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PALEOMAGNETIC STUDY OF ODP LEG 119 —KERGUELEN PLATEAU AND PRYDZ BAY

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Abstract: ODP Leg 119 drilled at the Kerguelen Plateau in the southern Indian Ocean and Prydz Bay in Antarctica. Hole 745B on the southern Kerguelen Plateau gave the excellent reversal sequence during the last 6 Ma including the Cobb Mt. event in the Matuyama chron and the unidentified subchron in the Gilbert chron. Limestone sequence at Hole 738C from Turonian to Santonian stage shows the low paleolatitude (54°S) compared with the present (64°S). This paleolatitude is nearly the same as the Tertiary paleolatitude estimated from VGP of Antarctica. The basaltic rocks below the limestone sequence showed two groups of magnetic inclinations around +50° and −70°. The magnetizations of the two polarities indicate that the eruption of the basaltic rocks occurred during a fairly long time. The large difference of the absolute inclinations suggests the possibility that the tectonic tilting has occurred in Hole 738C, near the southern end of the Kerguelen Plateau.

In Hole 742C of Prydz Bay, glacial sequence down to 316 mbsf (meter below sea floor) was drilled. Magnetic susceptibility of this sequence showed a good correlation with the change of lithology. Magnetic inclinations of the sequence from middle Eocene to Oligocene showed the dominant normal polarity zone with several short reversals. It suggests that a large glacier complex existed in Prydz Bay during earliest Oligocene and possibly during late middle Eocene period.

1. Introduction

Ocean Drilling Program (ODP) Leg 119 drilled six sites on the Kerguelen Plateau and five sites in Prydz Bay near Antarctica (Fig. 1). The Kerguelen sites form a latitudal transect from 49°S to 63°S. The sedimentation sequences at these sites provide valuable information about the paleoceanography of the Indian Ocean and also about the history of cooling in Antarctica. Most of coring of late Miocene to Quaternary sediments was accomplished using APC (advanced piston corer) technique, and consequently, the sediments displayed little evidence of drilling disturbance and have produced a good magnetostratigraphic record.

One aim of Leg 119 is to determine the tectonic history of the Kerguelen Plateau. The major tectonic event is the breakup of the Broken Ridge from the Kerguelen Plateau occurring at 45–42 Ma (MUNSCHY and SCHLICH, 1987). HOUTZ *et al.* (1977) suggested that the origin of the Kerguelen Plateau is oceanic island. While, COFFIN

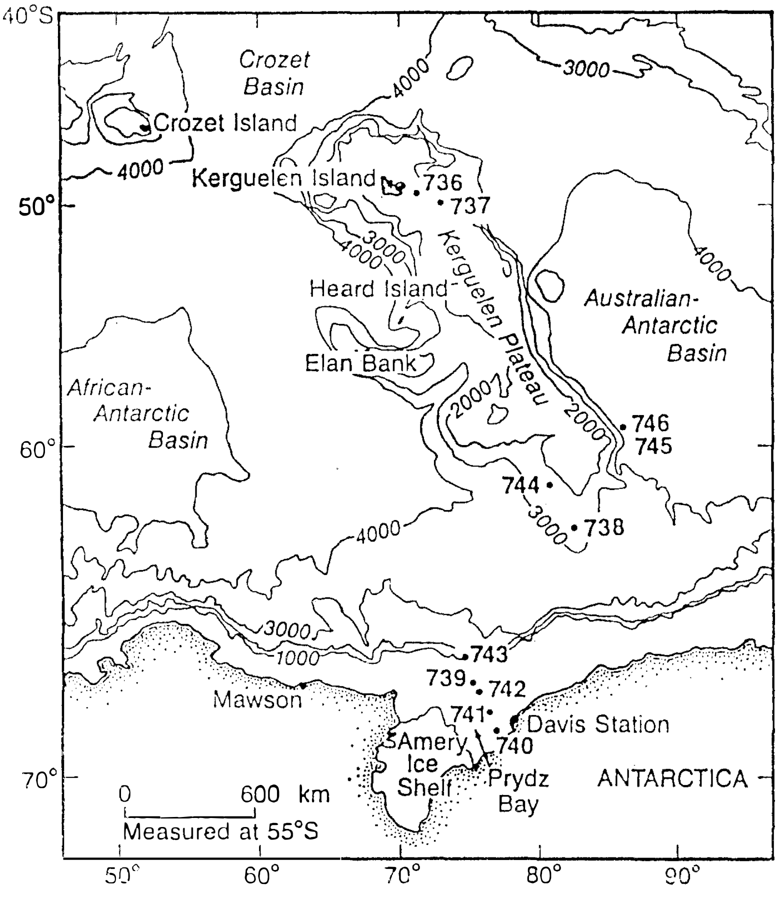

Fig. 1. Locations of holes drilled during Leg 119 (from BARRON, LARSEN *et al., 1989)*

et al. (1986) suggest that the northern, central and southern parts of the Plateau have different origins. Basaltic rocks were drilled in Hole 738 C, as well as limestones overlying the basalts which range in age from Turonian to Santonian of Cretaceous. They were utilized to examine the tectonic history of the southern Kerguelen Plateau.

The primary objective of Prydz Bay was to obtain the glacial history of Antarctica, specially the timing and nature of the initiation of the ice sheet. Previous results obtained by Leg 113 (LEG 113 SHIPBOARD SCIENTIFIC PARTY, 1987) in the Weddell Sea indicate that the glaciation at sea level occurred first during the late early Oligocene in East Antarctica. In Holes 739C and 742A, the sediments of the deep continental shelf were drilled. They include an older diamictite sequence that contains middle Eocene to Oligocene nannofossils. The magnetostratigraphy of these holes may be utilized to see the possibility of the initiation of ice sheet in the Eocene age.

2. Method

Measurement of the magnetization of the discrete samples collected from the drilled cores was made either by the cryogenic magnetometer (ScT or CCL type) or by the Schonstedt spinner magnetometer. Stability of the remanences was mainly examined by the alternating field (AF) demagnetization. Thermal demagnetization was carried out on some samples from limestone sequence and basaltic rocks in Hole 738C. For each hole, about 20% of the samples were chosen as the pilot samples. They were AF demagnetized systematically in steps of 2.5 or 5 mT at least up to 50 mT. Other samples were demagnetized in five steps based on the results of demagnetization of the pilot samples. Then, the characteristic direction of each sample was determined by the diagonal vector analysis.

The initial susceptibility was measured on the samples for several holes using a Bartington magnetic-susceptibility meter. The whole core magnetization was measured by a pass-through type cryogenic magnetometer on board. AF demagnetization up to 9 mT was available in this system.

To determine the Cenozoic magnetostratigraphy, the time scale by Berggern *et al.* (1985) was utilized, augmented by the time scale by McDougall (1979) and Mankinen and Cox (1988) referred to the subchrons not included in the time scale by Berggren *et al.* (1985).

3. Results and Discussion

3. 1. *Kerguelen Plateau*

In Hole 745B, a sedimentary sequence of diatom ooze was cored. The polarity sequence of this hole shows a good correlation with the reversal time scale. The short normal polarity zone, referred to as the "Cobb Mountain event" was observed between 57 and 56 mbsf in the Matuyama reversal sequence (Fig. 2). This event of an age around 1.1 Ma was first found by Mankinen *et al.* (1978) in the volcanic rocks from the northern California, although it is rarely observed in deep sea core studies. The "Cobb Mt. event" was confirmed in Hole 745B and proved to be the important event for the age determination of the deep sea sediments.

The continuous magnetic polarity pattern and biostratigraphy data indicate that

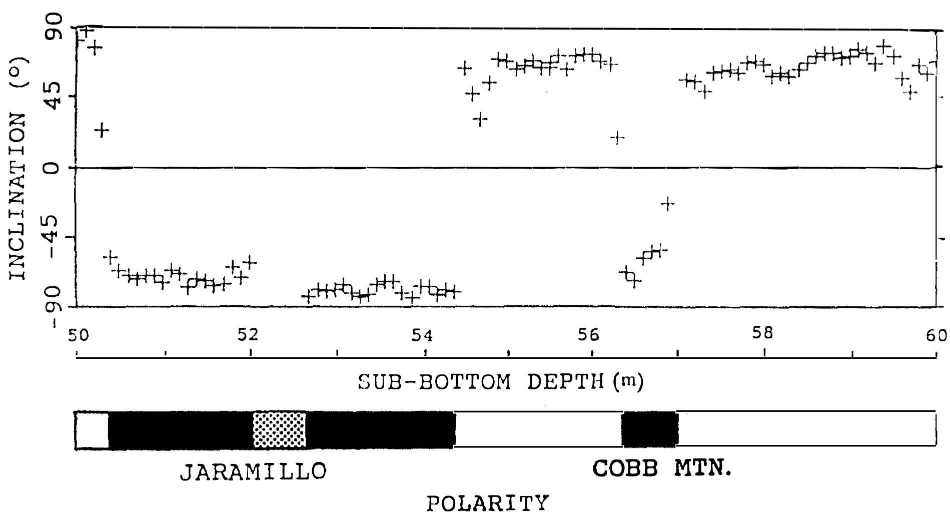

Fig. 2. Profile of magnetic inclination measured by the whole-core cryogenic after 9 mT AF demagnetization of the sequence between 60 and 50 mbsf of Hole 745B. Corresponding geomagnetic short events in the Matuyama chron are the Jaramillo and Cobb Mt. subchrons.

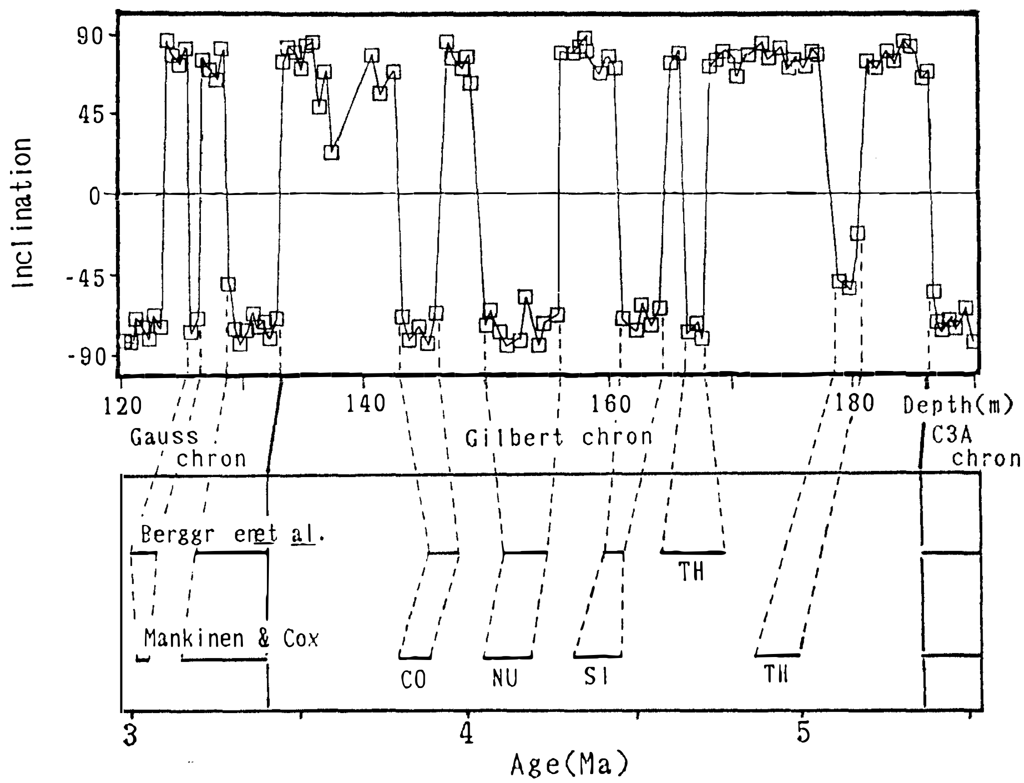

Fig. 3. Plot of magnetic inclination and polarity interpretation of the sequence between 190 and 120 mbsf of Hole 745B. Subchrons: TH = Thvera; SI = Sidufjall; NU = Nunivak; CO = Cochiti. The time scales referred are from BERGGREN *et al. (1985) and from* MANKINEN *and* COX *(1988).*

the sequence from 183 to 132.8 mbsf corresponds to the Gilbert reversed chron. In this sequence, five normal polarity zones can be identified.

The existing geomagnetic polarity time scales show four normal subchrons in the Gilbert chron. Comparing the representative two time scales in Fig. 3, the large difference in the age of the Thvera subchron becomes apparent. The age of Thvera (BERGGREN *et al.*, 1985) is about 0.3 Ma younger than the age of MANKINEN and COX (1988).

The large age difference for the Thvera subchron suggests the possibility that there are two different subchrons in the age of the formerly assingned Thvera subchron. The lowest normal zone in Hole 745B may be correlated to the Thvera subchron by MANKINEN and COX (1988). The next lowest normal zone may be correlated to the Thvera subchron by BERGGREN *et al.* (1985). Thus, the magnetostratigraphy of Hole 745B suggests the existence of five normal polarity subzones in the Gilbert chron rather than four.

The change of intensities of natural remanent magnetization (NRM) and susceptibilities with the depth downhole is shown in Fig. 4. A broad peak in NRM intensity and susceptibility exists between 200 and 160 mbsf. A second, more obscure broad peak is identified between 80 and 40 mbsf. Lithological studies found ice-rafted material in the two intervals (BARRON, LARSEN *et al.*, 1989) indicating the enhanced glaciation in

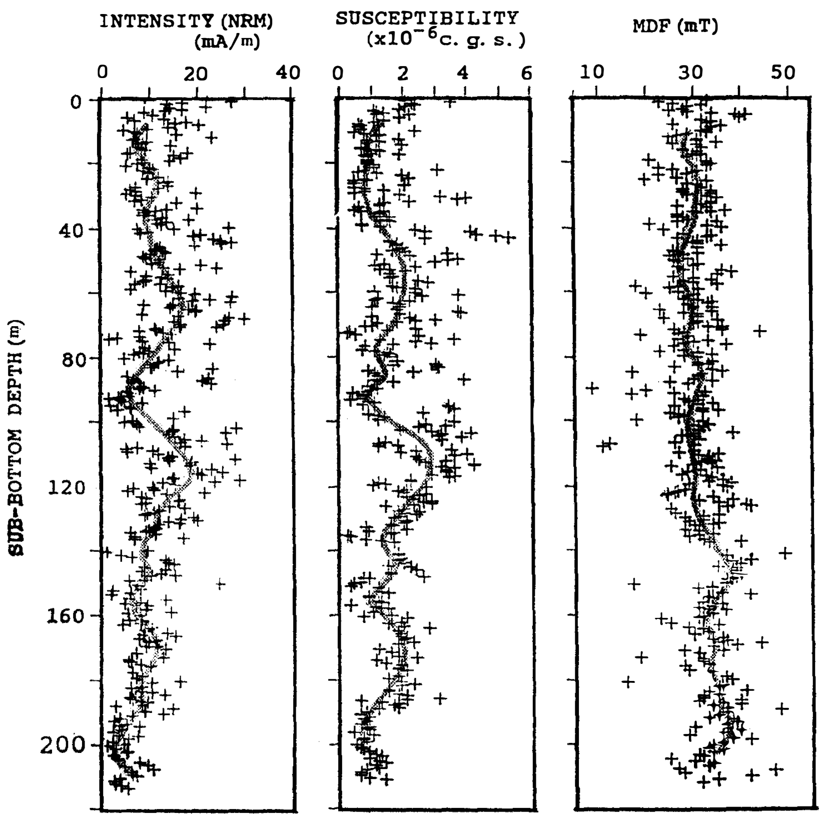

Fig. 4. Downhole variation of NRM intensity, magnetic susceptibility, and MDF values of Hole 745B.

the early Pliocene and Quaternary. The MDFs (mean destructive field) are almost constant in each sequence which suggests that the change of magnetic minerals during the enhanced glaciation is not serious. The NRM intensity and susceptibility increases may be caused by an increase in magnetic minerals within the ice-rafted material.

Scatter in the distribution of both data lessens below 120 mbsf and the broad decreasing trend is identified between 120 and 140 mbsf. KARLIN *et al.* (1987) explained similar decreasing trends in NRM intensities of suboxic marine sediment as an iron reduction effect. They showed that a decrease in MDF value occurs with that of NRM intensity and is caused by the dissolution of more stable finer grains in diagenesis process. Figure 4 shows that the average MDF of the sequence below 120 mbsf is about 5 mT higher than that of the upper sequence. That is, the change in MDF value shows the inverse trend with the change in NRM intensity. A short hiatus was identified around 120 mbsf, 3 Ma (BARRON, LARSEN *et al.*, 1989). These results suggest that the change in NRM intensity and susceptibility around 120 mbsf may have been caused by the change of lithology in the provided sediments and that diagenesis may not have played an important role.

Figure 5 shows the sedimentation rate for Holes 737A, 745B and 746A. The detailed data for each hole are shown in ODP Leg 119 Scientific papers (in print). Hole 737A on the northern Kerguelen is situated at the present-day Antarctic convergence. This hole drilled into the diatom nannofossil ooze. In Hole 746A, about 5 km north

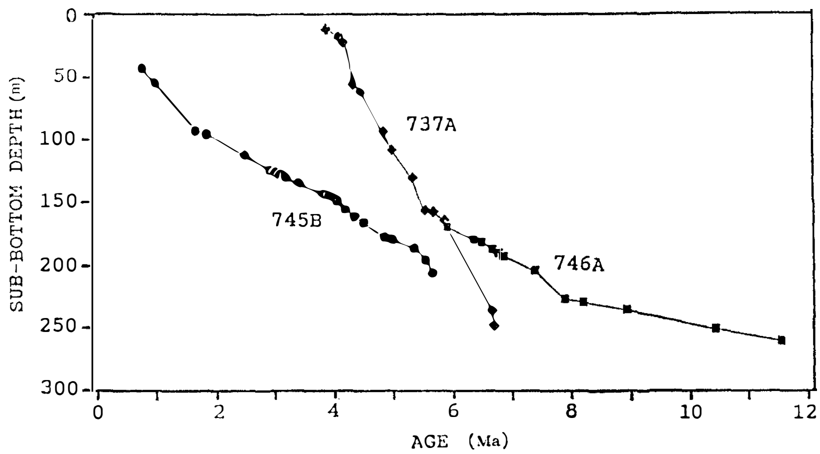

Fig. 5. Age vs. depth profile of Holes 737A, 745B and 746A. Time scale by BERGGREN et al. (1985) was mainly utilized for the magnetostratigraphy interpretation. As for the Cobb Mt., Reunion subchrons in the Matuyama chron and the subchrons in the Gilbert chron, time scale by MANKINEN and COX (1988) was used. As for the Gilsa subchron in the Matuyama chron, time scale by MCDOUGALL (1979) was used.

of Hole 745B on the same sedimentary ridge, the sedimentary sequence consists of silty clay with diatom ooze. The sedimentation rate in each hole is generally smooth. In Hole 745B, the depth to the sediment of around 6 Ma is about 30 m lower than that of Hole 746A. The sedimentation rate of Hole 737A on the northern Kerguelen is about three times higher (84 m/Ma) than the rate estimated from Holes 745B and 746A on the southern Kerguelen Plateau.

3.2. *Cretaceous sequence*

In Hole 738C on the southern Kerguelen plateau, lower Turonian to Campanian silicified limenstone and calcareous chalk of the age from Campanian to Maestrichitian, were sampled. Figure 6 shows the paleomagnetic inclinations for these sediments. The magnetizations of the limenstone sequence (*ca*. 90–70 Ma) between 480 and 440 mbsf are stable. The mean inclination is calculated as $70.6° \pm 7.3°$ by the method of MCFADDEN and REID (1982), which corresponds to the paleolatitude of $53.9° \pm 9.5°$S.

The estimated paleolatitude is much shallower than the latitude of 63°S for this hole calculated from the geomagnetic dipole. To check whether the low latitude is caused by the movement of Kerguelen or polar wandering, the paleolatitude was compared with the VGP (virtual geomagnetic pole) of East Antarctica. As shown in Fig. 7, the VGP positions available for our study are obtained only for the upper Tertiary and Jurassic and not for Cretaceous (MCELHINNY, 1973; FUNAKI, 1984). The calculated latitude using the Jurassic VGP of Antarctica shows 32°S and that of the upper Tertiary is 54°S. The Tertiary latitude is almost the same as the paleolatitude 54°S estimated from the limestone sequence.

Then, we may interpret the paleolatitude of Hole 738C as follows: If the Santonian VGP of Antarctica was situated near the Tertiary VGP, Hole 738C must have remained at the present location since Cretaceous. If the Santonian VGP is between the Jurassic and Tertiary VGPs, the paleolatitude obtained from the limenstone se-

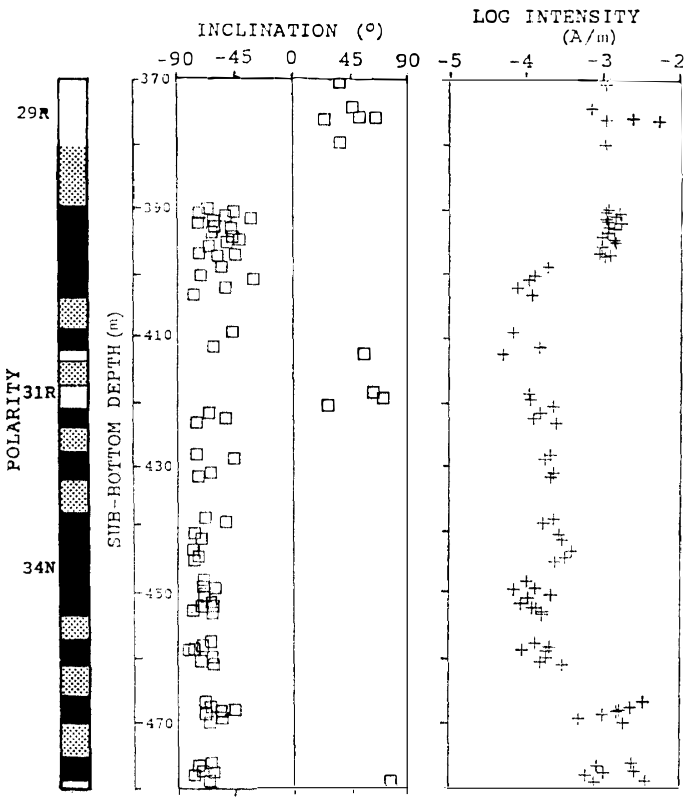

Fig. 6. *Plot of magnetic inclination and intensity vs. depth and polarity interpretation of the sequence between 480 and 370 mbsf of Hole 738C. Polarity numbers 29R, 31R, 34N are referred from* KENT *and* GRADSTEIN *(1985).*

quence is higher than the latitude estimated from the VGP. The case indicates the southward immigration of the southern Kerguelen Plateau in relation to Antarctica since Santonian.

3.3. Basaltic rocks and volcanoclastic rocks

Basaltic and volcanoclastic rocks were drilled under the Turonian limestone sequence. The petrological study indicates the basalts were erupted subaerially. The thermomagnetic analyses showed concave *Js-T* curves in many samples (Fig. 8). The results suggest that most of the samples have two kinds of magnetic minerals with the Curie temperatures around 310°C and over 500°C. The grade of the concave feature and the change in the saturation magnetization by heating were compared using the values A/C and B/C in Fig. 8. The positive correlation in these two parameters shows the oxidation stage of the magnetic minerals. The irreversible ratio B/C, ranging from 0.8 to 1.4 is not so large compared with the usual submarine basalts.

Figure 9 shows the NRM inclinations and the characteristic inclinations after demagnetizing the unstable components.

The inclinations between 530 and 510 mbsf after demagnetization showed a mode of around +50°, while the sequence between 510 and 503 mbsf showed the inclination from −80° to −60° (Fig. 9). Both polarities in inclinations were obtained, but their

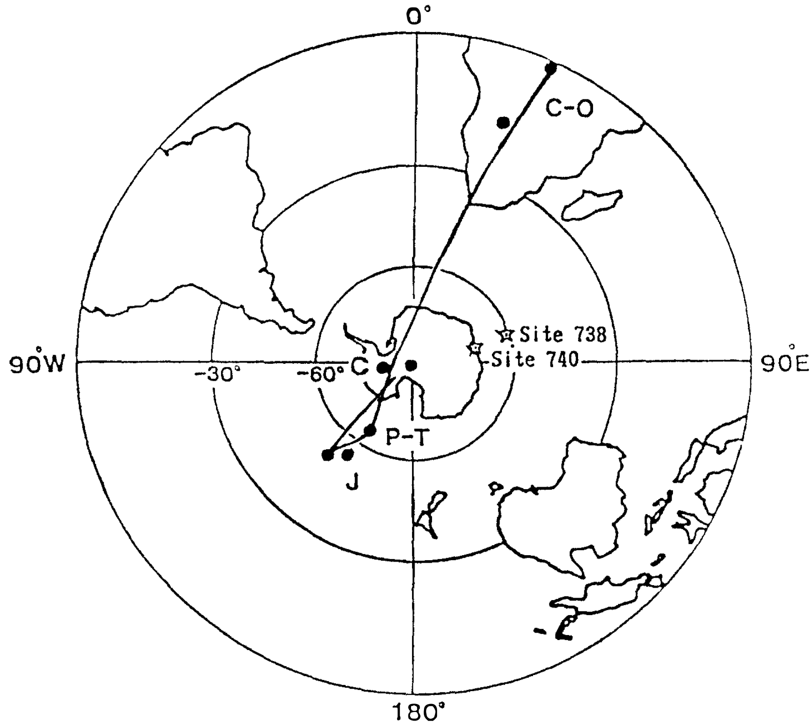

Fig. 7. Apparent polar-wander paths for Antarctica compiled by FUNAKI (1984). VGP positions are represented as follows. C-O: Cambro-Ordovician, P-T: Permo-Triassic, J: Jurassic, C: Cenozoic (Tertiary). The angular distance between Site 738 and VGP in Jurassic is more than 60°.

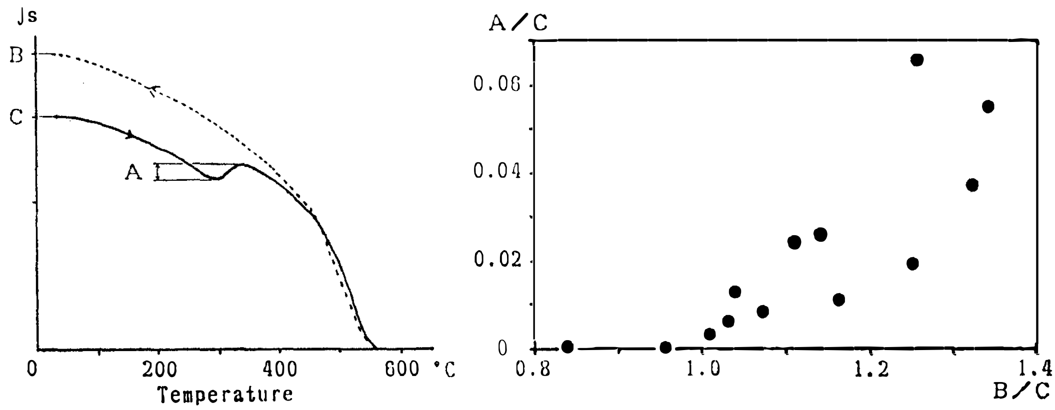

Fig. 8. Results of thermomagnetic analysis on the basaltic and volcanoclastic rocks of Hole 738C. The left figure shows the thermomagnetic curve of Sample 119-33R6-13. The heating and cooling was made at the vacuum of 10^{-3} Torr in the magnetic field of 4 T. Values of A, B, C in the left figure are calculated on the other samples in the same way. The right figure shows the plots of the values A/C vs. B/C from 13 samples.

absolute values of 50 and 70 are quite different. Two groups of inclinations with different magnetic polarities indicate that the eruptions of this sequence recorded a fairly long duration of the geomagnetic field. It is questionable why the absolute values of the two groups of inclinations are not antipodal.

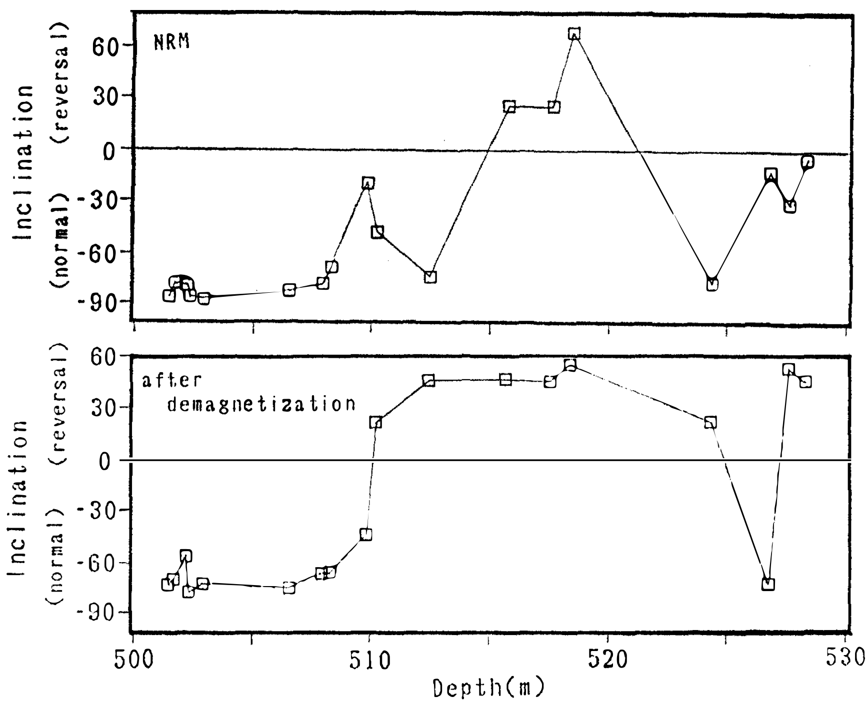

Fig. 9. Plot of magnetic inclination of the basaltic and volcanoclastic rocks of Hole 738C vs. depth. The upper figure shows the NRM inclinations and the lower shows the characteristic inclinations after demagnetization.

There remains the possibility that the shallow magnetic inclinations below 510 mbsf is due to that the secondary component was not adequately eliminated by the demagnetization. However, we cannot identify the rock magnetic difference between the sequence below 510 mbsf (reverse polarity) and the sequence above 510 mbsf (normal), from the analyses of thermomagnetic property, susceptibility, mean destructive AF field (temperature) and viscous remanent magnetization ratio. This suggests that some other tectonic process such as tilting may cause the shallow inclinations in the sequence below 510 mbsf, around Hole 738C, south rim of the sourthern Kerguelen Plateau.

3.4. *Prydz Bay*

In Hole 740A, non-marine red sediments were drilled from 225.5 to 56.6 mbsf. This sequence may be correlated with the Paleozoic to Mesozoic sequence of the Mahanadi graben in India (personal communication by B. TURNER). The preliminary paleomagnetic study shows the low magnetic inclination in this sequence, which corresponds to the paleolatitude of Gondwanaland from the late to middle Mesozoic time.

In Hole 742A, the sedimentary sequence of diamictites and diamicton was obtained down to 316 mbsf. The limited biological data indicate that the age of the sequence above 172.5 mbsf is assigned between Quaternary and Pliocene, and the sequence between 172.5 and 313.3 mbsf is assigned to middle Eocene to Oligocene. The left figure in Fig. 10 shows the variation of NRM intensity and susceptibility with depth. Abrupt changes in susceptibility are observed in several intervals of the sequence. These portions are correlated well with the locations where lithology changes.

Above 172.5 mbsf, a clear stepwise decreasing trend is shown in the susceptibility. Below 172.5 mbsf, both the NRM intensity and susceptibility show a similar small change. The samples above 172.5 mbsf are unstably magnetized and the MDF value is between 5 and 12 mT. The clear change in magnetic properties above 172.5 mbsf may be caused by the large magnetic minerals in the coarse-grained conglomerate.

An interval of unstable NRM and high susceptibility (right figure in Fig. 10) was also identified in the Miocene to Quaternary sequence in Hole 739C located about 30 km away. The abrupt change in susceptibility in these two holes suggests that some environmental change may have taken place in Prydz Bay between Pliocene (Miocene) and Oligocene.

The AF demagnetization experiments show the magnetization of the sequence below 170 mbsf of Hole 742A is generally stable. This sequence consists of homogeneous diamictite with smaller gravel content and includes many carbonate-cemented layers. Figure 11 shows the characteristic inclinations obtained from discrete samples and the whole core cryogenic data at 9 mT AF. Both data show that this sequence is dominantly normally magnetized. Several brief intervals of reversed polarity are concordant between the discrete data and the whole core data. The restricted biostratigraphy data show this sequence is from middle Eocene to Oligocene. The polarity time scale (BERGGREN *et al.*, 1985) at the right of Fig. 11 shows that the sequence between Anomalies 18 and 15 (42.7–38.8 Ma) is dominantly normally magnetized with several short reversed zones. In the case of the sequence below 172.5 mbsf in Hole

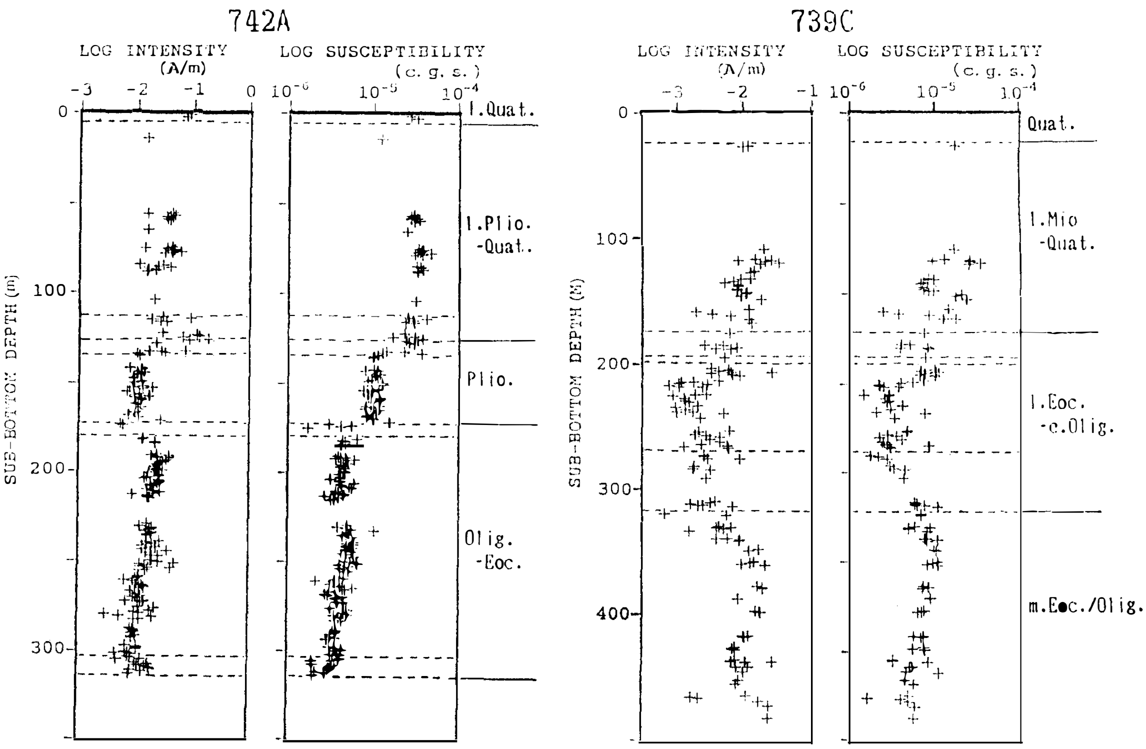

Fig. 10. Downhole variation of NRM intensity, magnetic susceptibility of Holes 739C and 742A. Dotted lines represent the lithological boundary. The estimated age from biology is shown at the right. Quat.=Quaternary; Plio.=Pliocene; Mio=Miocene; Olig.=Oligocene; Eoc.=Eocene; l.=lower; m.=middle; e.=early.

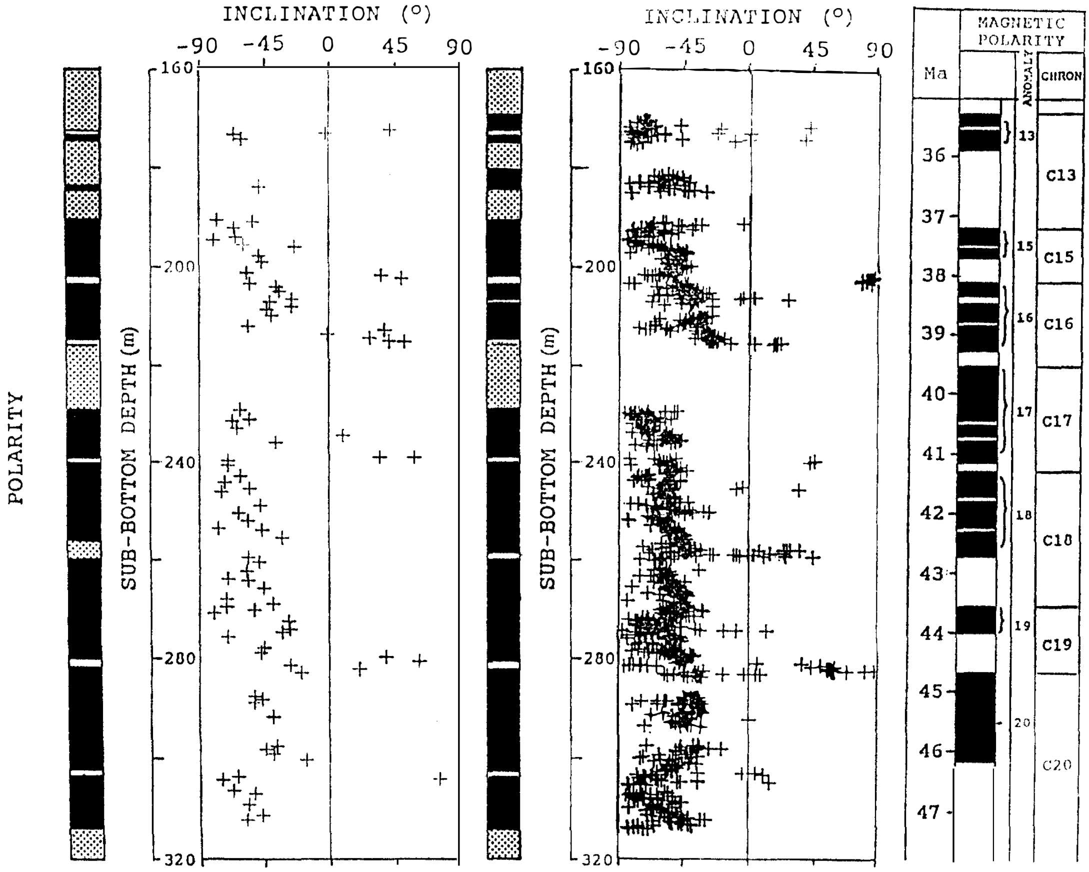

Fig. 11. Plot of magnetic inclination from discrete samples and from whole core measurements on the Hole 742C vs. depth downhole. Interpreted magnetic polarity is shown in the box at the left. At the right, time scale between anomalies 20 and 13 by BERGGREN *et al. (1985) is shown.*

742A, the assignment of this polarity sequence may be plausible. The magnetostratigraphic correlations suggest that a large glacier complex reached the region in Prydz Bay during earliest Oligocene and possibly during late middle Eocene period (about 42.5 Ma), 6 Ma earlier than that has been proposed for other Antarctic areas.

4. Conclusions

The late Miocene to Quaternary magnetostratigraphy of the Kerguelen Plateau showed the existence of the Cobb Mt. subchron in the Matuyama chron and the new unidentified subchron in the Gilbert chron.

In Hole 738C, the Turonian to Santonian limestone sequence showed stable and concordant magnetic inclinations. The paleolatitude determined from this sequence is 54°S, about 10° lower than the present latitude and nearly the same as that of the Tertiary VGP of Antarctica. The basaltic rocks under the Cretaceous limestone showed the mixed polarity. It indicates the eruptions cover a long time interval. The difference in the absolute inclinations of the two polarities is 20°, which suggests the tilting of the sequence after formation.

The magnetic susceptibility measured for the glacial sequence in Hole 742A of Prydz Bay showed a good correlation with the change of lithology. The stable inclinations obtained from the discrete samples and the whole core cryogenic data at 9 mT AF suggest that the sequence from middle Eocene to Oligocene is dominantly normal polarity with several short reversed polarity zones. It suggests the existence of a large glacier complex at Prydz Bay during earliest Oligocene and possibly during late middle Eocene period.

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