Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 37–47, 1986

PRELIMINARY STUDIES OF NATURAL REMANENT MAGNETIZATION OF THE ROCKS COLLECTED FROM ONGUL ISLANDS, EAST ANTARCTICA

Minoru FUNAKI[1] and Peter WASILEWSKI[2]

[1]*National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173*
[2]*Goddard Space Flight Center, NASA, Greenbelt, Maryland 20771, U.S.A.*

Abstract: A total of 331 rock samples collected from East and West Ongul Islands were studied paleomagnetically. Pyroxene gneiss and the majority of the garnet gneisses have unstable natural remanent magnetization (NRM), whose directions are similar to the present geomagnetic field in the Syowa Station area. These unstable NRMs can be related to the existence of pyrrhotite. Hornblende gneiss, the other garnet gneisses, granite, amphibolite, silicious rocks and pegmatite dykes have stable NRM. Magnetic carriers in stable rocks are considered to be iron oxide minerals (magnetite and hematite).

The formations over a wide area of the Lützow-Holm Bay region were magnetized at the final stage of metamorphism about 480 Ma ago in a reversed geomagnetic field direction, then granite intrusions occurred during a period of normal geomagnetic field conditions. The time interval of this sequence may not be very long from the consideration of virtual geomagnetic pole (VGP) positions. Our result of VGP positions (latitude 20.2°S, longitude 20.7°E) supports previous paleomagnetic results obtained from the Lützow-Holm Bay region and from East Antarctica for early Paleozoic time. VGP positions are located in low latitudes near the present-day Africa.

1. Introduction

East and West Ongul Islands, 69.0°S latitude and 39.5°E longitude, are located in Lützow-Holm Bay, along the Prince Olav Coast of Enderby Land, East Antarctica. These islands situated in the northeast of the Lützow-Holm Bay region, are separated from the Prince Olav Coast by the 5 km wide Ongul Strait. Syowa Station of the Japanese Antarctic Research Expedition (JARE) is located on the north coast of East Ongul Island.

Results of geological investigations of East and West Ongul Islands performed by TATSUMI and KIKUCHI (1959a, b), KIZAKI (1962, 1964), YANAI *et al.* (1974a, b) and ISHIKAWA (1976), are shown in Fig. 1. They concluded that the metamorphic basement rocks in this area consists dominantly of older granulite and younger intrusive rocks. The granulite lithologies number pyroxene, hornblende, garnet gneisses, and metabasite, and the intrusive rocks are pegmatite dykes and granite. Formation strikes for the gneisses are NE in the eastern part of East Ongul Island and from N to NNW in the western part of East and West Ongul Islands. Although the ages of the original sedi-

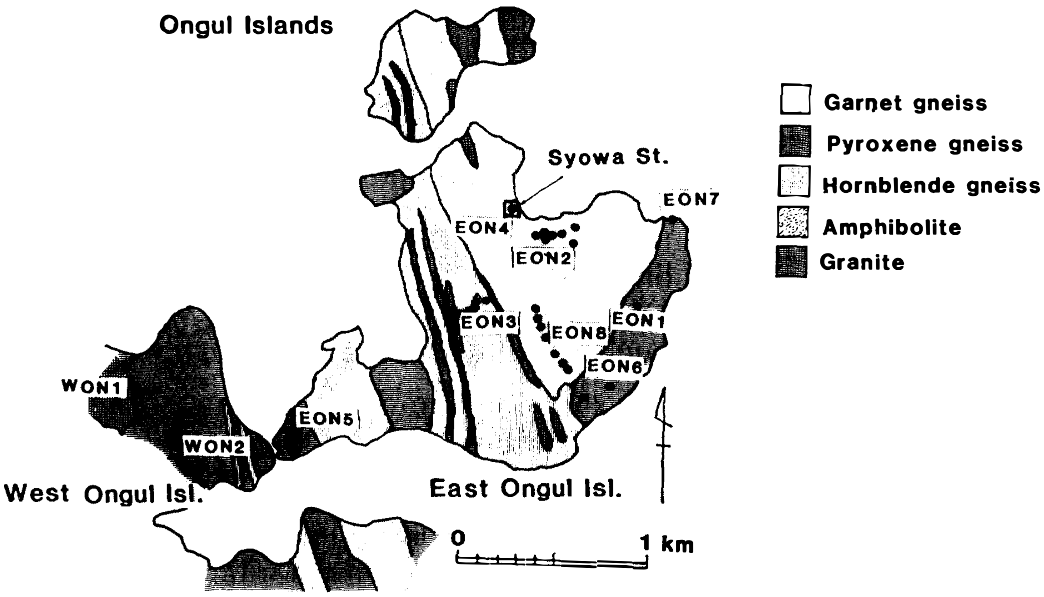

Fig. 1. Geological map and sampling sites of East Ongul Island and the eastern part of West Ongul Island in Lützow-Holm Bay.

mentary rock precursors of some of the granulites have not been determined, the time of metamorphism is estimated to be from 560 to 387 Ma by the K-Ar method (KANEOKA *et al.*, 1968; YANAI and UEDA, 1974) and from 726 to 465 Ma by the Rb-Sr method (NICOLAYSEN *et al.*, 1961; MAEGOYA *et al.*, 1968).

Paleomagnetic studies of rocks obtained from East and West Ongul Islands were carried out by NAGATA and SHIMIZU (1959, 1960), NAGATA and YAMA-AI (1961) and KANEOKA *et al.* (1968). They obtained several general conclusions: (1) samples with magnetic reversed polarity have stable natural remanent magnetization (NRM) but samples with normal polarity have unstable directions and weak NRM intensity. (2) The NRM direction is represented by an inclination of 58.0° and a declination of 335.7°, with a calculated virtual geomagnetic pole (VGP) position of latitude 18.2°S and longitude 19.6°E (NAGATA and SHIMIZU, 1959, 1960).

The present authors collected a total of 331 samples, using a 1-inch core engine drill, in East Ongul Island and in the eastern part of West Ongul Island. The collecting was done during the 1983–84 austral summer season as part of the JARE-25 geologic field program. Eight sampling sites in East Ongul and two in West Ongul Islands, are indicated in Fig. 1. These sampling sites covered every representative formation in this area.

2. AF Demagnetization

Several representative samples from each site were AF demagnetized up to 500 Oe in 50 Oe steps. Figure 2 shows typical NRM AF demagnetization curves for stable and unstable samples. Generally, pyroxene gneiss from sites EON1, 6 and 7 and garnet gneiss from EON2 and 4 have very unstable NRM's; the intensities decay steeply initially and then the directions shift widely in no apparent pattern. The unstable

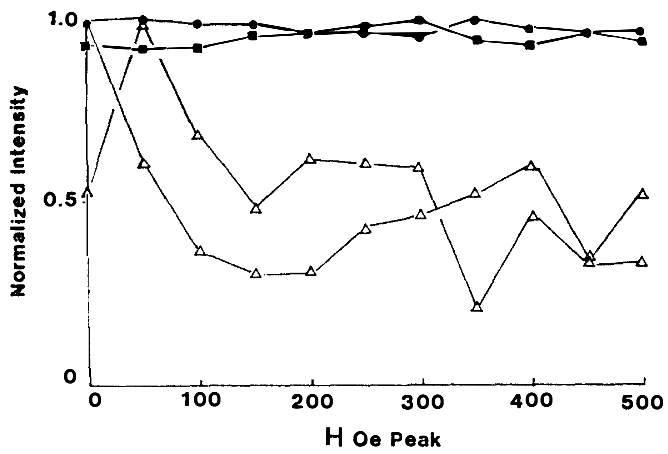

Fig. 2. Representative AF demagnetization (AF demagnetization to 500 Oe) curves for stable (solid circle and square) and unstable NRM (open triangle).

samples are originally magnetized in the normal direction (upward). Some samples of garnet gneiss from EON8 have stable NRM's, magnetized in the reversed direction, but others have unstable directions of normal polarity similar to the samples from EON2. Metabasite nodules of less than 1 m in diameter and pyrrohotite ore held in pyroxene and hornblende gneisses have stable NRM during demagnetization to 500 Oe. Compared with these pyroxene and garnet gneisses, the hornblende gneiss from EON3, granite from EON3, 5 and WON1 and pegmatite dyke from EON7 have fairly stable NRM's during demagnetization; their intensities show almost no decay and the directions exhibit a small shift. The polarity of these stable samples is normal for granite from WON1 and reversed for all the others. Amphibolite and silicious rocks at WON2 have stable NRM's of mixed polarity.

3. Mean NRM Directions

Based on the results of detailed AF demagnetization tests of representative samples, a decision was made to subject other samples to a demagnetizing field of 100 Oe. The results are summarized in Table 1. Original intensities of NRM, $I_n(0)$, are as strong as 20.39×10^{-5} emu/g for hornblende gneiss and as weak as 0.038×10^{-5} emu/g for amphibolite. Ratios of $I_n(0)$ to the NRM intensities after AF demagnetization to 100 Oe, $I_n(100)$, are almost 1 for pyroxene gneiss from EON7, hornblende gneiss, amphibolite with silicious part from WON2 and pegmatite. Other samples lose more than 30% of the initial NRM intensity by 100 Oe demagnetization. In general, samples with unstable NRM components are magnetized in normal directions which are almost parallel to the present geomagnetic field in the Syowa Station area. They lose up to several tens of percent of the NRM intensity by 100 Oe demagnetization.

Figure 3 illustrates examples of NRM direction changes before and after AF demagnetization to 100 Oe. Figure 3a is an example for unstable pyroxene gneiss from EON1. Originally many of the samples are magnetized to a steep inclination of normal

Table 1. Natural remanent magnetizations of the rocks and sites in East and West Ongul Islands.

Rock types	Site	No.	N/R	$I_n\,(0)_{E-5}$	$I_n\,(100)$ emu/g	$I_n\,(0)/(100)$	X_{E-5} emu/g/Oe	Minerals
Pyroxene gneiss	EON 1	29	N	1.348	0.688	0.510	0.603	
	6	31	N	0.984	0.484	0.492	0.664	
	7	9	N	0.887	0.827	0.932	0.558	
	Aver.	69	N	1.124	0.615	0.547	0.625	Pyrrhotite
Garnet gneiss	EON 2	133	N	6.200	1.688	0.272	2.133	
	4	10	N	4.308	0.981	0.228	0.798	
	8	53	N/R	0.399	0.243	0.609	0.604	
	Aver.	196	N	4.535	1.261	0.278	1.651	
Hornblende gneiss	EON 3	50	N	20.386	20.795	1.020	5.015	
Amphibolite	WON 2	20	N/R	0.038	0.038	1.019	0.549	
Granite	EON 5	10	N	6.476	2.346	0.362	15.834	Iron oxide
	WON 1	18	R	6.147	2.494	0.406	17.593	
	Aver.	28	N/R	6.265	2.441	0.390	16.965	
Pegmatite	EON 7	7	N	0.182	0.183	1.006	0.346	
Total		331		5.742	3.801	0.662	2.989	

polarity, resembling the present geomagnetic field direction, and these NRM directions scatter widely by 100 Oe demagnetization. (Although metabasite lenses have stable NRM against AF demagnetization, their initial NRM directions scatter widely.) Figure 3b is a mixture of unstable samples of normal polarity and stable samples of reversed NRM observed in the samples of garnet gneiss from EON8. Some of the reversed samples cluster in the quadrant bound by 270° to 0° declination. Figure 3c is hornblende gneiss from EON3 exhibits the highest coherency. Almost all samples have reversed polarity, and most cluster tightly initially and after 100 Oe demagnetization. Figure 3d illustrates the systematic distribution from high to low inclinations constrained in the declination range of about 270°–60°. This is observed for samples of amphibolite and silicious rocks from WON2.

The mean NRM directions of stable components for each site were calculated statistically and are tabulated in Table 2. NRM directions were selected for coherency in order to evaluate optimal cluster at a site. For example, although the directions of 37 samples from EON8 appeared to scatter widely by 100 Oe AF demagnetization, a total of 16 chosen samples contribute to a cluster of reversed polarity in the quadrant bound by 270° to 0° of declination. This coherency persists even after demagnetization as shown in Fig. 3b. Tabulation (in Table 2) of dema, Inc, Dec, K, α_{95}, pLat and pLon parameters identified as AF demagnetization field intensity, inclination and declination of mean NRM, precision, 95% confidence, paleo-latitude and -longitude, respectively, summarize the paleomagnetic results. The results show that NRM directions obtained from 5 sites are essentially parallel or anti-parallel. Clustering of NRM directions is better or almost the same by AF demagnetization to 100 Oe for EON3, 5, 8 and WON1, but is slightly worse for WON2. As the samples from WON2 have mixed polarity of variable inclinations, the scattering is probably related to the com-

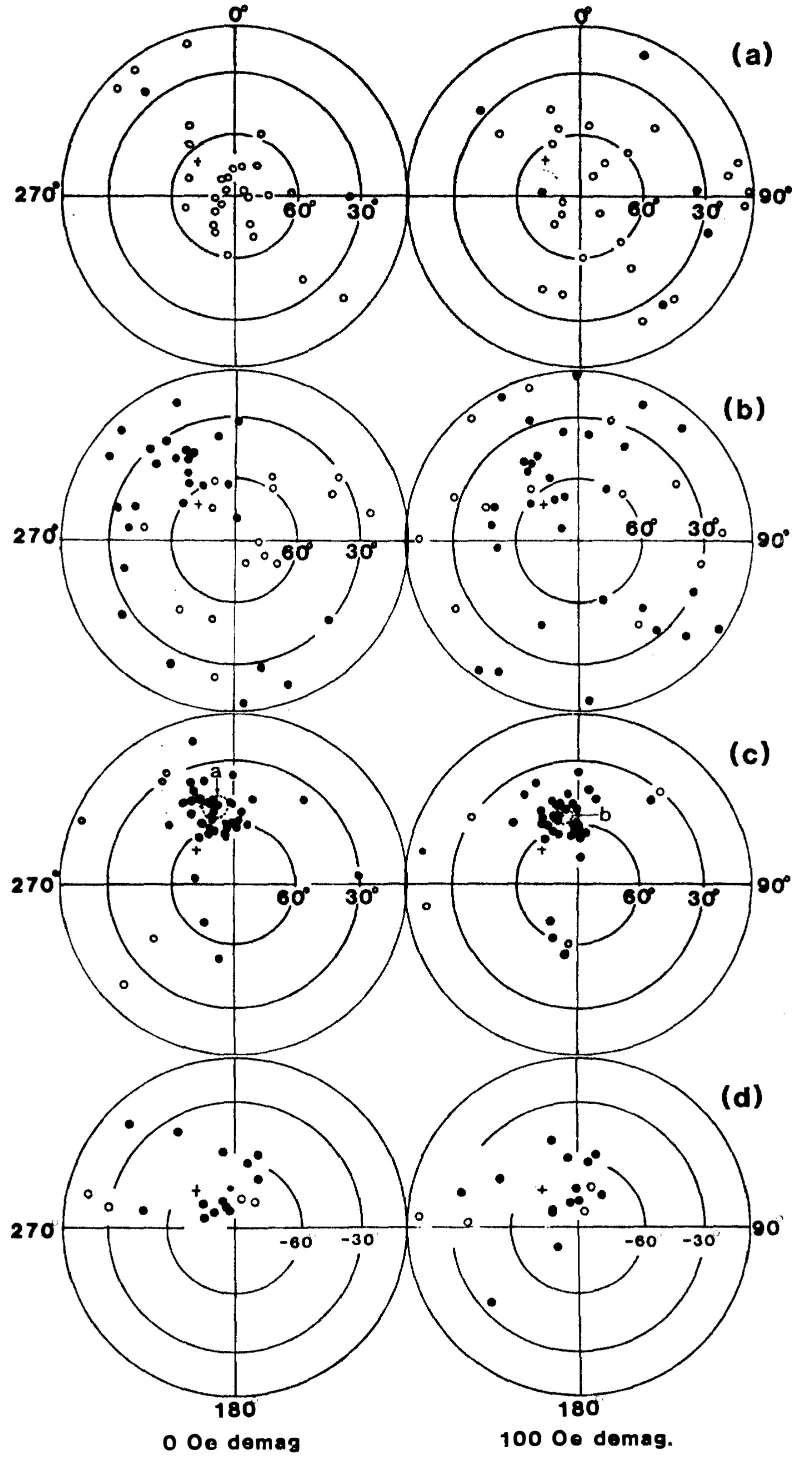

Fig. 3. Typical NRM directions for pyroxene gneiss (a), garnet gneiss at EON8 (b), hornblende gneiss (c) and amphibolite and silicious rocks at WON2 (d). (+): Present geomagnetic field direction at Syowa Station; (a, b): estimated values of 95% confidence for the NRM direction.

Table 2. Paleomagnetic results obtained from Lützow-Holm Bay area.

No.	Site*	No.	dema	Inc	Dec	K	α_{95}	pLat	pLon
1	EON3	35	0	50.0°	345.1°	19	5.7°		
			100	55.2	347.2	40	3.9	15.1S	28.7E
2	EON5	5	0	52.7	297.7	5	39.8		
			100	51.2	297.5	5	37.2	21.7S	19.1W
3	EON8	16	0	45.4	316.1	11	11.7		
			100	51.6	322.2	12	11.2	15.0S	7.1E
4	WON1	10	0	−67.2	321.4	44	7.4		
			100	−67.5	342.0	43	7.5	30.1S	26.3E
5	WON2	14	0	53.3	334.6	11	12.3		
			100	69.9	324.0	9	14.4	20.3S	14.2E
6	Total	80	100	59.1	336.8	14	4.5	20.2S	20.7E
7	EON	18		58.0	335.7	25	7.1	18.2S	19.6E
8	ONG	5		49	350	—	—	9S	32E
9	Lützow	7		60	341	—	—	21S	24E
10	EON	4		46.5	7	—	—	7S	33E

1-6: this study, 7: NAGATA and SHIMIZU (1959, 1960), 8, 9: NAGATA and YAMA-AI (1961), 10: KANEOKA *et al.* (1968).

* EON: East Ongul Island, WON: West Ongul Island, ONG: Ongul Islands, Lützow: Lützow-Holm Bay.

plicated make-up of the NRM directions. Mean NRM direction for 80 samples from 5 sites is Inc=59.1°, Dec=336.8°, K=14 and α_{95}=4.5 (normal directions are changed to reversed directions for this calculation).

4. Thermomagnetic Curves

Thermomagnetic curves (I_S-T curves) of representative samples from each site were measured from room temperature to 600°C in a 10 kOe external magnetic field. Vacuum condition and heating rate were 4×10^{-4} torr and 200°C/h, respectively. Obtained I_S-T curves are classified into 4 types based on reversibility and character of the heating and cooling curves, and the Curie points as shown in Fig. 4.

Type 1 curve is characteristic of every sample of pyroxene and garnet gneisses (excluding reversed NRM samples of garnet gneiss from EON8). Metabasites from EON1, 2, and 4 included in these gneisses also have this type of I_S-T curves. Type 1 curves exhibit two stages of magnetization increase manifested as humps in the heating curve. The first is probably associated with reordering in pyrrhotite (*i.e.* NAGATA and FUNAKI, 1983), the second is associated with oxidation of pyrrhotite. The net increase in magnetization noted in the cooling curve is an indication of magnetite production. The magnetization after heat treatment increases more than 30%. Since pyrrhotite ore collected from EON1 has this type 1 character, magnetic minerals responsible are estimated to be pyrrhotite in this preliminary study. Optically, pyrrhotite grains are detected in the type 1 samples by microscope investigation. These type 1 I_S-T curves suggest chemical oxidation of pyrrhotite to magnetite during heating under vacuum conditions.

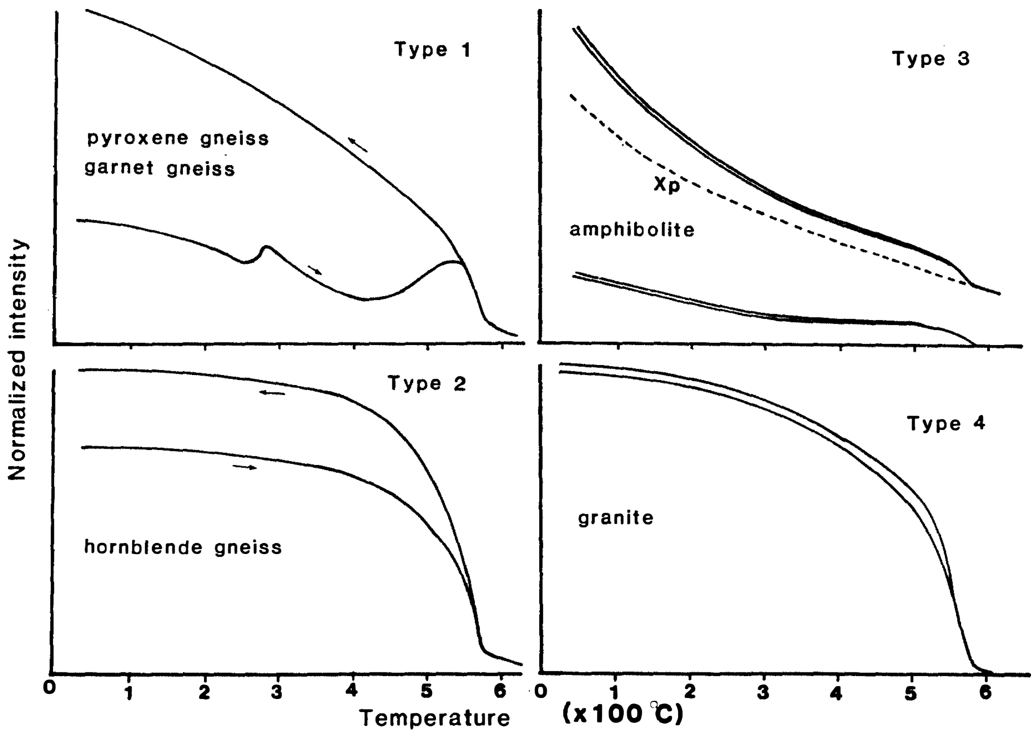

Fig. 4. Thermomagnetic curves of typical samples of pyroxene gneiss (type 1), hornblende gneiss (type 2), amphibolite (type 3) and granite (type 4).

Type 2 curve is obtained from the samples of hornblende gneiss at EON3. This type of irreversible I_S-T curve having a magnetite Curie point 580°C and magnetization increase on cooling is very similar to curves for maghemite under vacuum condition. Although there is no confirmation of maghemite in microscope studies, rather dominant hematite, magnetite and a minor amount of pyrite grains are observed. From this preliminary assessment, the increasing magnetization observed in the cooling curve may be due to reduction of hematite during heat treatment.

Type 3 I_S-T curve is characteristic for amphibolite from WON2 and reversed NRM samples of garnet gneiss from EON8. Type 3 curves are reversible, but the intensity is very weak generally being order of 10^{-3}emu/g at room temperature. As indicated the observed magnetization includes a large amount of paramagnetic component compared with ferrimagnetic component. The theoretically estimated paramagnetic component X_p (NAGATA *et al.*, 1972) is subtracted from the observed curve as shown in the figure. Consequently, a magnetite Curie point at 580°C, and minor ones around 300° to 400°C are identified clearly in the samples of amphibolite, but the temperature of the minor Curie points varies among samples. The Curie points of that garnet gneiss are not clearly defined because of a gradual change from 200° to 500°C. Almost no opaque minerals are observed, expect for a small amount of pyrite, during microscopic observation at 400x magnification.

Type 4 curve is obtained from samples of granite at WON1. The curves are typical reversible I_S-T curves for magnetite. Only one Curie point is observed at 580°C in the heating and cooling curves. As magnetite and ilmenite grains have been observed during microscopic examination, the magnetic mineral is considered to be magnetite.

Since the saturation magnetization of pegmatite dykes from EON7 is very weak (less than 10^{-3} emu/g), an I_S-T curve could not be obtained from this sample. However the thermal demagnetization results from these samples suggest that NRM directions are very stable up to 580°C and the intensities decay gradually from 30° to 530°C and steeply from 530° to 580°C. At 580°C the NRM is effectively demagnetized. From these viewpoints, the magnetic carriers are estimated to be pure magnetite grains and the pegmatite dyke rocks can probably be considered to have type 4 I_S-T curves.

5. Discussions

Although metabasite included in pyroxene and garnet gneiss have stable NRM, the pyroxene gneiss and most of the garnet gneiss are unstable during AF demagnetization. Magnetic carriers in the unstable samples are estimated to be pyrrhotite by I_S-T curves and microscopic observations. However, some of the garnet gneiss at EON8 is reversely magnetized and stable against AF demagnetization. NRM directions in these garnet gneisses are consistent with those of other stable components such as in the hornblende gneiss. The results of AF demagnetization of hornblende gneiss to 500 Oe show unusually stable NRM decay curves. NAGATA and SHIMIZU (1960) also reported similar stability in AF demagnetization curves of similar rocks in fields up to 400 Oe. They evaluated the NRM during thermal demagnetization, and estimated that the NRM carrier is essentially pure magnetite. Hornblende gneiss samples contain magnetite and hematite from consideration of NRM stability and microscopic observations.

The polarities of stable NRM appear to be reversed for hornblende gneiss from EON3 and normal for granite from WON1. Amphibolites with silicious part from WON2 have the mixture of normal and reversed polarities. Their NRM intensities are strong for high inclination samples but relatively weak for low inclination samples. These contrasting polarities and intensities for the NRM may be understood by considering that the originally reversed formations were heated above the Curie points by granite intrusions at the time of a normal geomagnetic field. Lithologies on Ongul Island acquired thermal remanent magnetization (TRM) during final metamorphism in the presense of a reversed field, and this was followed by granite intrusion which occurred when the geomagnetic field was in a normal direction. Consequently, the sampling site of WON2 was heated to some temperature less than 580°C; the samples including magnetic grains of low Curie point were remagnetized in a normal direction and high Curie point components survived. Samples of low inclination may include magnetic grains with high and low blocking temperature mixed polarities. Figure 5 shows the VGP positions of each site considered in this study. As the VGP positions of normal (No. 4) and reverse (Nos. 1, 2, 3 and 5) samples are almost anti-parallel within the 95% confidence level, the time of granite intrusion into the gneisses is probably very closely associated with the time of metamorphism.

Two structural styles of granite are observed in Ongul Islands, the one is concordant with schistosity and the other is disconcordant, which are magnetized in anti-parallel directions. From the observed direction of magnetization in the hornblende gneiss,

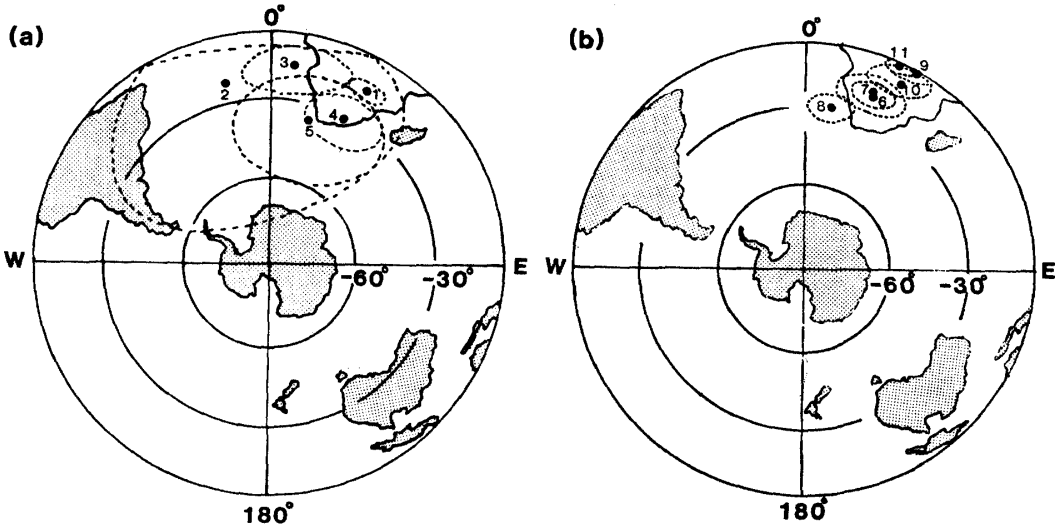

Fig. 5. VGP positions obtained from this study (a) and previous studies from East Antarctica for early Paleozoic time (b). 1: Hornblende gneiss, 2: pegmatite dyke, 3: garnet gneiss, 4: granite, 5: amphibolite and silicious rocks, 6: mean position of this study, 7: East Ongul Island (NAGATA and SHIMIZU, 1959, 1960), 8: Sør Rondane Mountains (ZIJDERVELD, 1968), 9: Mirny Station (McQUEEN et al., 1972), 10: Taylor Valley (MANZONI and NANNI, 1977) 11: Wright Valley (FUNAKI, 1984).

concordant granites of reversed polarity appear to be older than the discordant granites of normal polarity.

Magnetic polarity relationships of pegmatite dyke and pyroxene gneiss at EON7 could not be obtained directly due to unstable nature of the NRM of the pyroxene gneiss at EON7. However, mean NRM directions of the pegmatite dyke and other samples having stable NRM directions have the same α_{95} values as shown in Fig. 5a. Thus, there is a possibility that pegmatite dyke acquired NRM when formations of Ongul Islands were subject to the final stage of wide spread metamorphism.

Paleomagnetic results obtained from the Lützow-Holm Bay region are summarized in Table 2. Previous studies by NAGATA and SHIMIZU (1959, 1960), NAGATA and YAMA-AI (1961) and KANEOKA *et al.* (1968), reported only reversed magnetization and obtained NRM directions similar to our results. Therefore, the magnetic record of final metamorphism observed in Ongul Islands may be extended to the Lützow-Holm Bay region in general.

Metamorphism ages of the gneisses in the Lützow-Holm Bay region are 560 to 387 Ma by the K-Ar method (KANEOKA *et al.*, 1968; YANAI and UEDA, 1974) and from 726 to 465 Ma by the Rb-Sr method (NICOLAYSEN *et al.*, 1961; MAEGOYA *et al.*, 1968). Recently SHIBATA *et al.* (1986) obtained whole rock Rb-Sr age of 683.1 ± 13.2 Ma and mineral age 482.5 ± 9.5 Ma. The older age of about 680 Ma and younger age about 480 Ma may suggest the main stage of metamorphism and the final stage, respectively. It may be suggested therefore that the gneisses of the Ongul Islands were magnetized at about 480 Ma ago in the reversed geomagnetic field direction. Figure 5b shows VGP positions of early Paleozoic time obtained from East Antarctica, where numbers from 6 to 11 denote Ongul Islands (this study), East Ongul Island (NAGATA and SHIMIZU, 1959, 1960), Sør Rondane Mountains (ZIJDERVELD, 1968), Mirny Station (MCQUEEN *et al.*, 1972), Taylor Valley (MANZONI and NANNI, 1977) and Wright Valley (FUNAKI, 1984) respectively. The VGP distribution is limited in area as shown in Fig. 5b, located in the southern hemisphere near the present-day Africa; this may suggest that the acquisition of NRM at all these sites occurred almost simultaneously in time.

6. Conclusion

Pyroxene and garnet gneiss of East Ongul Island have very unstable NRM's almost parallel to the present geomagnetic field direction in the Syowa Station area, although some of the samples of garnet gneiss do have stable directions. These unstable NRM's appear to be associated with pyrrhotite. Hornblende gneiss and pegmatite dyke have very stable NRM's of reversed polarity. Their magnetic carriers are estimated to be hematite and a small amount of magnetite in the hornblende gneiss and magnetite in the dykes. Granite in Ongul Islands was classified according to the structural setting into two types; the first has reversed polarity and is concordant with gneissosity, the second has normal polarity and is disconcordant with gneissosity. The intrusion of the second type granite in the normal geomagnetic field caused the formations of reversed polarity around the granite to be remagnetized.

Stable NRM components in the gneisses of Ongul Islands appear to have recorded the geomagnetic field at the time of final metamorphism at about 480 Ma ago. However, the last geological evidence of this metamorphism appears to be intrusion of disconcordant granite in the gneiss after the peak metamorphism, but the time interval in this sequence may not be very long.

The obtained VGP position (latitude 20.2°S, longitude 20.7°E), using 80 samples from this study, is consistent with other ones reported from East Antarctica. When the formations of Ongul Islands were magnetized at about 480 Ma ago, Antarctica was located in a lower latitude near the present-day Africa.

Acknowledgments

The authors wish to thank Prof. T. HIRASAWA, leader of the 25th Japanese Antarctic Research Expedition party, and the members of JARE-25 summer party for their sampling support field companionship and general inspiration.

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(Received March 15, 1986; Revised manuscript received May 1, 1986)