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PALEOMAGNETIC STUDY OF MARINE SEDIMENTS FROM ANTARCTIC SEA —CENTRAL WILKES LAND MARGIN, DUMON D'URVILLE SEA AND VICTORIA LAND BASIN—

Hideo SAKAI[1], Eiichi KIKAWA[2], Takemi ISHIHARA[3], Hironori KOBAYASHI[1], Kiyoshi KOMORI[2] and Aiko SUNAGAWA[2]

[1]*Department of Earth Sciences, Faculty of Science, Toyama University, Gofuku 3190, Toyama 930-0855*
[2]*Global Environmental Laboratory, Faculty of Education, Toyama University, Gofuku 3190, Toyama 930-0855*
[3]*Marine Geology Department, Geological Survey of Japan, 1-3, Higashi 1-chome, Tsukuba 305-8567*

Abstract. Paleomagnetic study is conducted on sediment cores from the Antarctic Ocean off the Central Wilkes Land margin, the Dumont d'Urville Sea and Victoria Land Basin The Brunhes/Matuyama geomagnetic polarity boundary (B/M boundary, 0 78 Ma) and the Jaramillo geomagnetic event (0 99-1 07 Ma) are identified in five cores at the Central Wilkes Land margin One core from the Victoria Land Basin shows the B/M boundary The assigned magnetostratigraphical age indicates the sedimentation rate of between 3 and 5 mm/ky

The susceptibility variation with depth is studied The upper sequence younger than 0 4 Ma shows variation with larger amplitude than that of the lower sequence, however, the average and frequency dependence of susceptibility do not show distinct changes This suggests a change of sedimentary environment around 0 4 Ma, which may be correlated with the global climate change

The magnetic intensity normalized by susceptibility shows a distinct decrease around B/M boundary, the intensity is higher in the Brunhes epoch than that in the Matuyama epoch The result is similar to the variation of geomagnetic dipole moment studied by J P VALET and L MEYNADIER (Nature, **366**, 234, 1993) on the ODP cores from the Pacific Ocean This suggests that there was a global change of geomagnetic field intensity, between the Matuyama reversed epoch and the Brunhes normal epoch

key words magnetization of sedimentary cores, geomagnetic polarity reversals, Antarctic Sea, Brunhes/Matuyama boundary, secular change of geomagnetic intensity

1. Introduction

Remanent magnetization of a marine/lake sediment is preserved over a long period as a "fossil" of the geomagnetic field Comparison of the remanent magnetization vector with the geomagnetic polarity reversal history and/or the secular variation is an effective method of dating the sedimentary sequence Recently, the study of magnetic properties such as susceptibility of sediment shows that it is sensitive to the change of sedimentary environment (*e.g.*, BLOEMENDAL and DEMENOCAL, 1989; HELLER and EVANS, 1995; SAKAI *et al.*, 1997) That is, the paleomagnetic study is useful not only for dating of the sediment but also in research on the paleo-environment.

In this paper, we report on a paleomagnetic study conducted on short sedimentary cores from the Antarctic Ocean (Fig. 1). The cores were obtained in the TH94 cruise (1994–1995) and TH95 cruise (1995–1996) of R/V HAKUREI-MARU made by the Technology Research Center, Japan National Oil Corporation. The drilling of cores on cruise TH94 was done at the Central Wilkes Land margin (ISHIHARA *et al.*, 1996) and that on cruise TH95 in the Dumont d'Urville Sea and Victoria Land Basin in the western Ross Sea (TANAHASHI *et al.*, 1997). The paleomagnetic study aims to determine the age of these cores and also to investigate the change of sedimentary environment in the Antarctic Ocean by combining the paleomagnetic results with the magnetic properties.

For the general understanding of geomagnetism, the geomagnetic and/or paleomagnetic data at high latitude is important. Few paleomagnetic studies have been done on successive sedimentary sequences at high latitude in the southern hemisphere, especially in the Antarctic region. Therefore, this paleomagnetic study in the Antarctic Ocean will provide valuable results.

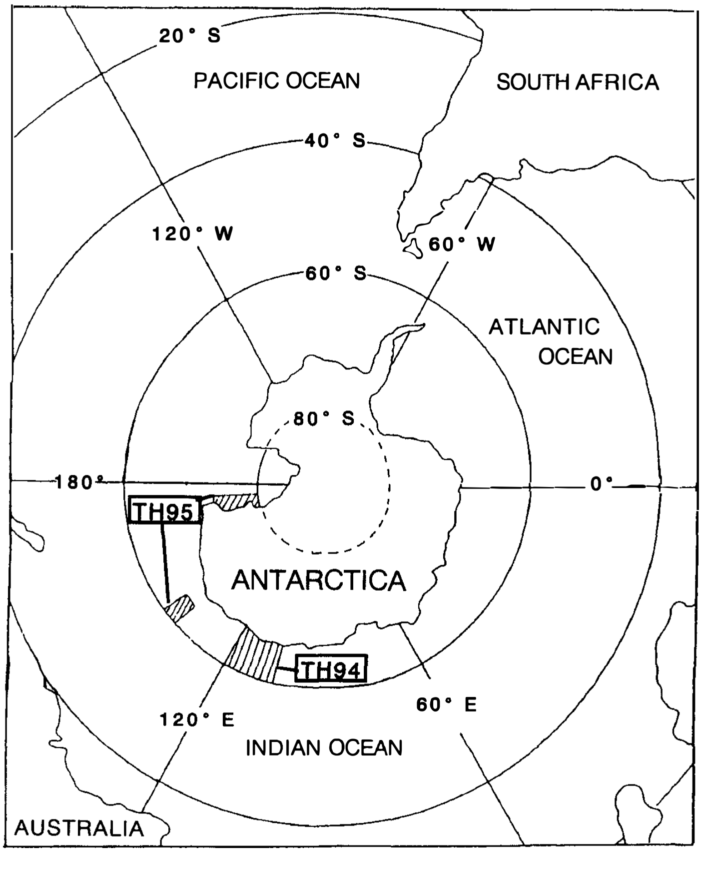

Fig 1 The drilling locations of sedimentary cores on the 1994 cruise at the Central Wilkes Land margin, and the 1995 cruise in the Dumont d'Urville Sea and Victoria Land Basin in the western Ross Sea

2. Samples

The cores used in this study were obtained by a sea-bottom gravity core drilling system, from the following two areas.

(A) Central Wilkes Land margin (Fig. 2A)

At the Central Wilkes Land margin, nine cores were obtained They include four

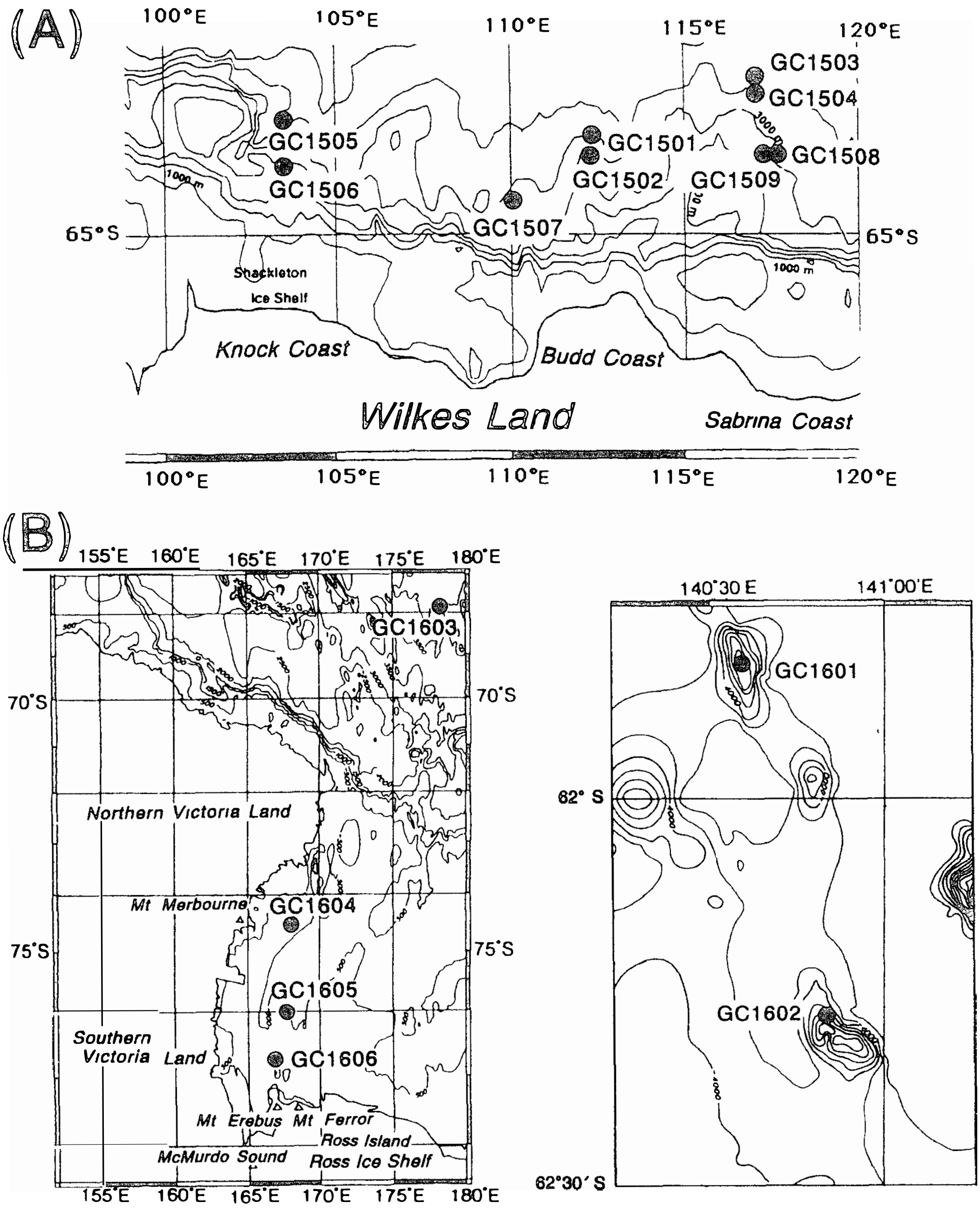

Fig 2 Core drilling locations

(A) Central Wilkes Land margin, nine cores in Table 1a

(B) Dumont d'Urville Sea and Victoria Land Basin in the western Ross Sea, five cores in Table 1b

cores GC1501–1504 at the Budd Coast margin, three cores GC1505–1507 at the Knox Coast margin and two cores GC1508–1509 at the Sabrina Coast margin. The depths of drilling points were 2000–3500 m. The sedimentary sequence is mainly composed of silty clay and siliceous silt.

(B) Dumont d'Urville Sea and Victoria Land Basin in the western Ross Sea (Fig. 2B)

Core GC1602 from the Dumont d'Urville Sea and four cores GC1603–1606 from Victoria Land Basin were studied. Depths of drilling points were 595–3690 m. Sediments are silty clay, siliceous silt and calcareous ooze.

The drilling points and cores are described in Table 1.

Each core was divided into sub-cores of 1 m length, which were then cut in half lengthwise. Samples for paleomagnetic study were collected successively from the half-cut subcores in 7 cc plastic cube cases (edge length is 2.5 cm). The vertical directions of the core was marked on the cubes for reference. As the core was rotated during drilling, the declination component of remanent magnetization is not useful. The inclination and total magnetic intensity are discussed.

Table 1a Locations and descriptions of cores from Central Wilkes Land margin

Location	Core No	Latitude	Longitude	Depth (m)	Length (cm)	Samples
off Budd Coast						
	GC1501	63°43′13″S	112°20′06″E	3060	540	265
	GC1502	63°59′23″S	112°20′24″E	2656	542	268
	GC1503	63°17′30″S	114°59′42″E	3368	524	259
	GC1504	63°19′43″S	116°00′06″E	3310	523	245
off Knox Coast						
	GC1505	63°32′19″S	103°30′24″E	3670	371	169
	GC1506	64°08′13″S	103°30′00″E	2048	114	41
	GC1507	64°35′01″S	118°26′18″E	2604	453	215
Sabrina Coast						
	GC1508	63°59′56″S	118°26′18″E	3232	532	248
	GC1509	63°59′53″S	118°17′12″E	3198	539	225

Table 1b Locations and descriptions of cores from Dumont d'Urville Sea and Victoria Land Basin

Location	Core No	Latitude	Longitude	Depth (m)	Length (cm)	Samples
Dumont d'Urville Sea						
	GC1601	61°49′29″S	140°35′42″E	3451	0	0
	GC1602	62°16′40″S	140°50′06″E	3692	370	154
Victoria Land Basin in the western Ross Sea						
	GC1603	67°49′17″S	178°17′00″E	3326	430	193
	GC1604	74°32′55″S	168°00′06″E	922	254	120
	GC1605	76°00′03″S	167°34′30″E	595	107	52
	GC1606	76°46′14″S	166°52′36″E	751	296	136

3. Results of Stepwise Alternating Field Demagnetization

The remanent magnetization of the samples from the sedimentary sequence was mainly measured by using a cryogenic magnetometer, 2G-760R, which has an automatic alternating field demagnetization (AF) system Some samples were studied with a spinner magnetometer (Natsuhara, SMM-85)

The remanent magnetization of sediment in the cores shows the intensity of 10^{-4} to 10^{-6} Am^2/kg At first, the stability of magnetization of the sediment is examined by a stepwise AF demagnetization experiment using the pilot samples selected from every 50 cm for each core. The stepwise AF field from 5 to 80 mT (or 85 mT) with the increment of 5 mT steps is applied on these samples.

Figure 3 shows examples of AF demagnetization data of samples with stable magnetization, represented in both Schmidt's equal area projection net and a ZIJDERVELD (1967) diagram In Schmidt's net, closed circles show the magnetization vector with downward inclination, and open circles show the magnetization with upward inclination. We can identify, in each Zijderveld diagram, the straight line crossing the plotted demagnetization steps The line going to the origin shows that the stable remanent magnetization was acquired at deposition.

Several samples show secondary acquired magnetization Most of the secondary magnetization is demagnetized by the AF field up to 15 mT, however, in some samples, the stable magnetization component cannot be found by AF demagnetization.

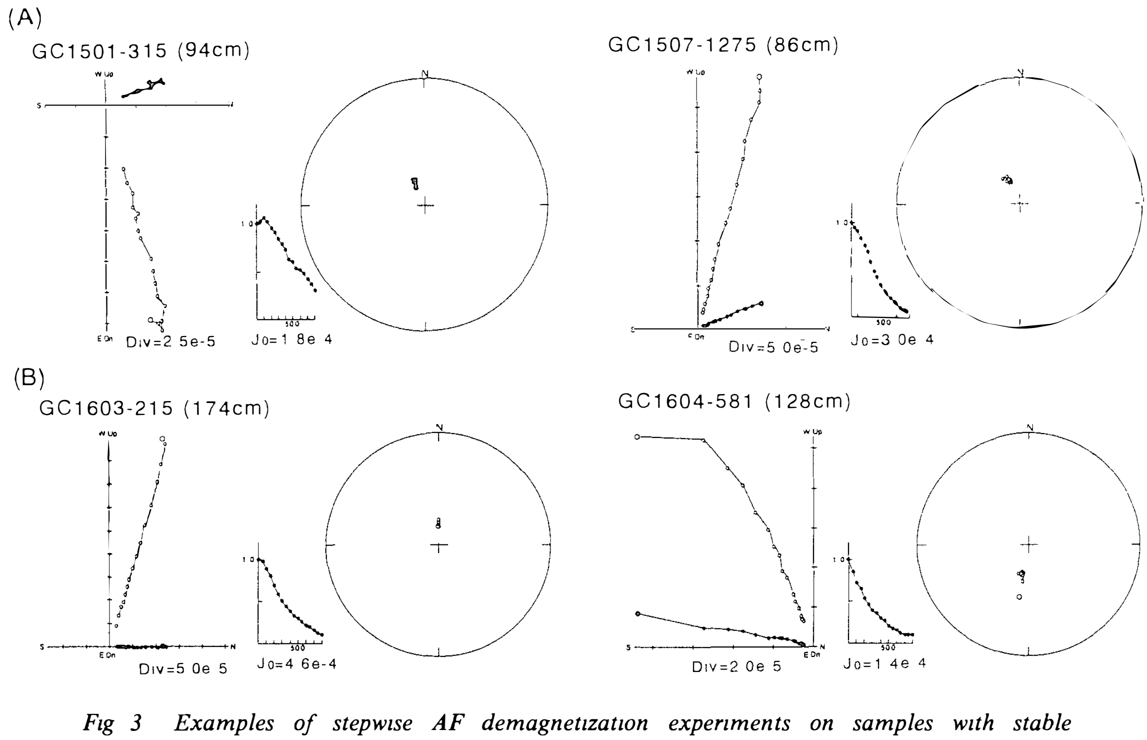

Fig 3 Examples of stepwise AF demagnetization experiments on samples with stable magnetization, represented on Schmidt's net and Zijderveld diagrams
(A) Samples from Central Wilkes Land margin
(B) Samples from Dumont d'Urville Sea and Victoria Land Basin
The stepwise AF field from 5 to 80 mT (85 mT for sample GC1507-1275) with increments of 5 mT step was applied to these samples

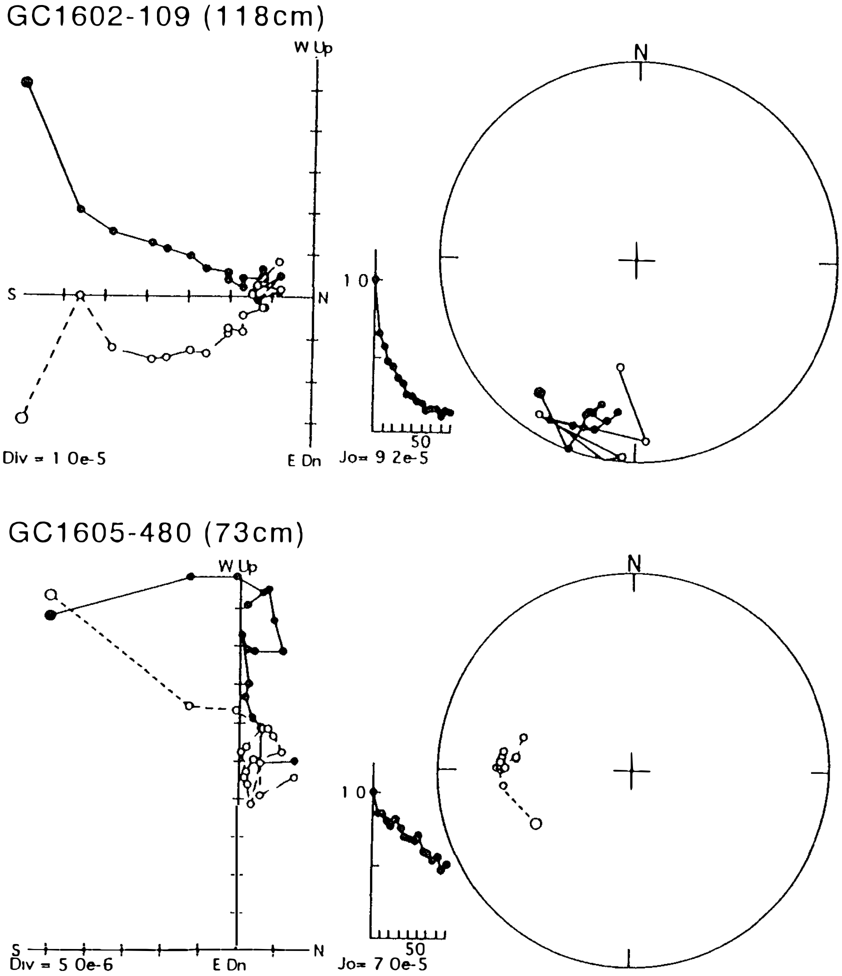

Fig 4. Examples of a stepwise AF demagnetization experiment for samples with unstable magnetization represented in Schmidt's net and Zijderveld diagram.

Figure 4 shows examples of the AF demagnetization result for samples with unstable remanent magnetization. Samples of the cores GC1506, GC1602 and GC1605 especially show such unstable magnetization.

As the secondary magnetization in most of the pilot samples can be eliminated by a demagnetization field of less than 15 mT AF, the residual samples are demagnetized at 15 mT, 20 mT and 30 mT AF. After examining the AF demagnetization results, the 30 mT AF data set was mainly used for discussion.

4. Paleomagnetic Results of Cores from Central Wilkes Land Margin

4.1. Magnetostratigraphy

Figures 5 and 6 show the inclination change with depth for cores of the Central Wilkes Land margin. The inclination data after demagnetization at 30 mT AF are used. Cores GC1505, GC1506, GC1508 and GC1509 in Fig. 5 have only normal (negative) inclination, which suggests that the ages of the cores are Brunhes geomagnetic normal epoch (< 0.78 Ma). The magnetostratigraphy of CANDE and KENT (1995) is referred to

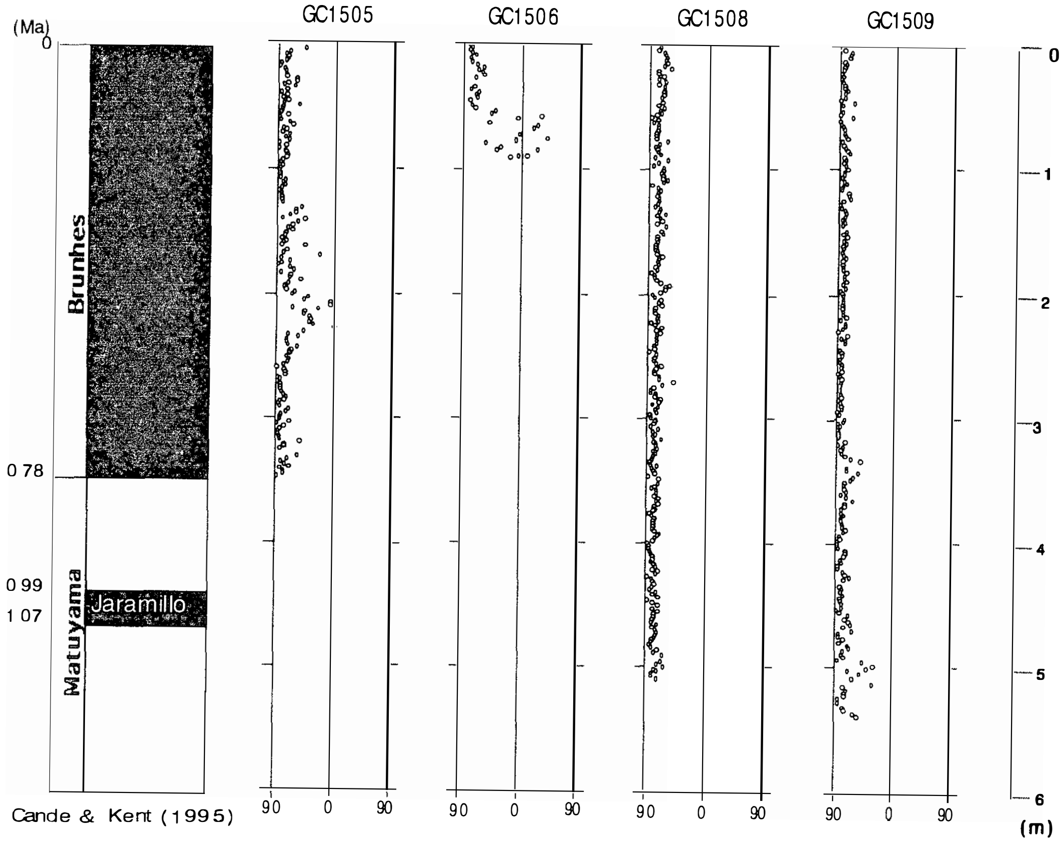

Fig 5 Inclination of remanent magnetization with depth for the four cores at the Central Wilkes Land margin, exhibiting only normal magnetic inclination Data after 30 mT AF demagnetization are used On the left, the magnetostratigraphy of CANDE and KENT (1995) is shown

Cores GC1501, GC1502, GC1503, GC1504 and GC1507 in Fig 6 show reversed (positive) inclination regions, which are interpreted to be the Matuyama reversed polarity epoch. In these five cores, both the Brunhes/Matuyama boundary (B/M boundary, 0 78 Ma) and the top of the Jaramillo event (0.99 Ma) are identified. In cores GC1502, 1504 and 1507, the bottom of Jaramillo (1 07 Ma) is also found.

A disturbed inclination region exists at depth around 2–3 m in cores GC1502 and GC1503, however, Af demagnetization shows that the magnetization of that region is fairly stable. It is possible that a mechanical disturbance occurred in that region during the drilling.

Table 2a shows the region of the core corresponding to the magnetostratigraphically dated period and the variation of the sedimentation rate for each core

The sedimentation rate is a few mm/ky so that one measured sample covers the 5 to 8 ky margin, which is adequate to find a geomagnetic short event or excursion However, no reliable reversed inclination zone is found in the Brunhes epoch (<0 78 Ma) for the studied cores. Especially, core GC1501 with stable magnetization shows successive normal inclination, and the average value agrees with that calculated from the axial eccentric geomagnetic dipole Paleomagnetic study of ODP site 745 (59.6°S, 85 9°E) in the southern Indian Ocean showed a successive geomagnetic reversal history

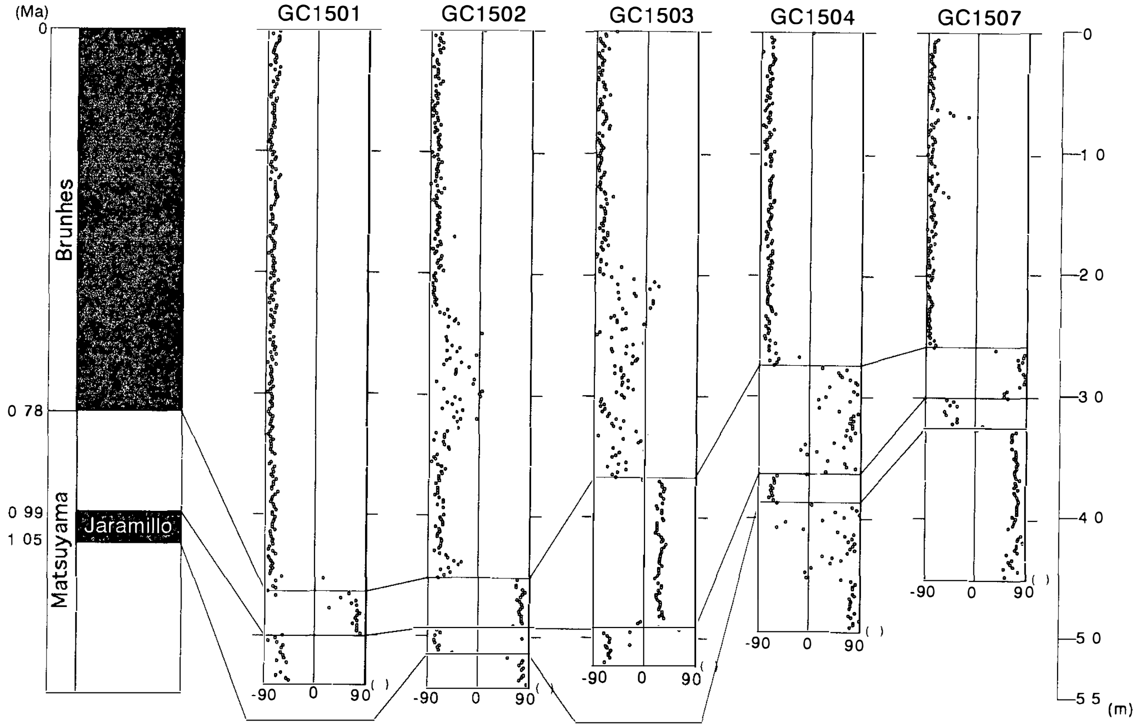

Fig 6 Inclination data with depth for five cores exhibiting reversed magnetization in Central Wilkes Land margin Data after 30 mT AF demagnetization are used On the left, the magnetostratigraphy of CANDE *and* KENT *(1995) is shown.*

covering the past 5 Ma; however, a short reversal event could not be identified during the Brunhes epoch (SAKAI and KEATING, 1991).

These results suggest the possibility that the short-period reversal may not appear clearly during the Brunhes epoch in the southeastern Antarctic Ocean, which may be related to low activity of the non-dipole component in this area.

4.2. Sedimentation rate

Figure 7 shows the sedimentation rate of each core, where the age of the top and bottom of geomagnetic reversal event is plotted as the abscissa with the core depth as the ordinate. It is possible that the uppermost region of the core was lost in the drilling. The drilling description shows that the lack of the core is not serious, so that in the figure, we assumed the age of the coretop to be the present. The age by analysis of diatom fossils determined from the same core (ISHIHARA *et al.,* 1996) is compared in each figure. The two data sets are fairly consistent in GC1502, 1503 and 1507. In GC 1501 and 1504, the age by diatom fossils is systematically slightly older than the magnetostratigraphically dated age. The average sedimentation rate calculated by magnetostratigraphical age is over 5 mm/ky for GC1501, 1502 and 1503, and that for GC1507 is lower than 3 mm/ky.

In Fig 8, the sedimentation rates for each magnetostratigraphical age (Table 2a) are plotted on the location map. This figure shows the spatial distribution of variations in the sedimentation rate, which is a useful method of evaluating sedimentary environments. Off the Budd Coast (GC1501, 1502 and 1507), the rate during the Brunhes

Table 2a Regions of cores corresponding to periods dated by magnetostratigraphy, and the variation of sedimentation rates in cores from the Central Wilkes Land margin

Core No	Region of core (cm)	Age (Ma)	Sedimentation rate (mm/ky)
GC1501	0–464	0–0 78	5 9
	464–496	0 78–0 99	1 6
	496–538	0 99–<1 07	>6 2
GC1502	0–454	0–0 78	5 7
	454–494	0 78–0 99	2 0
	494–518	0 99–1 07	3 2
	518–540	1 07–<1 78	>0 3
GC1503	0–330	0–0 78	4 2
	330–486	0 78–0 99	7 8
	486–522	0 99–<1 07	>5 1
GC1504	0–276	0–0 78	3 5
	276–364	0 78–0 99	4 4
	364–392	0 99–1 07	4 0
	392–492	1 07–<1 77	>1 4
GC1505	0–347	0–<0 78	>4 7
GC1506	0–114	undetermined	
GC1507	0–261	0–0 78	3 3
	261–297	0 78–0 99	1 8
	297–327	0 99–1 07	2 8
	327–440	1 07–<1 77	>1 7
GC1508	0–509	0–<0 78	>6 7
GC1509	0–537	0–<0 78	>6 8

epoch and the Jaramillo event is faster than the rate of the period from top of the Jaramillo to the B/M boundary On the other hand, GC1503 and GC1504 off of the Sabrina Coast show that the sedimentation rate during the period from top of Jaramillo to B/M boundary is faster than the rate in other periods.

Thus, the local and time difference of sedimentation rate may be related to the change of sedimentation circumstances, *i.e.*, the change of ocean current, glacial-interglacial change etc

5. Magnetostratigraphy and Sedimentation Rate of Cores from Dumont d'Urville Sea and Victoria Land Basin

Figure 9 shows the variation of inclination after 30 mT AF with depth in five cores A magnetic reversal was detected in two cores, GC1602 and 1603. In the figure, the appropriate B/M boundary for these cores is drawn.

Figure 10 compares the curves showing the sedimentation rates estimated by paleomagnetic methods and the analysis of diatom and radiorалian fossils, for the magnetostratigraphically dated cores In the figure, the age of the core-top is assumed to be the present The curves for GC1602 are much different The description of the

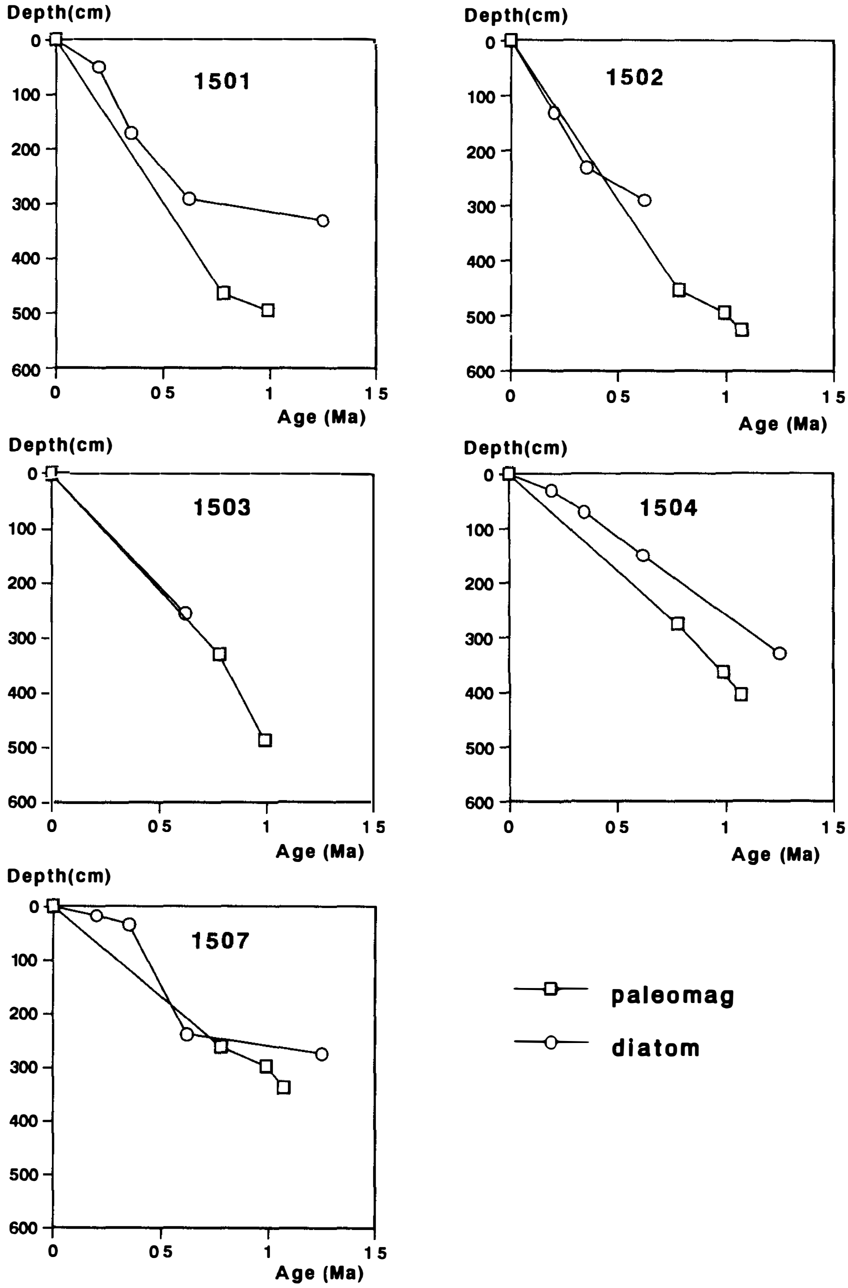

Fig. 7. Sedimentation rate of each core estimated from the paleomagnetic method and dating by diatom fossils

sediment suggests that the difference may be caused by the re-sedimentation process, which may also be the reason for the scattered inclination Therefore, the B/M boundary for GC1602 in Fig. 9 is not conclusive. Sedimentation curves for GC1603 are fairly consistent; the sedimentation rate in Brunhes epoch is estimated as 4.5 mm/ky. Table 2b shows the sedimentation rate estimated by the paleomagnetic method for each core.

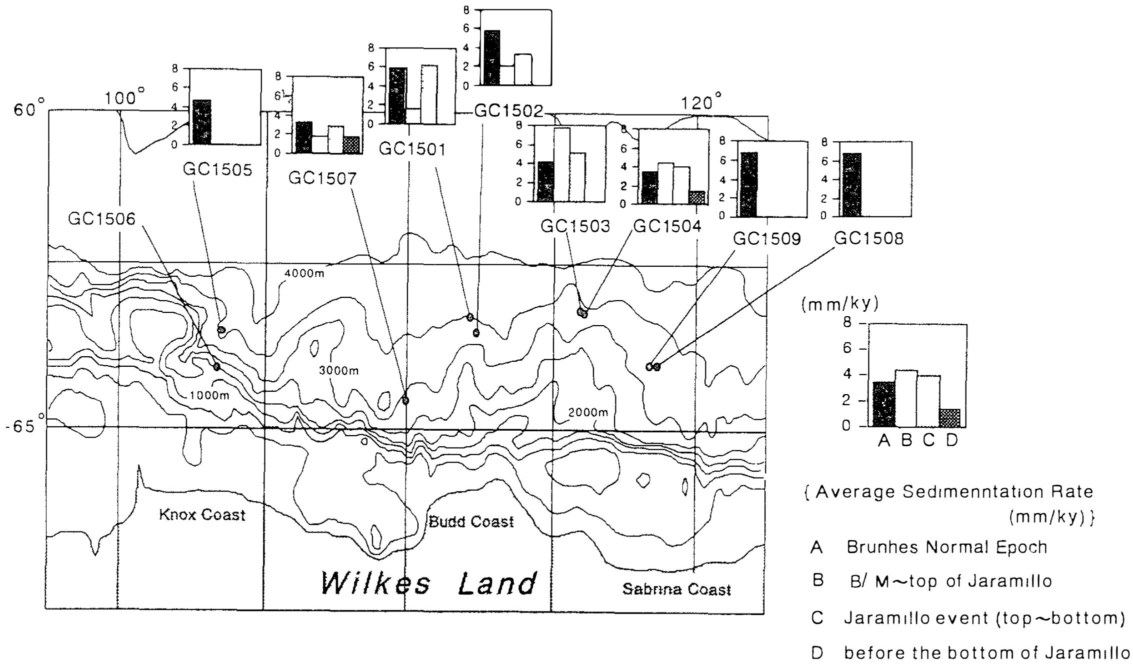

Fig 8 The sedimentation rate of each period in Table 2a plotted on a map of the Antarctic Ocean

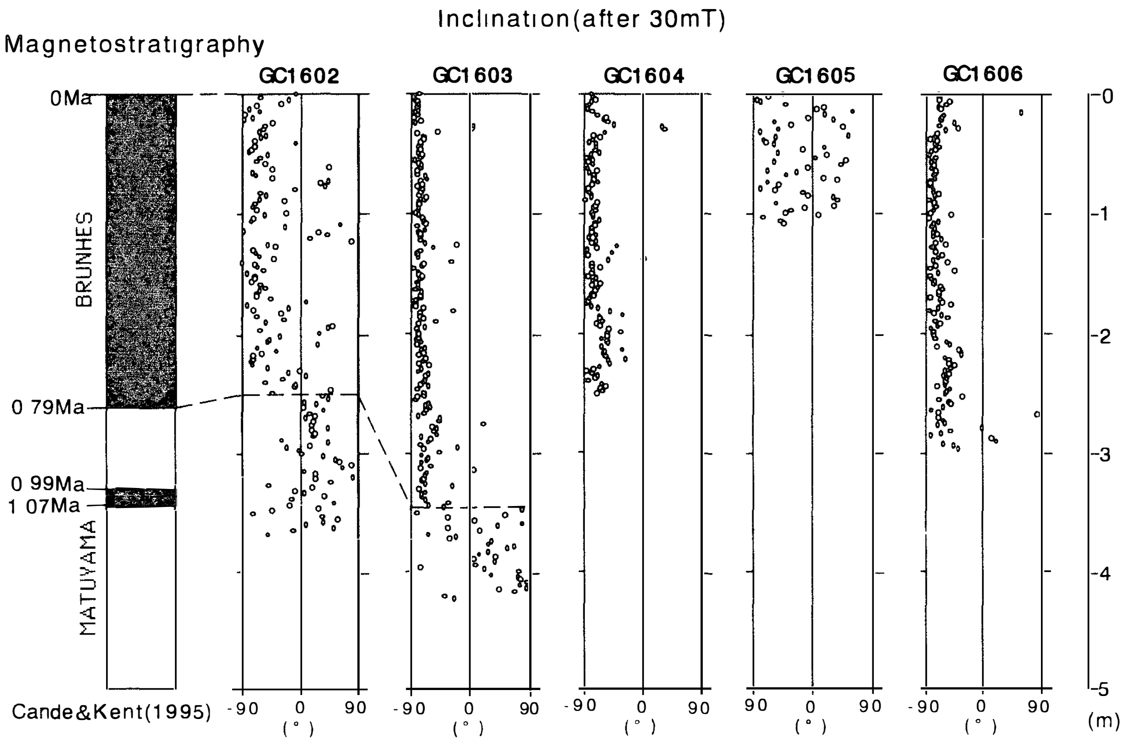

Fig 9 Comparison of the inclination data of five cores in Dumont d'Urville Sea and Victoria Land Basin On the left, the magnetostratigraphy of CANDE and KENT (1995) is shown

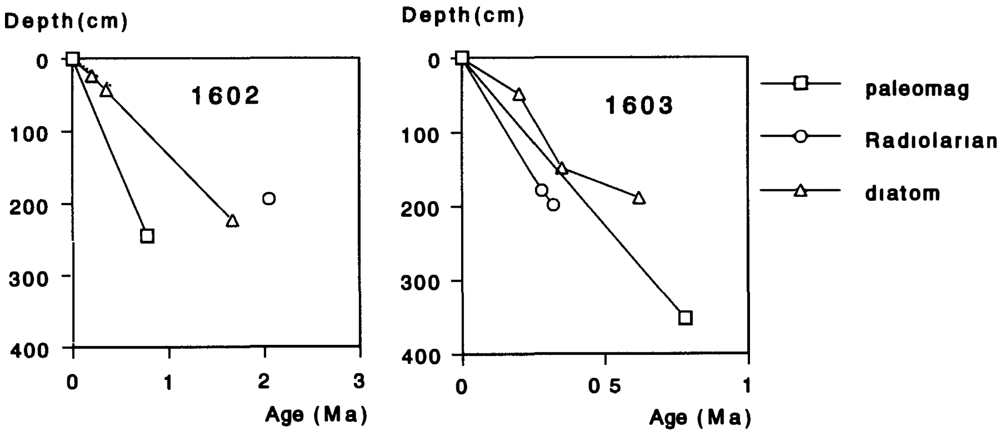

Fig. 10. Sedimentation rate estimated from paleomagnetic method and the analysis of fossils in cores GC1602 and GC1603.

Table 2b. Regions of cores corresponding to periods dated by magnetostratigraphy, and the variation of sedimentation rates in cores from Dumont d'Urville Sea and Victoria Land Basin.

Core No.	Region of core (cm)	Age (Ma)	Sedimentation rate (mm/ky)
GC1602	0–245	0–0.78	3.1?
	245–370	0.78–<0.99	>5.9?
GC1603	0–352	0–0.78	4.5
	352–430	0.78–<0.99	>3.7
GC1604	0–245	0–0.78	>3.2
GC1605	0–107	undetermined	
GC1606	0–296	0–0.78	>3.7

6. Rock Magnetic Properties

6.1. Study of susceptibility

Magnetic susceptibility was measured using a Bartington MS-2 susceptibility meter. Figure 11 compares the susceptibility variation with depth for five magnetostratigraphically dated cores at the Central Wilkes Land margin. The average susceptibility does not differ through the sequence. There is a tendency for the upper sequence younger than 0.4 Ma to show a larger variation in amplitude than the lower sequence. A similar tendency of the susceptibility variation is found in GC1603 from the Victoria Land Basin (Fig. 11C). The variation in the upper sequences of cores GC1501–GC 1503 has large amplitude, and seems to be similar to the change in SPECMAP (IMBRIE and IMBRIE, 1980).

The frequency dependence of susceptibility is examined from measurements at high frequency (HF, 4.6 kHz) and at low frequency (LF, 0.46 kHz). Figure 12 shows the variation of frequency dependence (FD: ((LF-HF)/LF)×100) with depth. Generally, a single-domain magnetic mineral changes its magnetic direction more easily, when acted on by the impressed high frequency alternating magnetic field, than a multi-

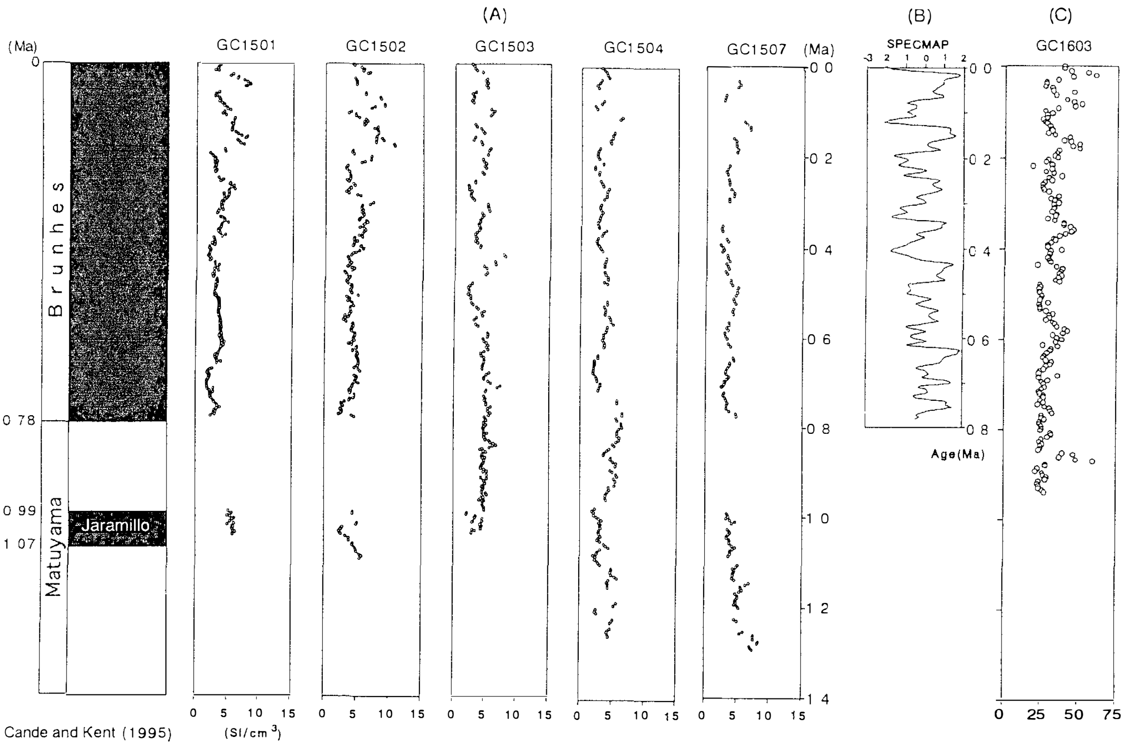

Fig 11 (A) Changes of susceptibility with depth for the five cores from Central Wilkes Land margin
(B) SPECMAP (IMBRIE and IMBRIE, 1980)
(C) Change of susceptibility for core GC1603 in Victoria Land Basin

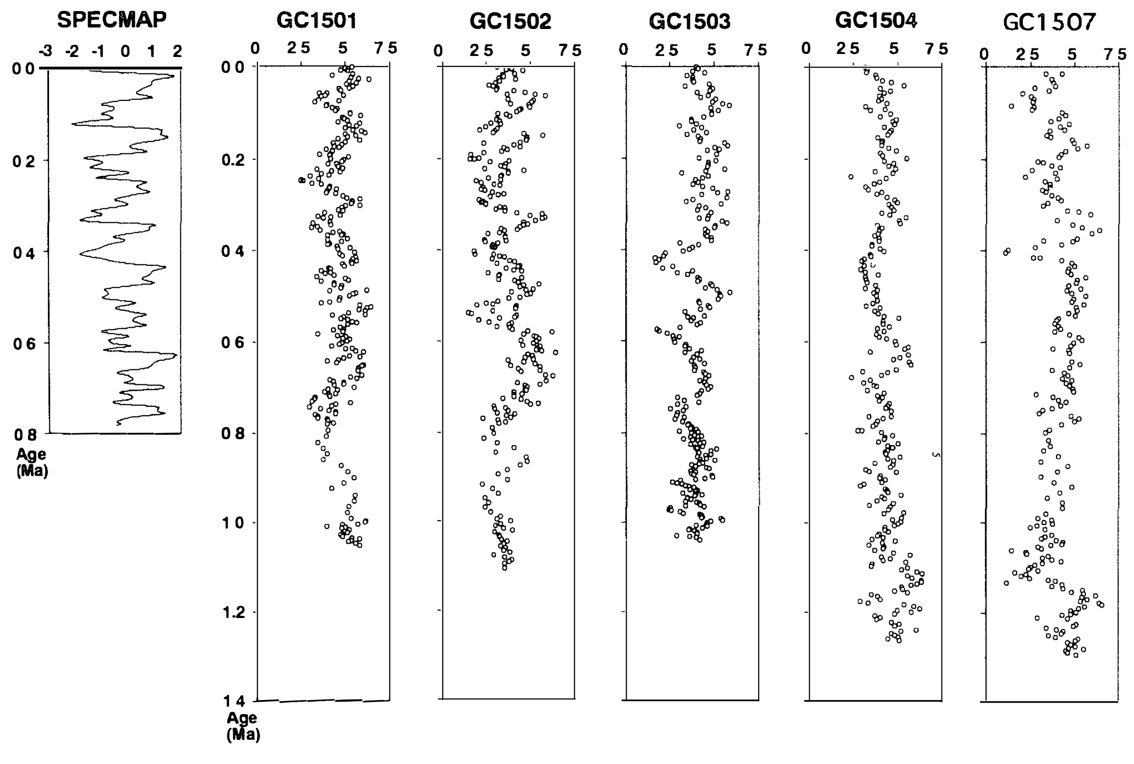

Fig 12 Change in the frequency dependence of susceptibility among the five cores from Central Wilkes Land margin

domain (larger) mineral, so that the FD for a multi-domain mineral is larger than that for a single-domain mineral (YAMAZAKI and KATSURA, 1990). That is, FD is useful in discussing the grain sizes of magnetic minerals. In Fig. 12, the variation of FD for the upper sequence (<0.4 Ma) is similar to that of susceptibility for each core. This suggests that the grain size of magnetic mineral changes in the sequence is related to the variation of content of magnetic minerals.

The domain structures of magnetic minerals in several samples were studied by magnetic hysteresis analysis using the MPMS (Quantum Design) of Toyama University. Figure 13 shows the data plotted on the diagram of DAY *et al.* (1977). This figure indicates that the preferred domain structure of the magnetic minerals in the studied sediment is a pseudo-single domain (PSD) and/or multi domain structure. The lower

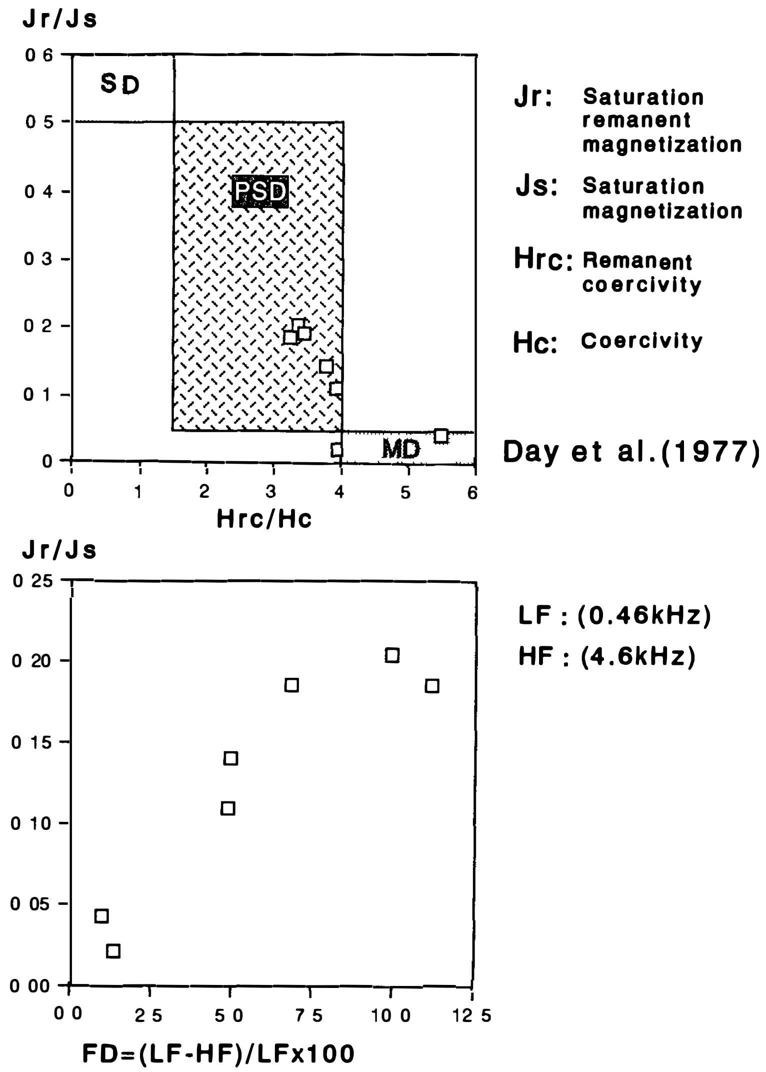

Fig 13 Magnetic domain structure studied on core GC1505
(A) Plots of the hysteresis parameters on the diagram by DAY et al (1979) SD, single domain, PSD, pseudo-single domain, MD, multi domain.
(B) Size dependence estimated by hysteresis analysis compared with that by the frequency dependence of susceptibility.

figure compares the *Jr/Js* (*Jr*: saturation remanent magnetization, *Js*: saturation magnetization) with FD There is a tendency for a plot with low *Jr/Js* (PSD-like particle) to show high FD (small magnetic mineral) This supports the result of the above discussion by FD study, concerning the change in particle size of magnetic minerals in the sedimentary sequence.

The amplitude of variation in susceptibility decreases around age 0.4 Ma, however, the average value and FD show no such distinct change This suggests that the variation of the content of magnetic minerals in the sediment increases its amplitude after 0.4 Ma, which can be correlated with the change of sedimentary environment in the southeastern Antarctic Ocean

MAASCH (1988) suggests that there was a transition of global climate pattern around 0.4 Ma Also, the study of physical properties in lake sediment shows that the cyclic variation with the period of 0.1 Ma increased its amplitude in past 0.4 Ma (KASHIWAYA, private communication) In the future, we need to examine the susceptibility change from the viewpoint of such a global environmental change around 0 4 Ma

6.2. Time variation of normalized intensity of remanent magnetization

Figure 14A shows the time variation of normalized remanent magnetization intensity by susceptibility for the five magnetostratigraphically dated cores in the Central Wilkes Land margin The normalized intensity of each core shows a distinct decrease

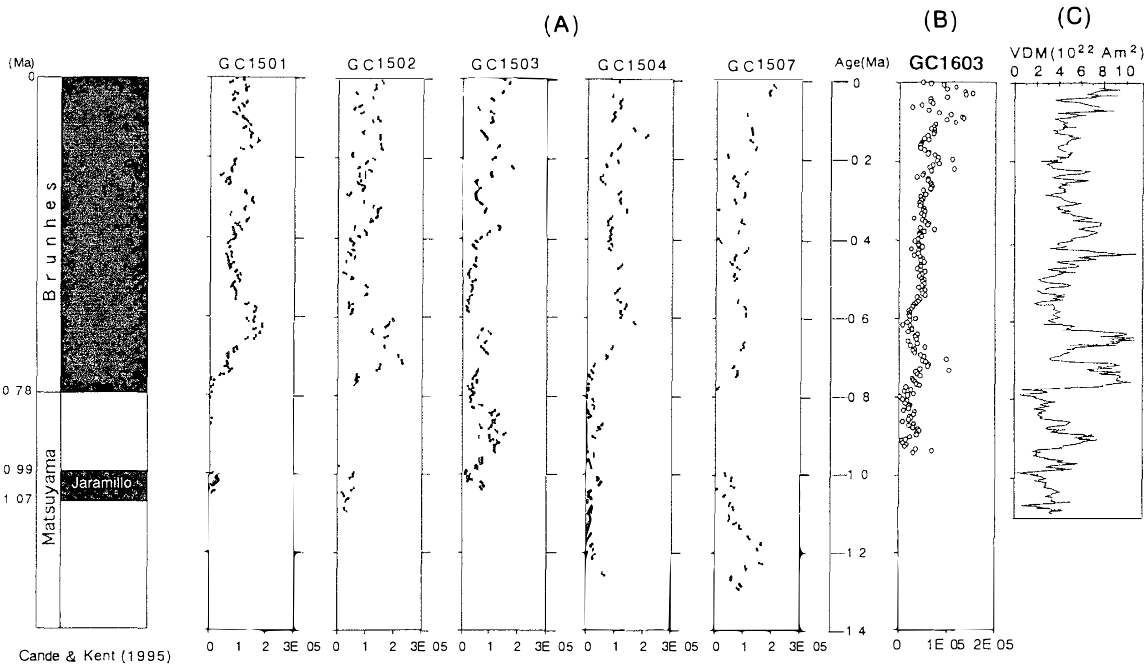

Fig 14 (A) Change of normalized intensity of remanent magnetization at the Central Wilkes Land margin
(B) Change of normalized intensity of remanent magnetization with depth for GC 1603 in Victoria Land Basin
(C) Variation of VADM with time for the sedimentary sequence of ODP cores Sites 848b and 851 in the Pacific Ocean (after VALET and MEYNADIER, 1993)

around the B/M boundary, and the value is much higher in the Brunhes epoch than in the Matuyama epoch. A similar pattern is found in the change of GC1603 in Victoria Land Basin (Fig. 14B).

VALET and MEYNADIER (1993) summarized the magnetic intensity and inclination data of the sedimentary sequence of ODP cores at Sites 848b and 851 in the Pacific Ocean, and calculated their effect on the variation of the virtual axial dipole moment of geomagnetic eccentric dipole (VADM) with time. Their results (Fig. 14C) show that the abrupt decrease of VADM around the B/M boundary and also that the VADN in the Brunhes normal polarity epoch was stronger than the value in the Matuyama reversed polarity epoch. The obtained magnetic intensity variation in this study is similar to their results. We consider that such a feature is caused by a global change of geomagnetic field intensity. For detailed discussion, we need to use other methods to estimate the geomagnetic intensity from remanent magnetization of sediments, for example using ARM and SIRM experiments.

7. Summary

Paleomagnetic study was conducted on the sediment cores of several m length obtained from the southeastern Antarctic Ocean.

For the nine cores of Central Wilkes Land margin, the Brunhes/Matuyama magnetic polarity boundary (0.78 Ma) and the top of the Jaramillo event (0.99 Ma) were identified in five cores, and the bottom of the Jaramillo event (1.07 Ma) was found in three cores. The assigned magnetostratigraphic age shows the sedimentation rate ranging between 3 and 5 mm/ky. The spatial distribution of variations in the sedimentation rate suggests a local difference between area off the Budd Coast and area off the Sabrina Coast. For the five cores from the Dumont d'Urville Sea and Victoria Land Basin in the western Ross Sea, the B/M boundary is detected in core GC1603, of which the average sedimentation rate during the Brunhes epoch is estimated to be 4.5 mm/ky.

The susceptibility variation with depth has been studied. The upper sequence younger than 0 4 Ma shows variation with larger amplitude than that of the lower sequence; however, the average and frequency dependence of susceptibility does not show such a distinct change. This suggests that there was a change of sedimentary environment in the southeastern Antarctic Ocean at 0.4 Ma, which may be correlated with a global climate change.

The magnetic intensity normalized by susceptibility shows a distinct decrease around the B/M boundary. The normalized intensity is much higher in the Brunhes epoch than that in the Matuyama epoch. The result is similar to the variation of VADM studied by VALET and MEYNADIER (1993) using ODP cores in the Pacific Ocean. The obtained result suggests a global change of geomagnetic field intensity, between the Matuyama reversed polarity epoch and the Brunhes normal polarity epoch. For detailed discussion, we should use other methods such as ARM and SIRM experiments to reliably estimate the geomagnetic intensity.

This study indicates that detailed paleomagnetic study using the sedimentary sequence from the Antarctic Ocean is important for the general understanding of geomagnetism and the paleo-environment.

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