Note on the Natural Remanent Magnetizations of Dirt-Ice Layers Collected from the Bare Ice Field in East Antarctica

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東南極大陸の裸氷域から採集された火山灰を含む氷層の自然残留磁気

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要旨: 東南極サウスビクトリアランドのアランヒルズ，東クィーンモードランドのやまと山脈及びセールロンダーネ山脈の裸氷域表面から採集された5試料の火山灰を含む氷 (dirt-ice) の持つ自然残留磁気 (NRM) の性質を調べた．これらの試料は 1.38–22.1×10^{-7} Am^2/kg の磁化強度を持ち，交流消磁に対し少なくとも 50 mT まで安定であった．NRM は肉眼で認められる dirt-ice 層にのみ認められ，いわゆる普通の南極氷からは，意味ある磁気は測定されなかった．Dirt-ice 層内での NRM の方向は一定であったが，その強度は試料によって，また層内の場所によって異なった．方向の記録された試料の持つ NRM の方向は，採集地点の現在の地磁気方向とほとんど同じであった．このことは，dirt-ice 層中の磁性粒子が，太陽ふく射による粒子周辺の氷の融解により回転し，その NRM が現在の地磁気方位に再配列した可能性を示している．

***Abstract*:** Natural remanent magnetizations (NRMs) of 5 dirt-ice layers including tephra collected from the Allan Hills in Southern Victoria Land, the Yamato Mountains and the Sør Rondane Mountains in Eastern Queen Maud Land, East Antarctica, were investigated. The NRMs with 1.38 to 22.1×10^{-7}Am^2/kg in intensity were very stable against AF demagnetization at least up to 50 mT. The magnetic layers consisted with the dirt-ice layers recognized by the naked eye, but magnetizations in the clear-ice were weak for any significant measurements. The uniform NRM directions were obtained in the dirt-ice layers with upward directions. Those of the oriented 2 samples (A, E) were almost parallel to the present geomagnetic field direction *in situ*. So, a possible mechanism is rearrangement of the magnetic grains adjusting the NRM directions to the geomagnetic field direction due to partial melting of the ice around the grains by the solar radiation.

1. Introduction

Colored ice (dirt-ice) layers including tephra were first described in ice cores of the Ross Ice Shelf drilled at Little America V by Gow (1963). They were further reported from bear ice fields and drilled ice cores from Southern Victoria Land (KEYS *et al.*, 1977: NISHIO *et al.*, 1984; KATSUSHIMA *et al.*, 1984; KATSUSHIMA and NISHIO, 1985), Marie Byrd Land (GOW and WILLIAMSON, 1976; KYLE and JEZEK, 1978), Dome C (KYLE *et al.*, 1981) and Queen Maud Land (NISHIO *et al.*, 1984; KATSUSHIMA *et al.*,

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1984; KATSUSHIMA and NISHIO, 1985) in Antarctica.

FUNAKI and NAGATA (1985) described the natural remanent magnetization (NRM) of a dirt-ice layer collected from the Allan Hills in Southern Victoria Land. The NRM (2.5×10^{-8} Am^2/kg) was fairly stable against AF demagnetization and showed a quite uniform direction in the layer toward the present geomagnetic field direction *in situ*. Although the tilting correction was performed referring to the stratum of the dirt-ice layer (11°), the direction did not shift away from the geomagnetic field (GMF) direction. So, it was difficult to identify when and where the NRM was acquired. However, they pointed out that the NRM direction was useful for the analysis of glacial movement and for the detection of tephra in drilled cores without destroying the sample.

We obtained newly 4 dirt-ice samples from the Allan Hills, the Yamato Mountains and the Sør Rondane Mountains in Eastern Queen Maud Land. The fundamental NRM characteristics of the dirt-ice layers are reported using the new and previous samples in this paper.

2. Samples

A block of the dirt-ice sample was collected by NISHIO and ANNEXSTADE (1980) from the Allan Hills (77°S, 160°E). The NRM was already described by FUNAKI and NAGATA (1985). Two pillared samples (A and A′) elongated vertically were prepared from the block. Sample A was cut into 18 sliced samples (A1 to A18, about 1 cm in thickness) 19.7–22.1 g in weight and sample A′ was cut into cubical 5 samples (A′1 to A′5) 32.4–34.9 g in weight. The dirt-ice layer of 8 cm in thickness was sandwiched between A6 and A14 samples (between 6 cm and 14 cm in depth from the surface) in sample A. The layer was recognized in every sample from A′1 to A′5 with 8 cm in total thickness.

Sample B of 12 cm in thickness was collected by the author in 1979 from the Allan Hills near the sampling site of the sample A but from a different layer. It was cut into 13 samples (B1 to B13) 12.1 to 34.3 g in weight. The dirt-ice layer was recognized throughout the whole sample by the naked eye.

Sample C consisting of the dirt-ice layer was collected by F. NISHIO in 1982 from the Yamato Mountains (72°S, 35°E). A cubical sample (C1) of 3.4 cm in thickness (40.9 g) was prepared.

Sample D of 16.5 cm in thickness was collected by Y. FUJII in 1984 from the Yamato Mountains. The sample was cut into 8 samples (D1 to D8) 6.1 to 12.6 g in weight. The dirt-ice layer was clearly recognized from surface (D1) to 14.5 cm (D7) in thickness.

Sample E was collected by N. AZUMA and S. FUJITA in 1989 from the Sør Rondane Mountains (72°S, 23°E). Three pillared samples elongated vertically were cut into 8 cubical samples respectively (E1 to E8, E′1 to E′8 and E″1 to E″8) with their weight 42.2 to 58.6 g. The clearly defined dirt-ice layer of 12 cm in thickness with the strike N20°W and dip 11°W of stratum was contained between E4 (E′4, E″4) and E6 (E′6, E″6), while E3 (E′3, E″3) included it partially at the bottom of the sample.

The dirt-ice layer in sample A was colored dark brown, while other samples had the layers of slight yellow in color recognized faintly by the naked eye. Samples A and E were recorded with the orientations but only upward direction was defined for samples B and C. However, any direction was not recorded for sample D. These samples have not melted up to the present as is indicated by the existing of air bubbles in the samples. The sampling sites were situated at about 1800 to 2000 m above sea level, where only dry snow can exist at such elevations even in the summer season (SHIMIZU *et al.*, 1978). The tephra included in the dirt-ice layer was 0.194 wt% for sample A and 0.0021 wt% for sample B. That of other samples may be quantitatively

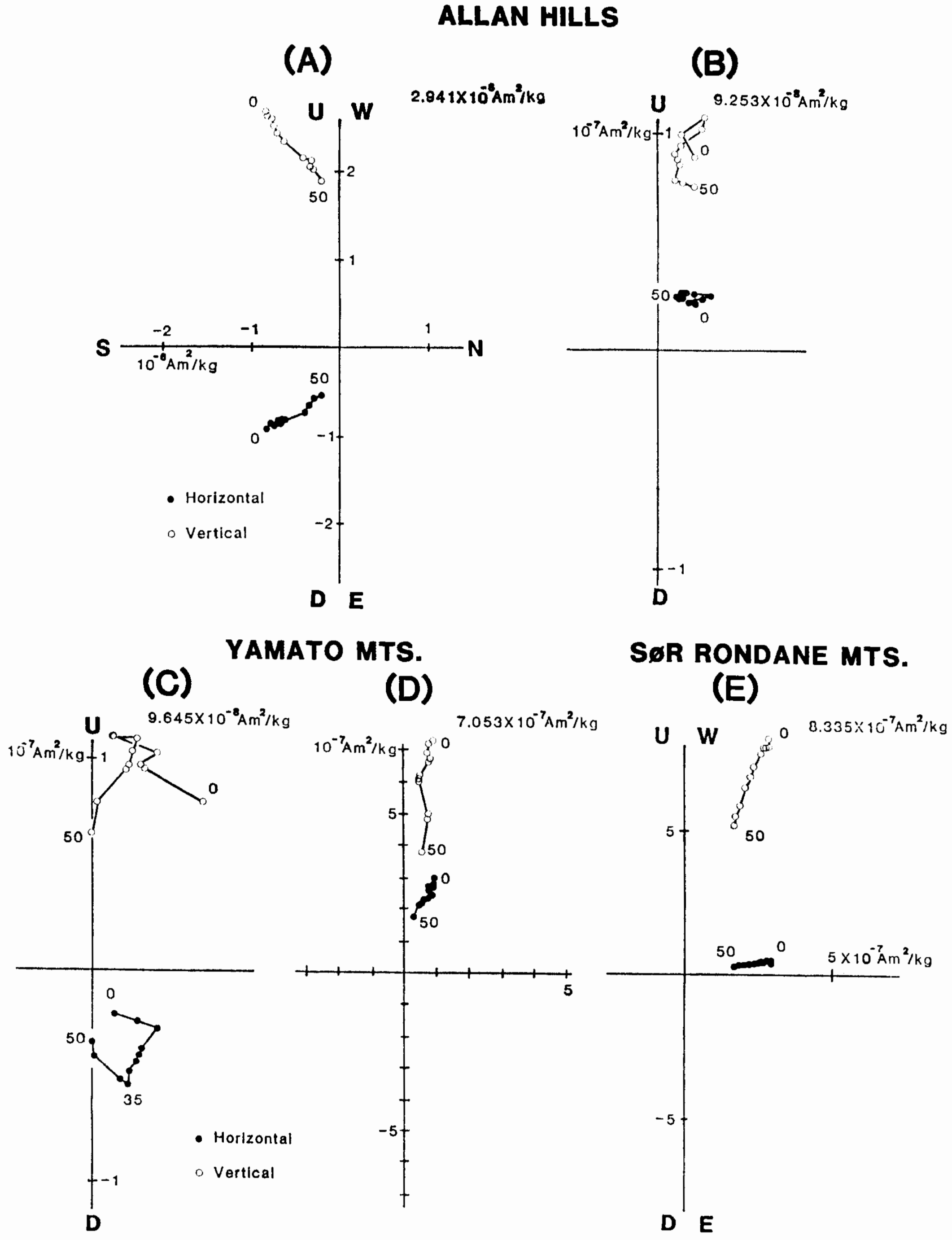

Fig. 1. AF demagnetization curves projected to the Zijderveld diagram. Adjusted inclination and declination for samples (A) and (E), adjusted inclination for the samples (B) and (C), direction not adjusted the direction for sample (D).

of the same order as sample B, inferred from their color. The surface of sliced or cubical samples were washed by distilled water after cutting the samples by a saw.

3. AF Demagnetization Properties

Representative cubical samples having the dirt-ice layer were demagnetized by alternating magnetic field up to 50 mT at intervals of 5 mT. They were cooled down to about −50°C by liquid nitrogen before demagnetized. A simplified AF demagnetization method (one axis demagnetization) was applied for 20 to 30 s in order to save the demagnetization time. The NRMs were measured with a 3-axis cryogenic magnetometer for less than 10 s. So, the samples did not melt during the experimental procedure.

The AF demagnetization curves projected to the Zijderveld diagram are shown in Fig. 1. The abscissae of the horizontal projection for samples B and C could not be adjusted due to the lack of information about the north direction. The coordinate of sample D was decided by an optional plain on account of the lack of directional information. The NRM intensities of these samples ranged from 0.93 to $29.4 \times 10^{-7}\,\mathrm{Am^2/kg}$ as denoted in the respective figures.

Samples A and E were magnetized to the upward direction (normal inclination) with an only single component of the hard NRM up to 50 mT. Their NRMs were decayed gradually toward the center or axes of the coordinates. Samples B and C were also magnetized to upward direction with the soft and hard NRM components. The soft component demagnetized by 10 mT of sample D was gradually demagnetized with a single component of the hard NRM up to 50 mT.

4. NRM of the Dirt-Ice Layers

Mean NRM intensity (R), inclination (I), declination (D), precision (K) and confidence of 95% probability (α_{95}) before and after AF demagnetization to 10 mT for samples A, B and D, 35 mT for sample C and 20 mT for sample E are listed in Table 1, where the R value was obtained from the samples having the tephra throughout the samples. Variation profiles of the NRM intensity from the top to bottom of samples A, B, D and E are illutstrated in Fig. 2.

Table 1. NRM directions of the dirt-ice layers.

	Sampling site	N	R	I	D	K	α_{95}	R^*	I^*	D^*	K^*	α_{95}^*
A	Allan Hills	14	22.1	−68.5°	164.0°	246	2.6°	22.8	−65.0°	165.0°	347	2.1°
B	Allan Hills	13	1.38	−85.6	(320.7)	60	5.4	1.32	−86.5	(318.7)	184	3.1
C	Yamato Mts.	1	4.94	−46.2	(106.6)	—	—	4.85	−50.8	(120.7)	—	—
D	Yamato Mts.	7	4.24	(−79.5)	(110.9)	60	7.8	—	—	—	—	—
E	Sør Rondane Mts.	12	7.08	−65.2	342.4	79	4.9	6.54	−66.2	350.0	78	5.0

Unit of R: $10^{-7}\,\mathrm{Am^2/kg}$

*: After AF demagnetization to 10 mT samples A, B and D, 35 mT for sample C and 20 mT for sample E.

( ): Relative inclination or declination.

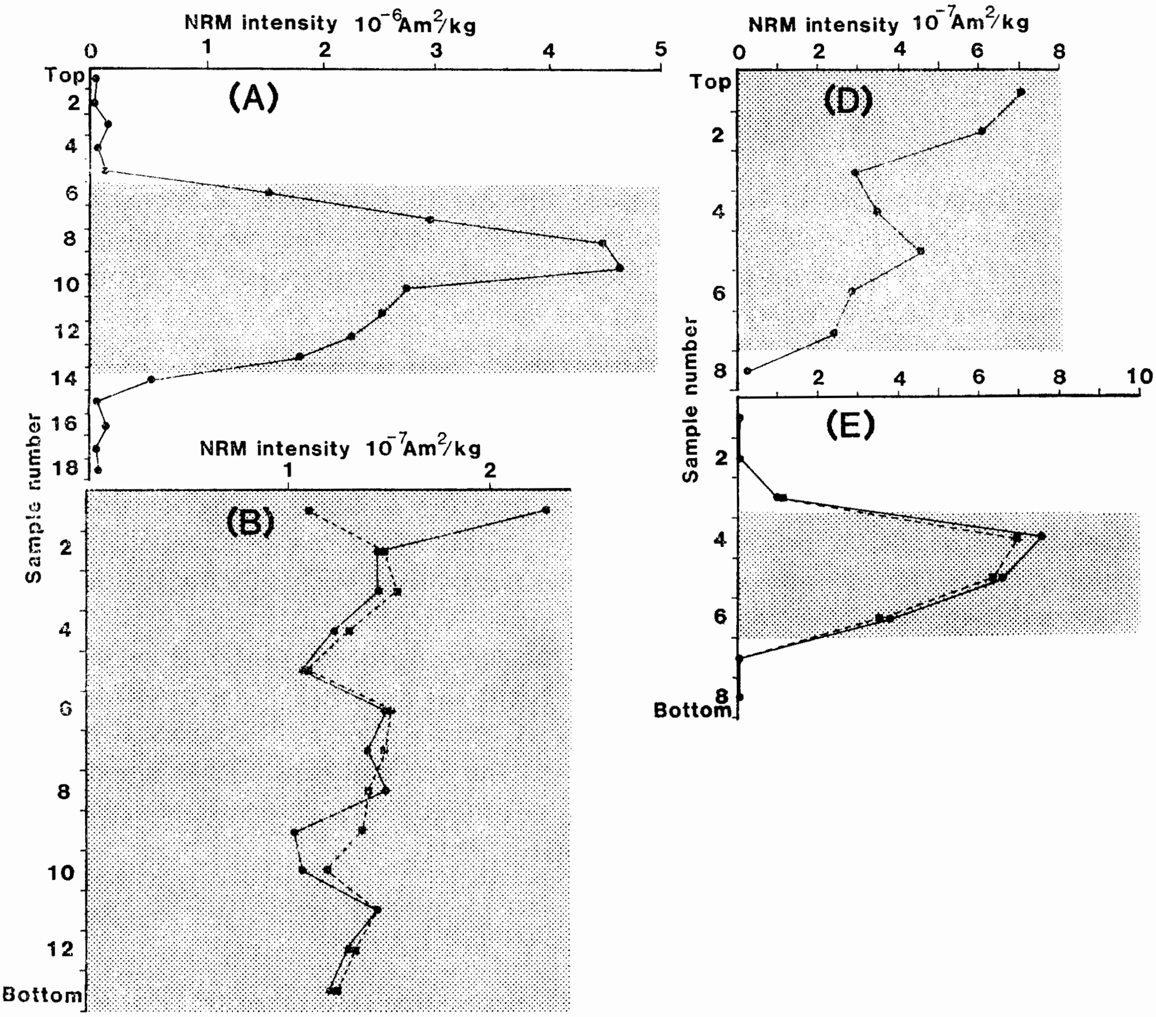

Fig. 2. Variation profiles of the NRM intensities from the top to the bottom of the samples. Solid line and circle: original NRM variations. Dotted line and solid square: NRM variations after AF demagnetizations. Shadow: visible dirt-ice layer. (A) and (B) from the Allan Hills, (D) from the Yamato Mountains, (E) from the Sør Rondane Mountains.

The NRM of sample A was measured between samples A6 and A14. It appeared suddenly and decayed with double steps. The peak intensity (4.7×10^{-6} Am^2/kg) in sample A9 was obtained from the center of the dirt-ice layer, while insignificant magnetizations ($<2\times10^{-7}$ Am^2/kg) were found in the clear-ice from A1 to A5 and from A15 to A18 samples. The NRM directions of the 14 samples (A6–A14, A1′–A5′) clustered clearly as reported by FUNAKI and NAGATA (1985). They converged to $I=-65.0°$ and $D=165.0°$ with $\alpha_{95}=2.1°$ by AF demagnetization to 10 mT.

Sample B consisted of 13 samples which showed a zigzag variation of the NRM intensities (1.02 to 1.52×10^{-7}Am^2/kg) with homogeneous directions, except surface's sample B1 (2.27×10^{-7}Am^2/kg), as shown in Fig. 2. The NRM of the B1 agreed with that of others after AF demagnetization to 10 mT. The directions of the original NRM clustered with $\alpha_{95}=5.4°$ and they converged to $I=-86.5°$ ($D=318.7°$ of relative declination) with $\alpha_{95}=3.1°$.

Sample D showed a zigzag variation profile of the NRM intensities (7.1–2.4 × 10^{-7} Am^2/kg) from samples D1 to D7, but very weak insignificant NRM was found in D8 (3.1 × 10^{-8} Am^2/kg). The original NRM directions of the 7 samples resemble each other as $\alpha_{95} = 7.8°$. Although every sample was not demagnetized by the optimum field, the directions may further converge taking the AF demagnetization result into account.

The NRM of sample E1 was recognized between samples E3 and E6. The intensities of the central part were 6.4 to 7.5 × 10^{-7} Am^2/kg, but any measurable NRMs (< 10^{-9} Am^2/kg) could not be obtained from samples E1, E2, E7 and E8. The pattern of the intensity variations after AF demagnetization to 20 mT almost coincides with those of original samples. Characteristics of the NRM intensities of samples E, E′ and E″ were essentially consistent with each other. Figure 3 shows the NRM directions obtained from the 12 samples (E3–E6, E′3–E′6, E″3–E″6) before and after the demagnetization and a tilting correction. The mean directions of the original samples clustered near the GMF direction with upward inclination and they shifted slightly eastward by AF demagnetization to 20 mT, although they were not separated considering their α_{95} values. When the tilting correction referring to the stratum was performed to the NRM direction ($I = -66.2°$, $D = 350.0°$) after AF demagnetization, it shifted away to $I = -55.3°$, $D = 12.9°$. Their directions completely separated from each other considering their α_{95} values.

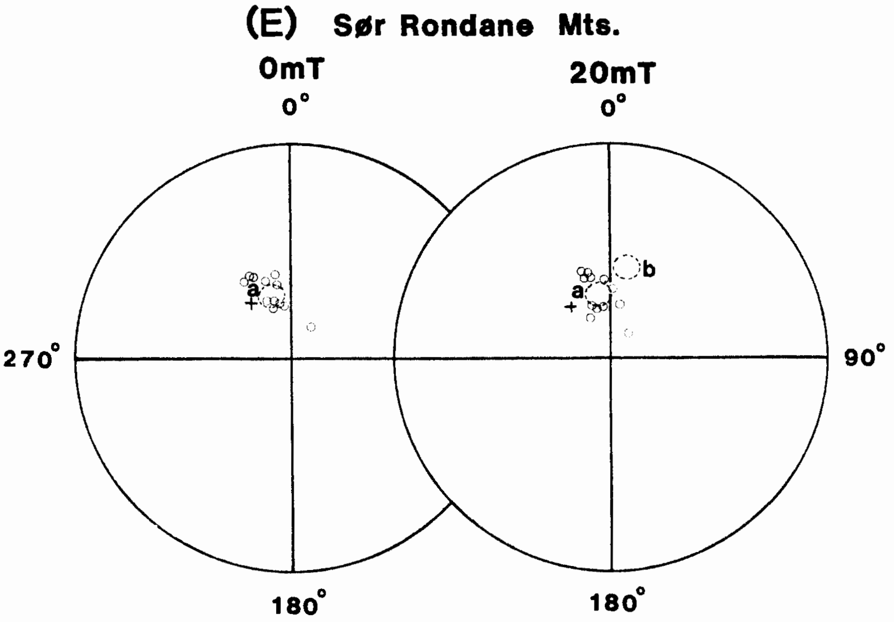

Fig. 3. Distributions of the NRM directions of the samples from the Sør Rondane Mountains before (left) and after (right) AF demagnetization to 20 mT. Open circles: upward inclination, cross: the present geomagnetic field direction in situ, ellipse a (b): α_{95} level before (after) tilting correction. Equal area projection.

5. Discussion

The NRM were measured only in the dirt-ice layers identified by the naked eye. The intensities of the layers ranged from 1.38 to 4.94 × 10^{-7} Am^2/kg for the sample B to

E which were slightly colored in yellow. It suggests that if the dirt-ice layer is recognized visually, the NRM intensity can be measured at least as 10^{-7}Am^2/kg at the center.

As the NRM of the dirt-ice was carried by the tephra of about 0.1 to 0.0021 wt% in this case, the intensity, 22.1×10^{-7}Am^2/kg for sample A and 1.38×10^{-7}Am^2/kg for sample B, can be converted into order of 10^{-3}Am^2/kg for the tephra. This intensity is comparable to the NRM of strongly magnetized sediments. The NRM directions were fairly uniform throughout in the dirt-ice layer. These NRM characteristics are completely consistent with the results reported by FUNAKI and NAGATA (1985).

According to YAMADA and WAKAHAMA (1981), the snow accumulation rate increased from 10 to 30 g/cm^2/a in the altitude range of 2000 to 2800 m of Mizuho Plateau. In general, the rate is very small in inland Antarctica. As the density of the Antarctic ice is estimated to be 9.3 g/cm^3 (NAKAWO and NARITA, 1985), an ice layer of 1 to 3 cm in thickness is added every year to the Antarctic ice sheet. Therefore, the dirt-ice layers of 8 to 14 cm in thickness used in this study are equivalent to the total mass of several years.

The tephra was reported as less than 210 μm in diameter from the Allan Hills (KATSUSHIMA and NISHIO, 1985) and 100 μm from the Yamato Mountains (NISHIO *et al.*, 1984). Residence time of these large tephra particles in air seems to be less than several years. Probably the tephra accumulated on Antarctica in a relatively short time, but it diffuses into the inner layer to form a thick dirt-ice layer. During this diffusing process, the NRMs of the magnetic grains may be aligned to the GMF direction based on NRM acquisition mechanisms proposed by SAKAI and FUNAKI (1987).

Every dirt-ice layer has very stable NRM against AF demagnetization up to 50 mT. Although the samples were stored at -20°C with random directions during several months to years, they (except sample D) kept upward NRM inclinations ($I=-46.2°$ to $-85.6°$) which are comparable with the inclination of the GMF ($-55°$ to $-90°$) in the Antarctic region. These results suggest that remagnetization and restriction of magnetic grain's movement during the storage are impossible. So the NRM may not have been disturbed up to the present after sampled from Antarctica. The NRM directions after AF demagnetization of sample A ($I=65.0°$, $D=15.0°$) and E ($I=-66.2°$, $D=350.0°$) were similar to the GMF directions at the Allan Hills, $I=-82°$, $D=150°$ (FUNAKI and NAGATA, 1985) and at the Sør Rondane Mountains, $I=-64°$, $D=324°$ (Fig. 3). The NRM directions after the tilting correction were clearly isolated from the GMF in both cases. In general, these NRM characteristics can be explained by remagnetizations after tilting of the layers, although folding tests for the NRM should be done in order to elucidate when, where and how the NRMs were acquired.

However, the following three kinds of explanation may be possible at present for the consistency of the NRM and GMF directions. (1) The NRMs of samples A and E were almost parallel with the GMF directions by the tilting of the dirt-ice layers. Probably the possibility is very small, because the consistency is casual. (2) The magnetic grains turn round to the GMF direction after the accomplished tilting which adjusted their NRM directions by the interaction of the magnetic momentum without melt of ice. However, there is no useful information to support this explanation glaciologically. (3) The grains turned to GMF direction under the partial melting of ice around the magnetic grains by the solar radiation when the layers came up to the surface, but the ice does not melt as a whole. The dirt-ice layers of samples A and E were overlaid with clear-ice layers of 5 cm and 10 cm in thickness respecitvely which are not completely transparent due to scattering of the small bubbles. There is no information whether the solar radiation affects the dirt-ice layers through the clear-ice with bubbles in inland Antarctica. However, rearrangement of the magnetic grains has been confirmed in an artificial ice where the magnetic grains through one centimeter of transparent ice turn round to the GMF direction easily adjusting NRM without melting ice as a whole by infrared rays (SAKAI *et al.*, 1990). NAKAO (1977) reported that only spherical bubbles were observed in the ice of the Langhovde Glacier (Prince Olav Coast) between the surface and 45 cm depth, while elongated bubbles existed in that ice deeper than 45 cm. He attributed the phenomenon to the effect of the solar rediation. Taking this result into consideration, the NRMs of the dirt-ice layers used in this study may have been acquired recently due to rearrangement of the magnetic grains by the interaction of magnetic momentum on the surface of Antarctica as explained in (3). The NRMs of the layers showed that the interior ice sheet must be measured for establishment of the dirt-ice paleomagnetism.

6. Conclusion

The dirt-ice layers have the hard NRM components associated with the minor soft ones against AF demagnetization, but the clear-ice showed only insignificant magnetization due to very weak intensity. Uniform NRM directions appeared in the dirt-ice layer, although the intensities varied (1.38 to $22.1\times10^{-7}\mathrm{Am^2/kg}$) with the layers and the samples. Two samples (A, E) from the Allan Hills and the Sør Rondane Mountains showed almost parallel NRM directions to the present GMF direction, and other 2 samples (B, C) have upward inclination of middle to high angle. It seems therefore that the magnetic grains were recently rearranged adjusting the NRM directions to the geomagnetic field direction. Plausible rearrangement might occur by the interactions of magnetic momentum under the partially melting ice around the magnetic grains due to the solar radiation.

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