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NATURAL REMANENT MAGNETIZATIONS OF GRANITE AND SYENITE FROM PINGVINANE AND LUNCKERYGGEN IN THE SØR RONDANE MOUNTAINS, EAST ANTARCTICA

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Abstract: The characteristics of the natural remanent magnetizations (NRMs) of granite and syenite from Pingvinane and Lunckeryggen in the western Sør Rondane Mountains were elucidated. In order to endorse the NRMs, AF and thermal demagnetization, thermomagnetic and magnetic hysteresis properties were analyzed. Furthermore, microscopic observations were carried out for identification of the magnetic grains.

Consequently, reliable mean NRM directions acquired in early Silurian period were given from the Pingvinane granite as $I=68.3°$, $D=315.3°$, $\alpha_{95}=4.1°$ and the Lunckeryggen syenite as $I=74.0°$, $D=327.3°$, $\alpha_{95}=7.0°$. Part of the syenite and granite from Lunckeryggen showed different NRM directions as $I=79.8°$, $D=201.3°$, $\alpha_{95}=9.3°$, and as $I=39.8°$, $D=178.9°$, $\alpha_{95}=12.1°$, respectively, although their meaning was not elucidated in this paper. The syenite and granite from Lunckeryggen include magnetite for NRM carriers with heterogeneous size distributions, which would cause a wide scattering of their NRMs.

The virtual geomagnetic pole positions calculated from the established NRMs were at 37.4°S, 10.5°W, for the Pingvinane granite and 44.6°S, 1.0°E, for the Lunckeryggen syenite. These positions are consistent with the previous result reported by J.D.A. ZIJDERVELD (J. Geophys. Res., 73, 3773, 1968).

1. Introduction

The Sør Rondane Mountains, centered at latitude 73°S and longitude 26°E with an area of about 200×75 km, consists of several ranges and nunataks in Queen Maud Land, East Antarctica. The mountains are largely underlain by high grade metamorphic and intrusive rocks forming a part of the Precambrian shield.

A party of the 30th Japanese Antarctic Research Expedition (JARE-30) operated paleomagnetic sampling in the western Sør Rondane Mountains. The party collected a total of 1379 paleomagnetic rock samples of gneisses, granite, tonalite, syenite and dolerite from Selungen (Seal), Pilten, Brattnipene, Otto Borchgrevinkfjellet, Nils Larsenfjellet, Pingvinane, Lunckeryggen, Utnibba (nunatak 1550) and Vesthaugen, as shown in Fig. 1. As we have obtained some results for the granite and syenite from Pingvinane and Lunckeryggen, the characteristics of natural remanent magnetizations (NRMs) are described in this paper.

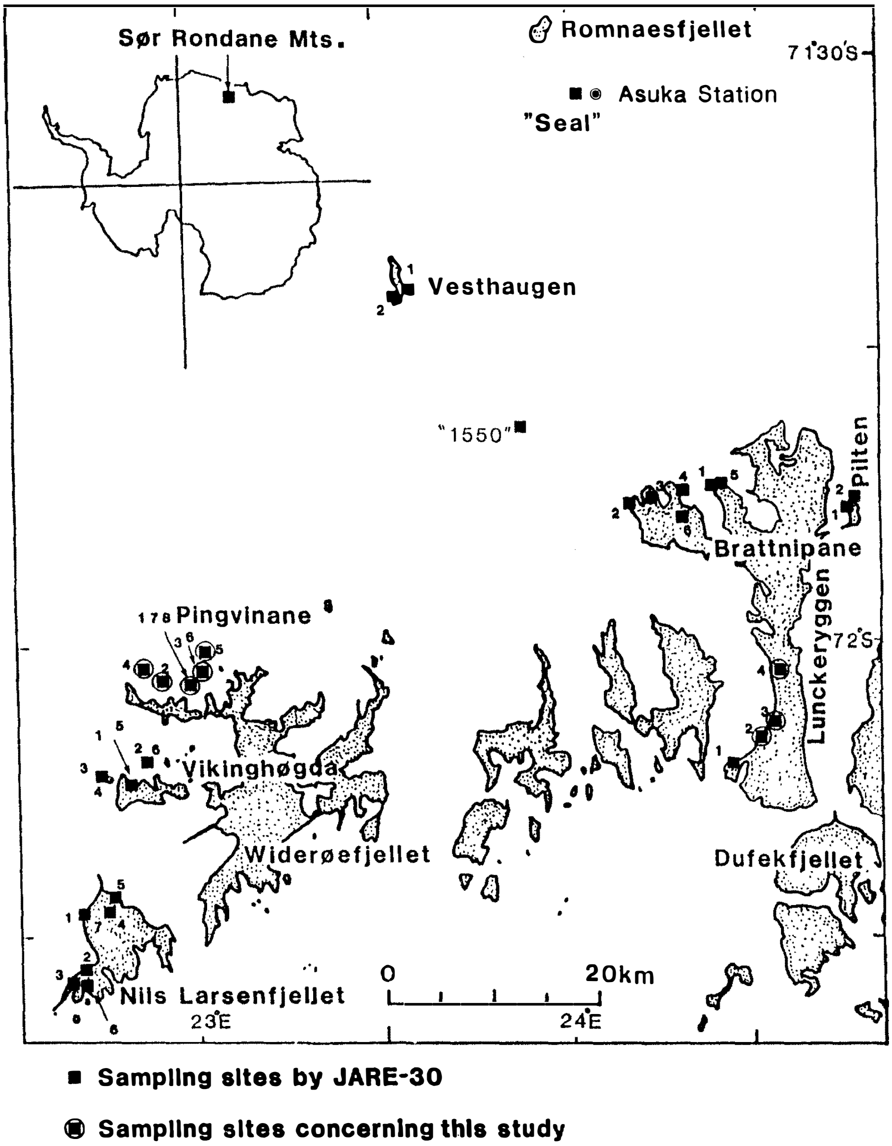

Fig. 1. A map of the western Sør Rondane Mountains and the paleomagnetic sampling sites by JARE-30.

The samples were collected using an engine core drill for 1-inch diameter core. A hot drilling water we prepared in order to solve the problem of freezing. Hand samples were collected at almost all the sites, especially deep in the mountains, because of logistic difficulty in converying the drilling equipment. The magnetic compass was available for the identification of the sample directions, where the inclination and the total intensity of the geomagnetic field are $-63°53'$ and 43073 nT respectively (SAKAI *et al.*, 1990).

ZIJDERVELD (1968) carried out a paleomagnetic study for the granite from "the Seal", monzonite from Vesthaugen and syenite from Lunckeryggen in the central and western Sør Rondane Mountains. These samples had stable NRMs of reversed inclination (downward). He elucidated that a virtual geomagnetic pole (VGP) of the lower Ordovician was located at 28.5°S, 9.5°E with α_{95} (confidence of 95% probability) $=4.5°$ from the NRMs. However, he could not take any significant NRM components in granite from Vengen and Lunckeryggen, granitic dyke in syenite from Lunckeryggen, basaltic dyke from nunatak "1550" and kersantite dyke from Vesthaugen. TAKIGAMI *et al.* (1987) also reported a VGP position of gneiss at one site in Brattnipene, showing a similar position to that of the Cambrian-Ordovician ones of East Antarctica, as summarized by FUNAKI (1984), although a large value of $\alpha_{95}=19.5°$ was obtained.

2. General Geology

Geological surveys of the Sør Rondane Mountains were carried out by the Belgian Antarctic Expeditions during 1958 to 1970. According to their results, the Sør Rondane Mountains are composed of various kinds of metamorphic and plutonic rocks (VAN AUTENBOUER and LOY, 1972). The western Sør Rondane Mountains were surveyed again by JARE-25 and -26 (1983–1985). The metamorphic rocks in this region were divided into two groups (KOJIMA and SHIRAISHI, 1981); the northern group is composed mainly of pelitic to psammitic gneisses, while in the southern group intermediate gneisses occur predominantly. Between the northern and southern groups, a pronounced shear zone, characterized by occurrences of cataclastic or mylonitic gneisses, runs from west to east. The granite from Pingvinane and the syenite and granite from Lunckeryggen in this study belong to the northern and southern groups respectively. Plutonic rocks from Lunckeryggen to Brattnipene regions were classified into the older (late Proterozoic) and younger (early Paleozoic) intrusive rocks by SAKIYAMA *et al.* (1988). The older intrusive rocks having gneissose structure are low in the value of magnetic susceptibility in general, while most of the younger ones give high values. The syenite and granite from Lunckeryggen are assigned to the younger group.

The geochronological data about the Sør Rondane Mountains were reported as 1167+127 Ma by Rb/Sr (SHIRAISHI and KAGAMI, 1989), 470–550 Ma by Rb/Sr (PICCIOTTO *et al.*, 1964, 1966) and 440–450 Ma by $^{40}Ar/^{39}Ar$ (TAKIGAMI *et al.*, 1987). These ages may be explained that the Sør Rondane Mountains were formed or metamorphosed in the middle Proterozoic eon and were affected by thermal even associated with metamorphism or platonism in the Ordovician to early Silurian period.

3. Basic Magnetic Properties

3. 1. AF demagnetization

The representative samples, more than 3 samples selected from each group, were AF demagnetized up to 50 mT by 5 mT steps. Figure 2 shows typical demagnetization curves of 4 groups. The NRM (1.67×10^{-6} Am²/kg) of the Pingvinane granite (site 4) was relatively stable against the demagnetization; both of the intensity and direction did not shift largely between 20 and 30 mT. However, the Pingvinane granite (sites 1 to 3 and 5 and 6) was magnetized very weakly (order of 10^{-7}–10^{-8} Am²/kg) toward flatten or upward (normal) direction. As their NRMs were very unstable against the

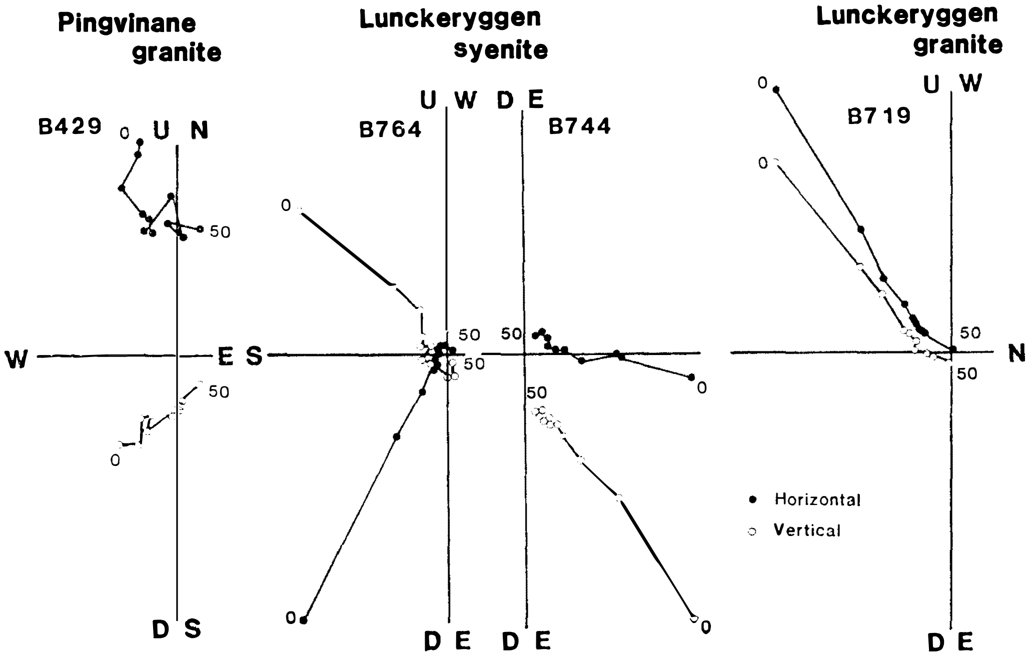

Fig. 2. Zijderveld projections of the samples having stable NRM components against AF demagnetization.

demagnetization, the NRMs might have been acquired in the present geomagnetic field.

The original NRMs ($2.45–3.61 \times 10^{-5}$ Am^2/kg) of the Lunckeryggen syenite (sites 3 and 4) were a mixture of the reverse and normal magnetization. The magnetically soft components were generally removed by AF demagnetization up to 15 mT and then the hard NRM components of the reversed inclination appeared. The hard NRMs were essentially stable up to 50 mT. However, none of the hard ones were recognized in the samples magnetized to normal inclination.

The NRM of the Lunckeryggen granite (site 2, 1.49×10^{-4} Am^2) were decomposed into a large amount of the soft component associated with small hard one. The soft component vanished up to 35 mT and the residual hard one appeared, although the hard one was destroyed by the demagnetization around 45 mT.

From these AF demagnetization tests, the optimum demagnetization fields were deciced to be 10 mT for the Pingvinane granite (site 4), 25 and 35 mT for the Lunckeryggen syenite (sites 2 and 4) and 40 mT for the Lunckeryggen granite (site 2).

3.2. Thermal demagnetization

The thermal demagnetization was performed for the representative 3 samples at a site to have the stable NRM component from room temperature to 630° by 50°C steps, although the samples of the Pingvinane granite at sites 1, 2, 3, 5 and 6 could not be measured due to their weak intensities.

Thermal demagnetization curves of the Pingvinane granite (site 4) showed very stable NRM directions up to 580°C, then scattered at 630°C. The intensity increased gradually to 430°C and declined steeply up to 580°C with some zigzag variations. A

NRM unblocking temperature was determined at 580°C for the Pingvinane granite.

Normal and reverse NRMs in the Lunckeryggen syenite (site 3) showed different thermal demagnetization characteristics as shown in Fig. 3. The reverse NRM of the sample (B744) was stable in its direction up to 580°C, particularly in the range of 130° and 380°C. Its intensity curve showed a clearly defined NRM unblocking temperature at 430° and 580°C. Simultaneous acquisition of the NRMs implied by that no directional change were observed below and above the lower unblocking temperature. The normal NRM of the sample (B764) was relatively stable up to 180°C and became unstable to 630°C in the direction, as shown in Fig. 3. The intensity curve showed a steep decline up to 130°C and a hump between 380° to 530°C. No significant magnetization was observed at temperatures higher than 530°C. In the case of the Lunckeryggen syenite at site 4, the highest NRM unblocking temperatures appeared between 430° to 530°C which were evidently lower than those of the syenite (site 3) with reverse NRM. Since the direction changed at random during the hump, there is a possibility of chemical alterations of magnetic grains.

The Lunckeryggen granite (site 2) was thermally demagnetized in a steep and double staged decay mode, as shown in Fig. 4. The normal inclinations were reserved up to 380°C and turned over to the reverse in the range of 430° to 530°C. No significant NRM remained over 580°C.

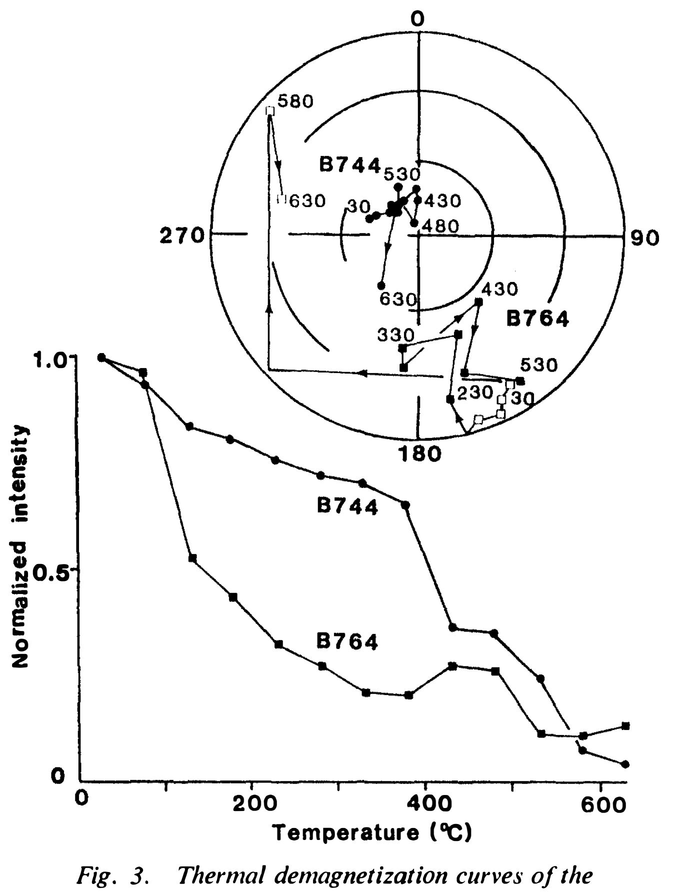

Fig. 3. Thermal demagnetization curves of the Lunckeryggen syenite (site 3).

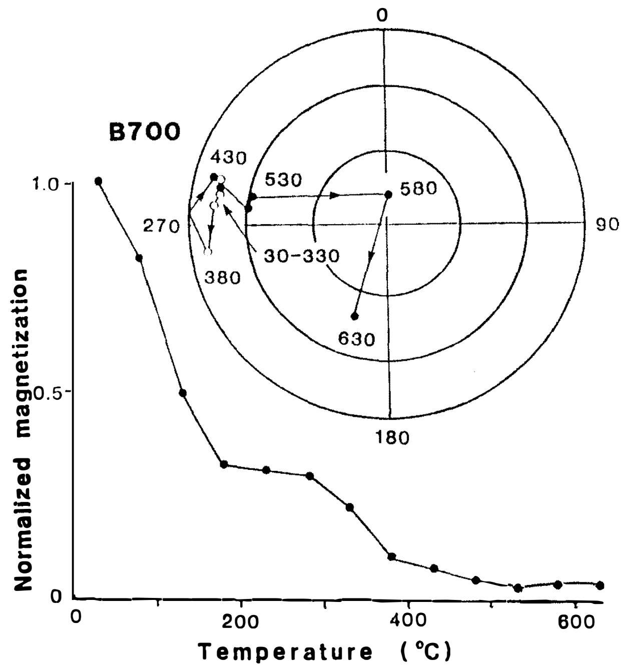

Fig. 4. Thermal demagnetization curves of the Lunckeryggen granite (site 2).

3.3. Thermomagnetic and magnetic hysteresis analyses

Thermomagnetic (Js-T) curves were obtained for a representative sample from one site by the magnetic balance in 10^{-3} Pa atmosphere under 0.4 T steady external magnetic field. The Pingvinane granite was found to have too weak spontaneous magnetization to obtain significant results.

The Js-T curves of the Lunckeryggen syenite were obtained for the samples

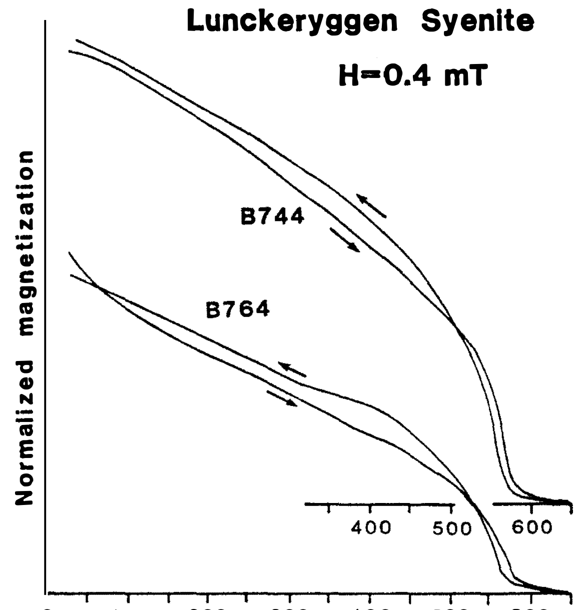

Fig. 5. Thermomagnetic curves of the Lunckeryggen syenite. Samples B764 and B744 are magnetized to the normal and reverse, respectively.

magnetized reversely (B744) and normally (B764). The 1st run curves were almost reversible ones and the 2nd run ones were completely overlaid to the cooling curve of the 1st run. No significant differences were observed in the curves between the two samples, as shown in Fig. 5, although their thermal demagnetization curves were quite different. Pure magnetite was identified from the Curie point 580°C.

The magnetic hysteresis properties were measured for the Lunckeryggen syenite by a vibrating sample magnetometer at room temperature. However, those of the other samples were not measured because their spontaneous magnetizations were to weak. Saturation magnetization (I_S), saturation remanent magnetization (I_R) and coercive force (H_C) were determined from the hysteresis curves for the two Lunckeryggen syenites with normal and reverse NRMs; these values were smaller for the former than the latter: $I_S=0.21\,Am^2/kg$, $I_R=0.016\,Am^2/kg$ and $H_C=7\,mT$; $I_S=0.22\,Am^2/kg$, $I_R=0.024\,Am^2/kg$ and $H_C=10\,mT$. These values indicated that fine-grained magnetite is included in the samples magnetized reversely more than in the normally magnetized ones.

3.4. *Microscopic observations*

The microscopic observations were performed for the samples having hard NRM components. The Pingvinane granite (site 4) included a small amount of ilmenite grains, less than 65 μm in diameter, and pyrite (FeS_2) grains which were heavily oxidized to hematite (Fe_2O_3) or goethite (FeOOH) almost completely in the margin of the grains. No magnetite grains were identified under the microscope. A very small amount of fine-grained magnetite was present in this sample, estimated from the NRM intensity ($1.82\times10^{-6}\,Am^2/kg$ for this sample) and the NRM unblocking temperature at 580°C.

Two syenite samples (site 3) with normal and reverse NRMs were observed. The former included magnetite grains of dominant diameter 30–100 μm. The grains were clearly cut by ilmenite lamellae of 0.5–1.0 μm in diameter. Its NRM ($R=1.62\times10^{-5}\,Am^2/kg$, $I=-74.2°$, $D=151.2°$) was demagnetized to ($R=0.23\times10^{-5}\,Am^2/kg$, $I=-23.1°$, $D=151.2°$) by the AF demagnetization to 35 mT. On the other hand, the latter sample included magnetite grains, less than 30 μm in diameter, having exolution of ilmenite lamellae like the former sample. The NRM ($R=4.43\times10^{-5}\,Am^2/kg$, $I=3.2°$, $D=245.9°$) was AF demagnetized to ($R=2.18\times10^{-5}\,Am/kg$, $I=75.1°$, $D=224.6°$) at 25 mT.

The Lunckeryggen granite with normal NRM ($R=1.07\times10^{-4}\,Am^2/kg$, $I=-35.9°$, $D=218.9°$) contains large-grained magnetite (1.4–0.5 mm in diameter) which was partially cut by the ilmenite lamellae. Pyrite grains, less than 60 μm in diameter, were oxidized to hematite and goethite along the internal cracks and grain boundaries. While the granite with reverse NRM ($R=8.32\times10^{-5}\,Am^2/kg$, $I=62.2°$, $D=48.2°$) contains magnetite grains of less than 130 μm and pyrite grains of 140 μm in diameter. Internal structures of these grains are essentially consistent with those of the former.

4. NRM Directions

Every sample supposely having stable NRMs was AF demagnetized at 3 levels around the optimum field. The mean direction of the site calculated from the best

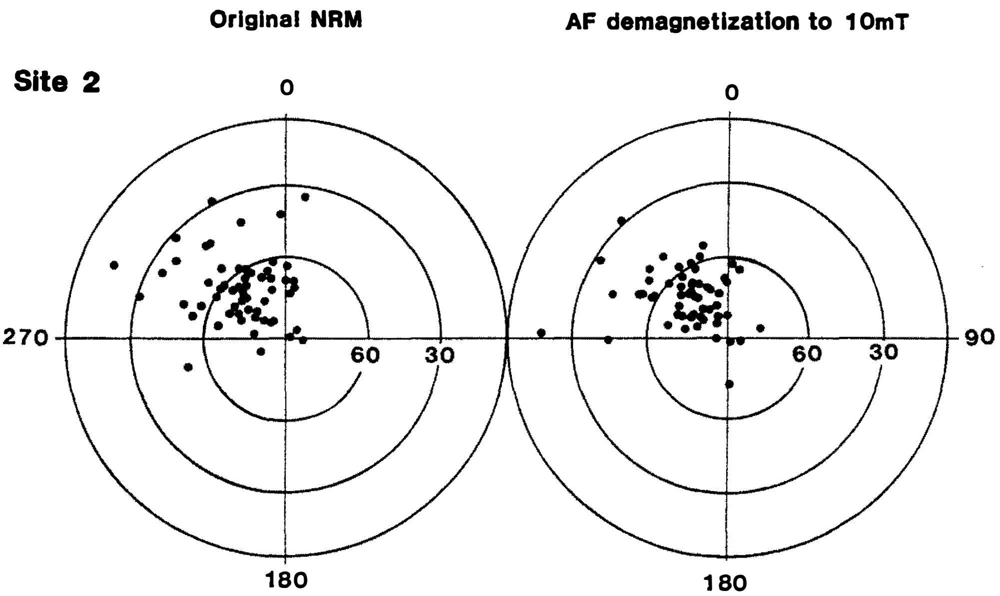

Fig. 6. NRM directions of the original and after AF demagnetization to 10 mT for the Pingvinane granite (site 4).

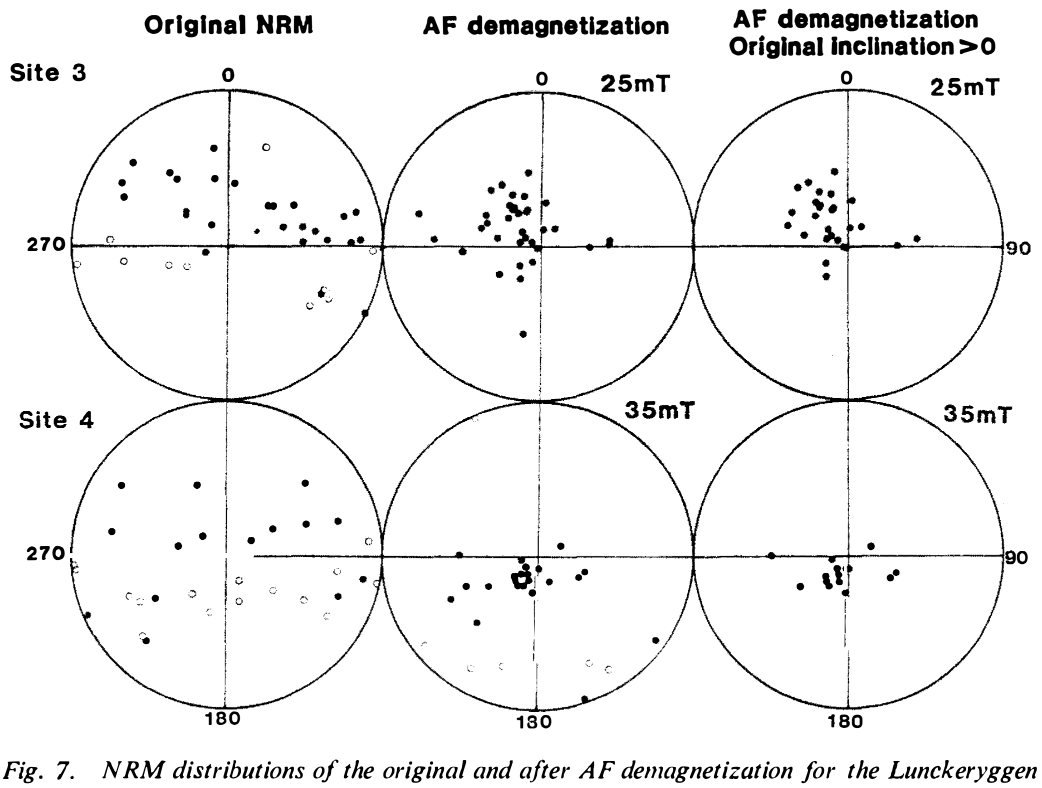

Fig. 7. NRM distributions of the original and after AF demagnetization for the Lunckeryggen syenite (sites 3 and 4). Left: original NRM directions, center: after AF demagnetization to 25 mT and 35 mT for the syenite (sites 3 and 4 respectively, right: after AF demagnetization to remove normal NRMs from the original NRM distributions.

clustering result was adopted for the representative NRM of the site; 10 mT for the Pingvinane granite (site 4), 25 and 35 mT for the Lunckeryggen syenite (sites 3 and 4 respectively) and 40 mT for the Lunckeryggen granite (site 3) were decided.

The NRMs of the Pingvinane granite (site 4, 60 samples) clustered well with reverse direction. They converged around the mean direction of $I=68.3°$, $D=315.3°$ with $\alpha_{95}=4.1°$ after the demagnetization to 10 mT, as shown in Fig. 6.

The NRMs of the Lunckeryggen syenite (site 3, 37 samples; site 4, 29 samples) showed widely scattered directions in the two hemispheres along a great circle through E-W (left in Fig. 7). The NRM directions were well clustered (center in Fig. 7) after AF demagnetization (25 mT for site 3, 35 mT for site 4) with several exceptions. A better clustering was obtained after discarding the normal NRMs, which were unstable in AF and thermal demagnetizations (right in Fig. 7). Consequently, the mean NRM

Table 1. Paleomagnetic results of Pingvinane and Lunckeryggen in the Sør Rondane Mountains.

No.	Site	Demag.	N	I	D	K	α_{95}	Lat.	Long.
1	Pingvinane	0	60	64.9°	319.4°	17	4.6°		
	site 4 granite	10		68.3	315.3	21	4.1	37.4°S	10.5°W
2	Lunckeryggen	0	27	65.2	34.3	3	18.0		
	site 3 syenite	35		74.0	327.3	17	7.0	44.6°S	1.0°E
3	Lunckeryggen	0	14	81.1	326.3	2	32.7		
	site 4 syenite	25		79.8	201.3	19	9.3	82.9°S	71.5°W
4	Lunckeryggen	0	34	−10.3	177.4	1	58.8		
	site 2 granite	40		39.8	178.9	5	12.1	40.6°S	158.4°W

Demag.: AF demagnetization field intensity (mT), N: number of sample, $I(D)$: inclination (declination) of mean NRM, K: precision parameter, α_{95}: circle of confidence of 95% probability, Lat. (Long.): latitude (longitude) of VGP position.

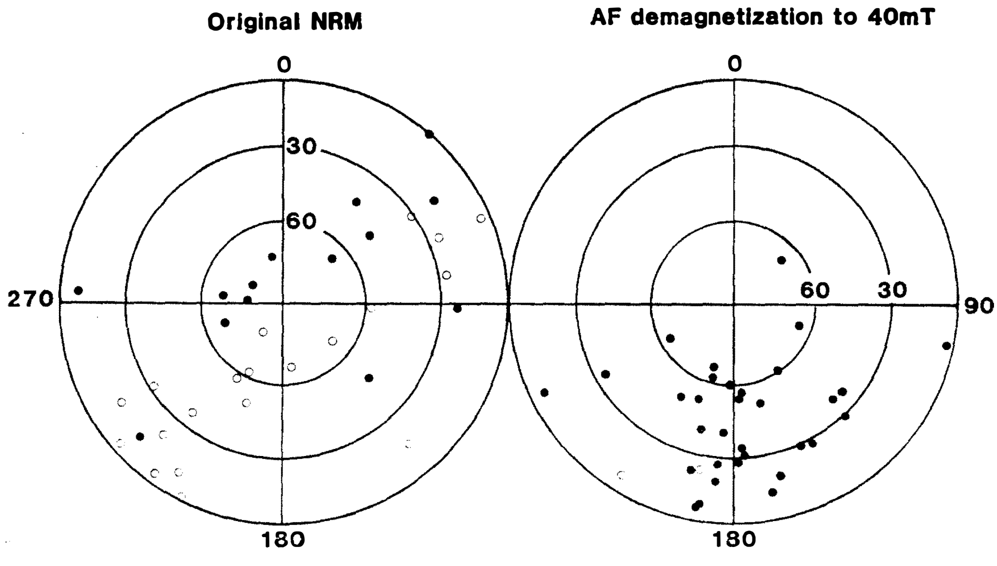

Fig. 8. NRM distribution of the original and after AF demagnetization to 40 mT for the granite from Lunckeryggen site 2.

directions and the α_{95} values appeared as $I=74.0°$, $D=327.3°$ with $\alpha_{95}=7.0°$ from 27 samples at site 3 and $I=79.8°$, $D=201.3°$ with $\alpha_{95}=9.3°$ from 14 samples at site 4, as shown in Table 1.

The NRM directions of the Lunckeryggen granite (site 2, 34 samples) were scattered widely throughout the two hemispheres nearly along the graet circle of NE-SW (Fig. 8). By the AF demagnetization to 40 mT, they roughly clustered around the mean direction of $I=39.8°$, $D=178.9°$ with a large $\alpha_{95}=12.1°$. Even though the normal magnetizations were discarded, the confidence was not improved. Therefore, the above values were used for the paleomagnetic discussions.

5. Discussions

The NRMs of the Pingvinane granite, except site 4, were fairly unstable and were magnetized toward the present geomagnetic field direction. Similar NRMs were already reported from several rocks in the central to western Sør Rondane Mountains; Vengen, Lunckeryggen and nunatak "1550" by ZIJDERVELD (1968) and Austhovde by TAKIGAMI *et al.* (1987). Such magnetic unstable rocks may be exposed in a wide area of this region. The unstable NMRs may result from viscous remanent magnetization (VRM) acquired in the present geomagnetic field in the Sør Rondane Mountains estimated from their normal inclinations. On the contrary, the Pingvinane granite (site 4) acquired relatively stable NRMs with reversed inclination. Their NRM carriers were estimated to be pure magnetite from the NRM unblocking temperature of 580°C, although they were undetected under the microscope. The hematite and geothite in the granite, which were produced by oxidation of pyrite, possibly disturb the NRMs. Although these problems have remained, the antiparallel mean NRM direction to the present geomagnetic field gives some significance to its paleomagnetic reliability.

The large amount of the soft magnetic components of the Lunckeryggen syenite evidently caused the scattering of the NRMs, because they acted on NRMs in an upward or horizontal direction and a cluster with reversed inclinations appeared after removal of them. So it is considered that scattering of their NRM directions was caused by a large amount of soft components acquired in the present geomagnetic field. The I_R and H_C values of the syenite with reverse magnetization are larger than those with the normal one. This feature is explained by the magnetite grain-size; the syenite with reverse magnetization included finer-grained magnetite compared with that with normal one. Since there is obvious differences in the internal structures of magnetite grains and the thermomagnetic curves between the samples with normal and reverse NRMs, the grain size of the magnetite possibly controlled the NRM directions. The variation of the NRM directions throughout the hemispheres (Fig. 7) may suggest heterogeneous size distributions of the magnetic grains in the syenite. Difference of the thermal demagnetization between the syenite magnetized normal and reverse, is also explained by the low magnetic coercivity; only VRM component was demagnetized thermally up to about 230°C for the sample B764 (Fig. 3). If a small amount of the hard NRM component remained in this sample at higher temperature, it is disturbed by the noise caused by chemical alterations during the heating process. Relatively large directional variations with reversed inclination in the higher temperatures for this sample may suffer this phenomenon. From viewpoints, the reverse NRMs are usablc to calculate the reliable mean NRM directions for the Lunckeryggen syenite.

The Lunckeryggen granite contains magnetite which was confirmed by the Curie point 580°C, the NRM unblocking temperature at 580°C and microscopic observation. Any differences in magnetic grains were not recognized between the samples with normal NRM and the reverse one, except the grain size. So the magnetite grain size possibly controls the inclinations of the granite; the samples including large-grained magnetite (1.45 mm in diameter) were magnetized to the normal, while those including smaller one were magnetized to reverse. The granite also included hematite and geothite which are weathering products of pyrite, judging from their structures. The NRM directions of several granites were still scattered after AF demagnetization to 40 mT (Fig. 8). The large-grained magnetite, hematite and geothite were responsible for the scattered directions which appeared in high field demagnetization.

ZIJDERVELD (1968) reported paleomagnetic results from the central to western Sør Rondane Mountains. His results indicated that the granite of "The Seal", monzonite of Vesthaugen and syenite of Lunckeryggen recorded the stable NRMs with reversed inclination. Their directions resemble each other, being as $I=61°–66°$ and $D=340°–344°$. A VGP position related to the mean NRMs at Lat. = 28.5°S, Long. = 9.5°E and $\alpha_{95}=4.5°$, was in the southwest of the Cambrian-Ordovician VGPs from East Antarctica summarized by FUNAKI (1984). Newly obtained VGP positions from the Pingvinane granite (A) and the syenite of Lunckeryggen site 3 (B), as shown in Fig. 9, are consistent with his result (E). Although they are not overlaid with each other taking consideration of their α_{95} values, they were magnetized probably in the same thermal event.

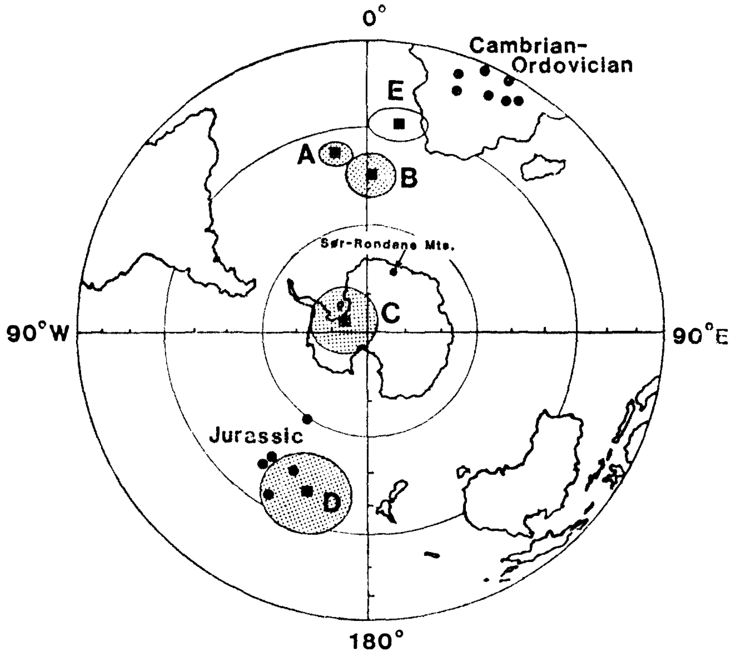

Fig. 9. VGP positions obtained from this study and the previous result for East Antarctica. A: granite from Pingvinane site 4; B, C: syenite from Lunckeryggen site 3, 4; D: granite from Lunckeryggen site 2; E: from Sør Rondane Mountains reported by ZIJDERVELD (1968).

Ages for intrusive or metamorphism in this region were estimated to be 999–1167 Ma by Rb/Sr and Sm/Nd (SHIRAISHI and KAGAMI, 1989), 470–550 Ma by Rb/Sr (PICCIOTTO *et al.*, 1964) and 440–450 Ma by $^{40}Ar/^{39}Ar$ and K/Ar (TAKIGAMI *et al.*, 1987). Probably the ages indicate that this region was formed or metamorphosed in middle Proterozoic and metamorphosed in Ordovician to early Silurian period. $^{40}Ar/^{39}Ar$ and K/Ar ages indicate acquistion age of NRMs, because argon trapping and magnetization occurred almost simultaneously below the Curie point of magnetite (580°C). So it is supposed that a metamorphism in middle Ordovician to early Silurian period caused NRMs of the Pingvinane granites the Lunckeryggen syenites and also rocks studied by ZIJDERVELD, which gave the VGPs denoted by A, B and E in Fig. 9.

The VGP positions of the Lunckeryggen syenite of site 4 (C) and of the granite of site 2 (D) are far from those mentioned above. Their paleomagnetic meaning can be understood by one of the following considerations:

(1) The VGPs C and D were overlaid on the apparent polar wander path of Gondwana at Carboniferous and Jurassic parts (MCELHINNY and BRIDEN, 1971). So the NRMs were recorded in the respective periods.

(2) The rocks in this region acquired NRM by the metamorphism during the early Silurian period and by intrusion of the Lunckeryggen granite (site 2) in the Jurassic period. Consequently, the syenite of site 4 was remagnetized partially. However, expected NRM components of the Jurassic period were not obtained from the decomposition of the hard NRM by thermal demagnetization, as shown in Fig. 3.

(3) Regional deformations occurred at Lunckeryggen site 4 and site 2 after acquisition of NRMs was accomplished in the early Silurian period.

(4) The VGPs are based on wrong results of imperfect demagnetization; remaining hard VRM or artificial noise possibly disturbed the experimental data.

Further investigations should be performed for the Lunckeryggen syenite and granite.

6. Conclusion

The Pingvinane granite of site 4 recorded reverse NRMs, while that of sites 1, 2, 3, 5 and 6 recorded normal NRMs resulting from the present geomagnetic field. As the syenite and granite from Lunckeryggen include magnetite with heterogeneous size distributions, which are considered to have caused wide scattering of their NRMs. The Lunckeryggen syenite (sites 3 and 4) recroded reveres and well clustered NRMs with mean directions considerably separated from each other beyond their α_{95} values. The Lunckeryggen granite (site 2) also recorded reverse NRMs but the VGP position was different from the others. The VGP positions of the Pingvinane granite (site 4) and Lunckeryggen syenite (site 3) were essentially consistent with the result by ZIJDERVELD (1968). The NRMs in consideration were acquired under a metamorphism in the early Silurian period. However, the meaning of the VGPs from the Lunckeryggen syenite of site 3 and granite of site 2 could not be elucidated at present.

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