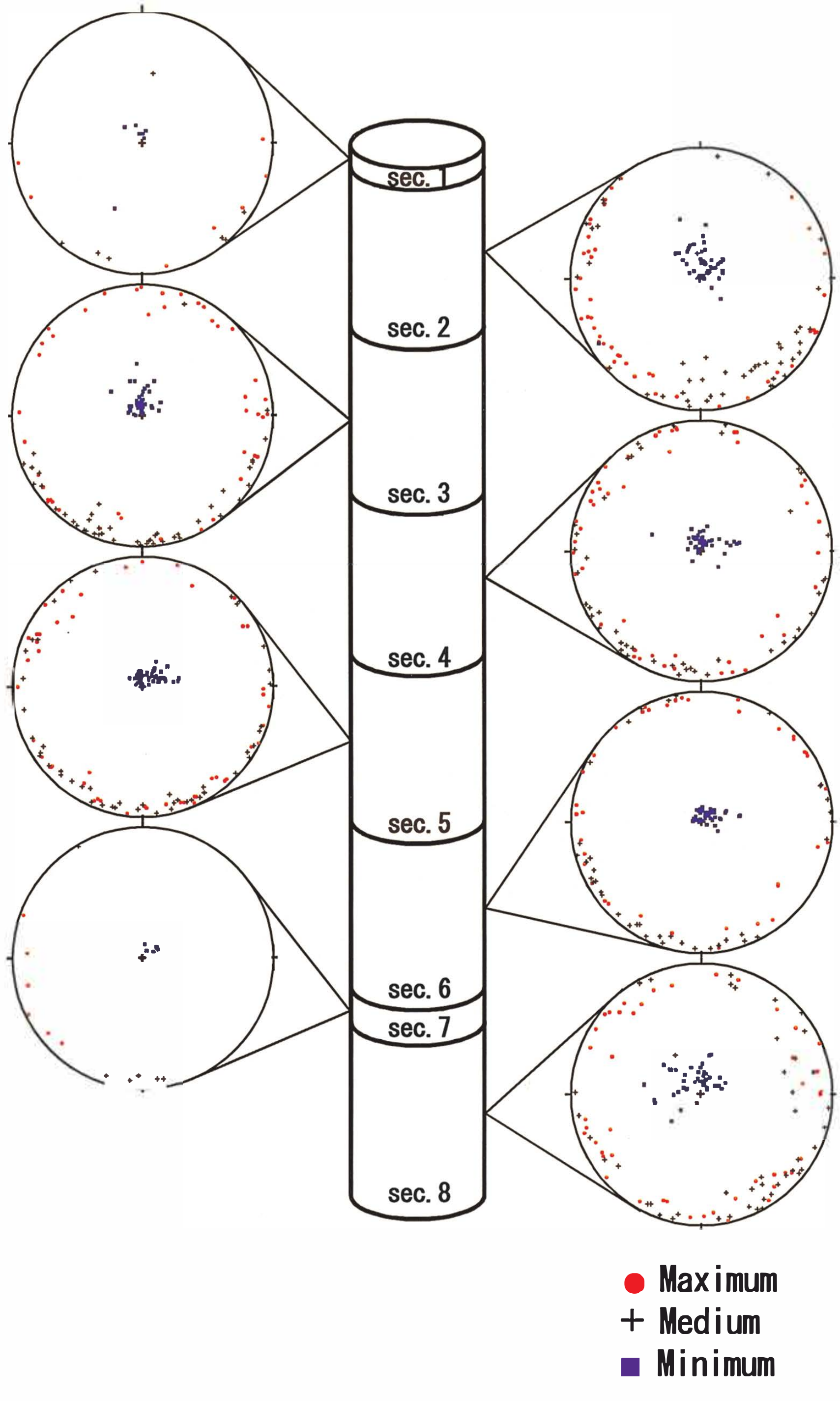

Fig. 9. Directional distribution of principal axes (Maximum, Intermediate: Medium, Minimum) of AMS ellipsoid for discrete specimens is represented by the Schmidt's projection net.

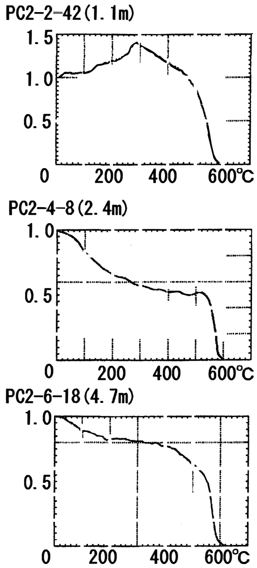

Fig. 10. Change of susceptibility in the high temperature range (up to 700°C).

to study the coercive force of the magnetic mineral.

The study of susceptibility in a high temperature range (up to 700°C) was conducted on several samples by the KLY-3S system. The results in Fig. 10 suggest that the PC2 core sediment may include magnetite, and possibly iron sulphide mineral.

In Fig. 11, the variations of the rock magnetic properties of the sediment with depth are shown. The susceptibility, ARM and SIRM show concordant variation with depth, which suggests that the variation of these parameters is mainly caused by variation of magnetic mineral content in the sediment. We can identify a large fluctuation of rock magnetic parameters around the depth from 2.5 m to 2.0 m in the core. The susceptibility, ARM and SIRM considerably decreased in this area, where chemical analysis (Sugisaki and Sakamoto, in prep.) also shows abrupt decrease of the iron component. In the following, this area from 2.5 m to 2.0 m is named area-A.

Sedimentological analysis indicates that area-A was deposited in the interglacial period where the biogenic component was abundant compared with the surrounding core region. In the upper region of the core from area-A, the rock magnetic parameters (and also the chemical parameter) show more fluctuation with larger amplitude than those in the lower region. This suggests that the sedimentary condition around Northwind Ridge in the Chukchi Sea may have changed since area-A was deposited.

In this interglacial period around area-A, increase of biogenic components caused the content of magnetic mineral to decrease in the sediment (dilution effect), which may explain the decrease of the susceptibility, ARM and SIRM. During the most active interglacial period, there may have been an open sea without sea ice around Northwind Ridge, and decrease of terrigenous grains transported by ice-rafted debris (IRD). We suppose that the kind and/or size of magnetic minerals in the sediment may have

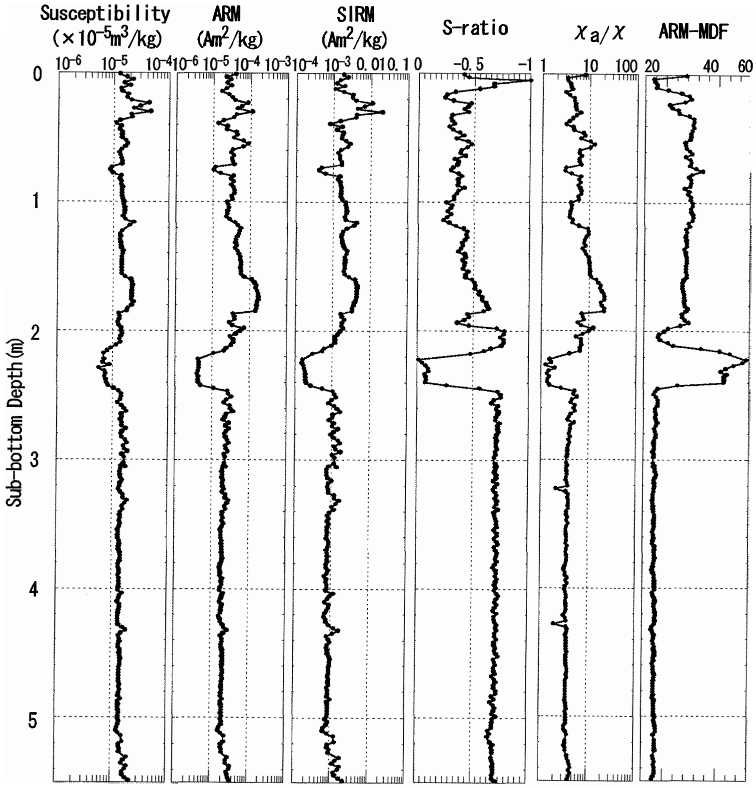

Fig. 11. Variation of magnetic properties with depth. Magnetic susceptibility (χ), ARM, SIRM, S-ratio, χ_a/χ, median demagnetizing field of ARM (ARM-MDF) are shown.

changed by the decrease of IRD particles in the active interglacial period (similar to the study on Lake Baikal sediment, Sakai *et al*., 2000).

Generally, sizes of IRD particles are larger than those of other particles. Increase of ARM-MDF and decrease of the S-ratio suggest that there is a concentration of magnetic particles with high coercive force around area-A, which may explain the possible decrease of large IRD particles in the most active interglacial period (particularly when the magnetic mineral was magnetite). However, the decrease of χ_a/χ around area-A indicates a concentration of large magnetic particles, which is inconsistent with the above interpretation. There may have been a change of the kind of magnetic mineral around area-A. For further discussion of the abrupt change of rock magnetic properties around area-A, more magnetic study with chemical analysis is necessary.

We attempted to examine the relation between the above rock magnetic properties and the appearance of geomagnetic excursions. A clear relation between them could not be identified. Though we cannot deny the unknown rock magnetic process to induce the reversal of remanent magnetization, clear reversals of remanent magnetization, obtained through demagnetization analysis, identified through a fairly long successive length of the core suggests that reversed polarity magnetizations in core PC2 may represent geomagnetic polarity reversals. In the following, the age of core PC2, and the correlation of reversed polarity magnetizations with previously known geomagnetic polarity reversals, are discussed.

5. Sedimentation cycles and polarities of remanent magnetization

5.1. Sedimentation cycle of core PC2

As cited in Section 2, the lithology of core PC2 is characterized by sedimentary cycles of distinct alternations of dark and brownish layers.

Generally, it is difficult to determine depositional ages of cores in the Arctic Ocean. The reason is that the number of foraminiferal tests (composed of $CaCO_3$) in sediments during the glacial periods is too small, and also, ^{14}C dating or oxygen isotope analysis from microfossils is difficult. However, a rough estimate of the age can be inferred from cyclic changes of sediment facies. In core PC2, alternations of laminated gray mud and brown sandy mud are clearly recorded which may be correlated with glacial-interglacial cycles during the Pleistocene.

During interglacial periods in the Arctic Ocean, sandy grains and gravels were supplied to the sea floor as IRD. The IRD grains were transported from the coastal region with active movement of the sea ice, and then released in to the sea when the ice melted in summer. During glacial periods, IRD deposition was strongly limited due to slow movement and little melting of the thick developed permanent sea-ice under the cold environment. In addition, the sediment color also suggests glacial-interglacial cycles reflecting the bottom environments. That is, massive or bioturbated brownish layers were formed under the well oxygenated condition during interglacial periods; on the other hand, laminated dark gray layers indicate the poor oxygen bottom condition during glacial periods. Therefore, alternations of laminated gray mud and brown sandy mud are closely related to the glacial-interglacial cycles.

Phillips and Grantz (1997) have shown that lithostratigraphic cycles of several sediment cores recovered from Northwind Ridge can be correlated among core sites, and also correlated with the glacial-interglacial cycles. Because the drilling site is close to their examination area, the correlation of litho-cycles can be applied to that of core PC2. In Fig. 2, litho-cycle 1 corresponds to the marine-isotope stage (MIS)-1, *i.e.* Holocene, and litho-cycles 2 and 3 are coincident with MIS-2 to MIS-5 and MIS-6 to MIS-7, respectively. Two laminated gray mud layers recognized in about 1.2 m and 2.8 to 5 m of core PC2 are probably correlated with the upper part of litho-cycle 2 (MIS-2 to MIS-4) and the upper part of litho-cycle 3 (MIS-6), respectively. The depth around 5.5–5.7 m is composed of laminated mud containing some gravel. The correlation of this part requires further examination, however, we may correlate roughly the depth *ca.* 5.7 m with the middle or base of MIS-7 (*ca.* 250 ka). Then, the age of core bottom is estimated to be 250–300 ka (MIS-8).

5.2. Geomagnetic polarity of core PC2

Through the comparison of lithostratigraphic analyses with glacial-interglacial cycles, we estimate that sedimentary cycles of the core are correlated to marine isotope stages up to MIS-8. The paleomagnetic age of PC2 is in the Brunhes geomagnetic normal polarity epoch. In Fig. 12, inclination change and assigned polarity reversals on core PC2 are shown with the result of lithostratigraphic analysis. There have been several paleomagnetic studies reporting geomagnetic excursions (events) during the few hundred thousand years in the Brunhes epoch. In this figure, the excursions found in the eastern Arctic Ocean and surrounding areas (Greenland Sea, Iceland Sea) are shown (Nowaczyk and Baumann, 1992; Nowaczyk and Antonow, 1997; Nowaczyk and Frederichs, 1999).

Though age control is not adequate, we attempted correlation with geomagnetic excursions around the main polarity reversal areas (a, b, c, d, e) of core PC2 in Fig. 12.

Reversal area-a found in the upper part of litho-cycle 2 may be correlated to the Mono Lake and Lashamp geomagnetic excursions. Reversal area-c and area-d in the lower part of litho-cycle 2 (MIS-5) may be correlated to the Fram strait excursion and Blake excursion, respectively. Around reversal area-b, correlation to the Norwegian/Greenland excursion is considerable; however, the estimated age of area-b from the

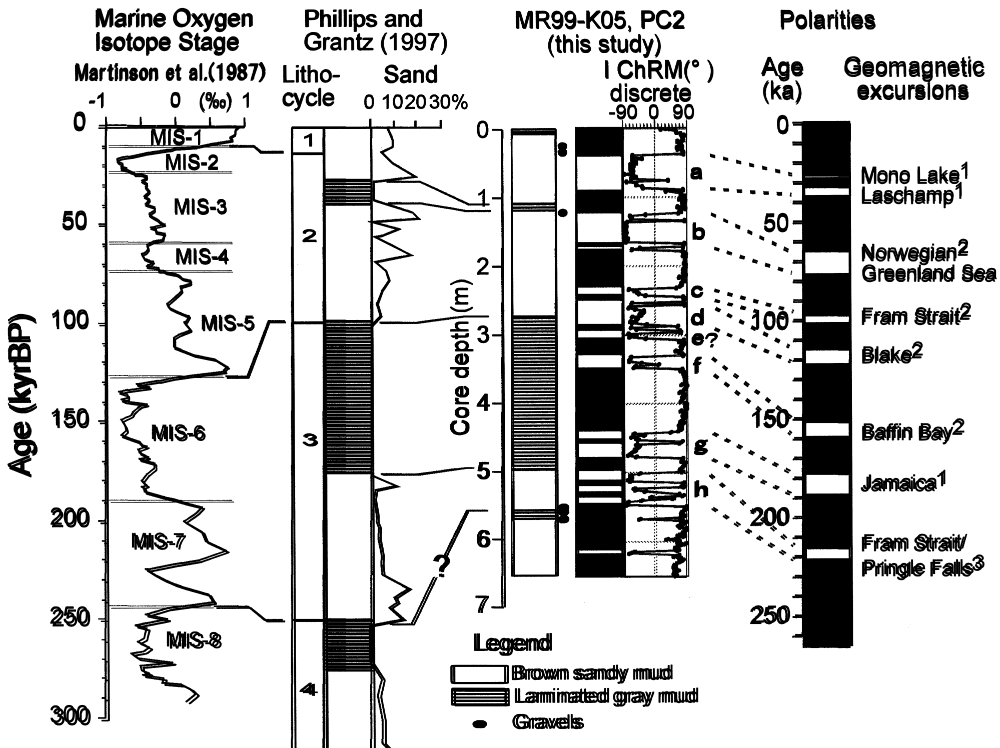

Fig. 12. Inclination change and assigned polarity reversals of the core PC2 with depth are shown with the result of lithostratigraphic analysis. At right, previously reported geomagnetic excursions during the last few hundred thousand years are shown. 1: Nowaczyk and Antonow (1997), 2: Nowaczyk and Baumann (1992), 3: Nowaczyk and Frederichs (1999).

lithocycle study (lower than MIS-4) is not concordant with the excursion age, so that more examination is necessary. Reversal areas e, f and g are found in the laminated mud layer from 2.8 to 5 m (MIS-6). Area-f and area-g probably correlated with the Baffin Bay and Jamaica excursions, respectively. The correlation of reversal area-e needs further examination. The Fram Strait/Pringle Falls excursion is the only reported excursion around 200–250 ka in the Arctic area; therefore, it may be correlated to reversal area-h though it consists of three reversal parts.

The correlation in Fig. 12 is not exact; however, most of the polarity excursions formerly found around the Antarctic area can be assigned to reversals of magnetization in core PC2. Paleomagnetic excursions in the Brunhes epoch are generally discussed based on reversals (or intermediate state polarity) of inclination data only; therefore, polarity data of PC2 utilizing both inclination and declination are valuable.

Clear polarity reversed area of core PC2 in Fig. 12 have long duration compared with formerly reported excursions in the Brunhes epoch. Another possible interpretation is that the long duration of reversed polarity is an apparent period caused by the high sedimentation rate during the geomagnetic excursion. However, the sedimentation condition to account for the higher sedimentation rate during the reversed polarity seems to be fairly difficult. Therefore, we conclude that the long area of geomagnetic polarity reversal is caused by a long duration of excursion.

Referring to the suggestion of Lund *et al.* (2001) that the geomagnetic excursion state may have a strongly multipolar spatial pattern of variability, we consider that the many clear geomagnetic excursions in core PC2 may be associated with the characteristic geomagnetic field (the high activity non-dipole field) around the area of this study. To advance this study, we are planning to do further dating studies by methods such as microfossils, ^{10}Be, and relative paleointensity of the geomagnetic field.

6. Conclusions

During the MR99-K05 cruise of JAMSTEC, a piston core PC2 6.48 m in length was obtained from Northwind Ridge of the Chukchi Sea, western Arctic Ocean.

The remanent magnetization of sediment shows clear and well correlated reversals in inclination and declination. Furthermore, most of the polarity reversals identified in the discrete specimens are concordant with reversals found in u-channel samples. Though we cannot deny the possibility of an unknown rockmagnetic process inducing the reversal of remanent magnetization, clear reversals of magnetization examined by af demagnetization analysis, in the fairly long successive range of the core indicates that the reversed magnetizations in core PC2 may be related to past geomagnetic polarity reversals.

Sediments of core PC2 are characterized by three distinct alternations of dark and brownish layers. Based on the comparison of lithostratigraphic cycles with glacial-interglacial cycles, the bottom of core PC2 might be correlated to the marine isotope stage of MIS-8 (*ca*. 250–300 ka). When comparing with formerly known geomagnetic polarity records over several hundred thousand years, we find that core PC2 includes many clear geomagnetic excursions with long duration. Though further dating studies are necessary to determine the age of the core, the many clear observed excursions in core PC2 are related to characteristic geomagnetic features around the western Arctic region during the past few hundred thousand years.

Acknowledgments

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