Proc. NIPR Symp. Antarct. Geosci., 5, 61–74, 1991

TILTING MOVEMENT OF SØR RONDANE MOUNTAINS AND POSSIBLE APPARENT POLAR-WANDER PATH FOR PRECAMBRIAN TO CAMBRO-ORDOVICIAN FROM NILS LARSENFJELLET

Katsuyasu TOKIEDA[1] and Minoru FUNAKI[2]

[1]*Department of Physics, Faculty of Sciences, Shimane University, 1060, Nishikawazu, Matsue 690*
[2]*National Institute of Polar Research, 9-10, Kaga 1-chome, Itabashi-ku, Tokyo 173*

Abstract: Alternating field demagnetizations were performed for 479 hand samples (32 sites) collected from the Sør Rondane Mountains, East Antarctica. Clear convergence of natural remanent magnetization (NRM) was observed for only 82 samples (17%) from 8 sites. They were dolerites, tonalites, syenites and hornblendites, all having NRM strength more than 10^{-6} Am^2/kg. Samples less than 10^{-7} Am^2/kg, including granites, granitic rocks and granitic dike or vein, yielded no paleomagnetically significant results.

The virtual geomagnetic pole positions (VGP) from 1550 nunatak dolerite, Brattnipene dolerite and Lunckeryggen syenite fall on a fairly small area, well matching with reported ones from Pingvinane granite and some rocks in the Sør Rondane Mountains. Their radiometric ages are confined to early Ordovician. On the other hand, the Ordovician VGPs from elsewhere in East Antarctica are significantly deviated from those from the Sør Rondane Mountains These facts lead us to a conclusion that the mass of the Sør Rondane Mountains was undeformed locally, but tilted as a whole relatively to the rest mass in East Antarctica.

A Precambrian VGP, 60.4°S, 21.5°W in 662±23 Ma, was estimated from magnetically cleaned remanences and a newly determined ^{40}Ar-^{39}Ar age of Nils Larsenfjellet tonalites, with further proposing of an apparent polar-wander path (APWP) for Precambrian to Cambro-Ordovician from Nils Larsenfjellet.

No attempt of thermal demagnetizations and other methods of the rock-magnetism have been done to verify the quality of the magnetically cleaned remanence. A serious paleomagnetic significance is provided, however, with the fact that the analogous VGPs were obtained from a variety of rocks of similar ages.

1. Introduction

The Sør Rondane Mountains, located at 73°S, 26°E in East Antarctica, occupy an area of 200×75 km on the Precambrian shield of high-grade metamorphic and intrusive rocks, and several high ranges and nunataks emerge from the thick ice covering.

The Belgian Expedition first reported wide varieties of metamorphic and plutonic rocks in the mountains (VAN AUTENBOUER and LOY, 1972). A prominent shear zone is developed to traverse the mountains from west to east, showing a variation of rock types from pelitic and psammitic gneisses in the north side to intermediate ones in the south side (KOJIMA and SHIRAISHI, 1981).

The radiometric ages from the Sør Rondane Mountains reported so far are 1167 ±127 Ma by Rb/Sr (SHIRAISHI and KAGAMI, 1989), 470–550 Ma by Rb/Sr (PICCOTTO *et al.*, 1964, 1966) and 440–450 Ma by $^{40}Ar/^{39}Ar$ (TAKIGAMI *et al.*, 1987), suggesting that fundamental geological structure of this region was set and modified two times through plutonism or metamorphism which occurred in the middle Proterozoic and in the Ordovician to early Silurian.

The first paleomagnetic study of the Sør Rondane Mountains was executed by ZIJDERVERD (1968). He reported stable NRMs of reversed inclination from Seal granites, Vesthaugen monzonites and Lunckeryggen syenites.

We carried out a paleomagnetic study on the western Sør Rondane Mountains in the 30th Japanese Antarctic Research Expedition (JARE-30). A total of 1379 oriented rock samples were collected either by a portable engine drill for 1 inch diameter cores or by a hammer for hand samples.

FUNAKI and TOKIEDA (1990) reported some characteristics of NRMs of the granite and syenite from Pingvinane and Lunckeryggen, which were obtained by the engine drill. This article describes the results of alternating field (AF) demagnetization on the hand samples.

2. Samples

The drill has a good facility to obtain fresh cores even from a massive plane rock. In the polar region, however, its full operation is often limited by the problems of transportation and freezing of core coolant. On the other hand, hand samples are

Table 1. List of hand samples from Sør Rondane Mountains.

Lacality	Site number	Rock kind (Quantity of samples)
Vesthaugen	32	Dolerite dike (18)
1550 nunatak	28*	Dolerite dike (8)
Pilten	4	Granitic rocks in gneiss (20)
Brattnipene	5, 29, 30, 31	Dolerite (23, 20. 9, 11)
	27	Granitic rocks in greiss (24)
Pingvinane	18*	Granitic dike rock (23)
	19, 29*	Aplite vein (26, 13)
	21*	Pegmatite vein (11)
Tanngarden	15	Granitic dike rock (20)
	16	Aplite dike (10)
Otto Borchgrevink	6, 9	Granitic rocks in gneiss (26, 22)
	8	Granitic dike rock (23)
Lunckeryggen	23	Hornblendite (20)
	24*	Granite (15), Tonalite (10)
	25	Syenite (10)
	26	Granitic dike rock (13)
Nils Larsenfjellet	10*, 11, 14	Tonalite (20, 20, 17)
	12	Tonalite (18), Dolerite dike (12)

Drill samples are also collected from the site (*). Locarities are listed in the order north to south.

obtainable anytime if rocks are easy to be broken by a hammer. Actually, in our field works in the Sør Rondane Mountains, most rocks except Pingvinane granites allowed hand samples from fresh portions of them.

The basic plan for our sample collection was that the drill was used for steady supply of the samples from main country rocks, while hand samples were supplementary from some intrusion including dike or vein; only hand samples were collected at several sites where drilling was impossible. The hand samples were oriented using a small tripod hinged with a clinometer and a magnetic compass adjusted to the steep and strong field (Collinson, 1983). We obtained 479 hand samples from the Sør Rondane Mountains in the JARE-30 operation as shown in Table 1. Figure 1 shows localities of hand samples which gave us valuable paleomagnetic information as described below.

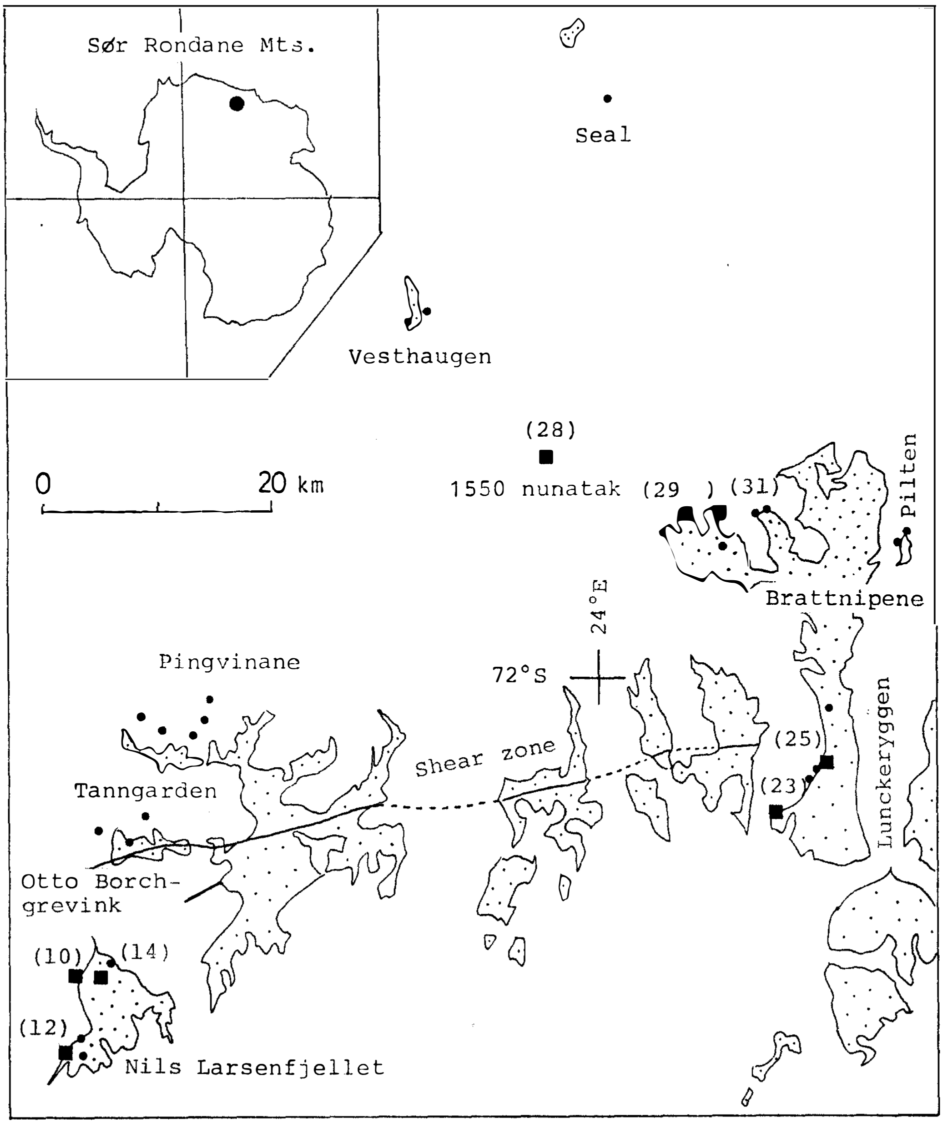

Fig. 1. Locality of sample collection in JARE-30. Solid squares denote sites of hand samples which show clear convergence of NRM directions after AF demagnetization. Figures in brackets are site numbers.

3. Alternating Field Demagnetization and Paleomagnetic Elements

Core specimens of one inch diameter were prepared by drilling the hand samples which were molded in plaster of Paris, with careful transfer of an orientation within an error of 1°. Magnetizations of the specimens were measured either by a spinner magnetometer for those having strength more than 10^{-6} Am^2/kg or by a SQUID

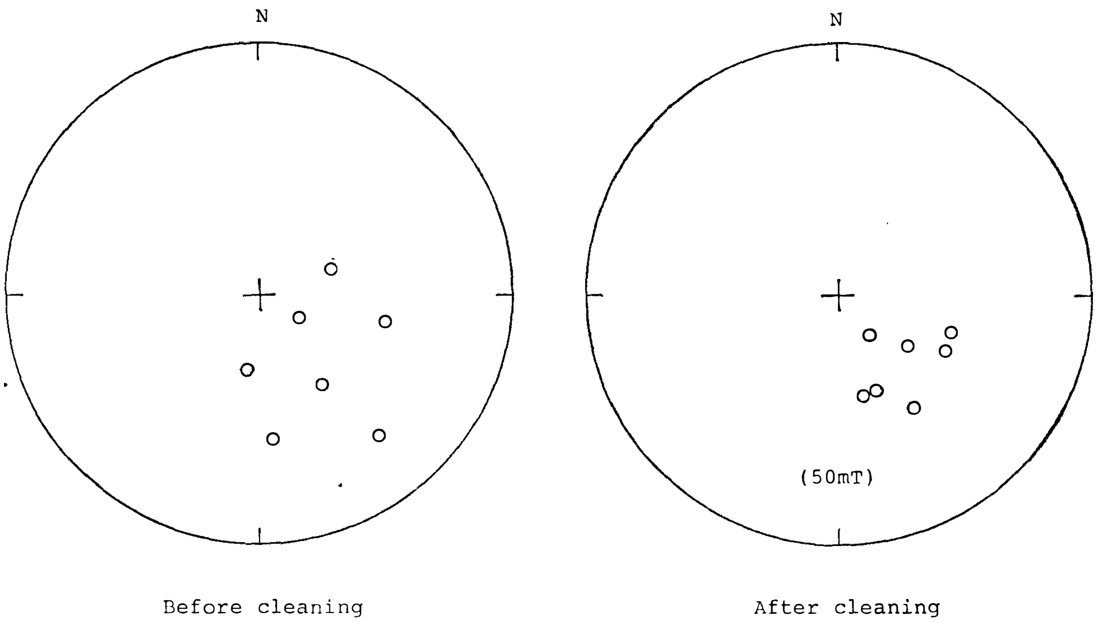

Fig. 2a. NRM directions before and after AF demagnetization, for 1550 nunatak dolerites (site 28).

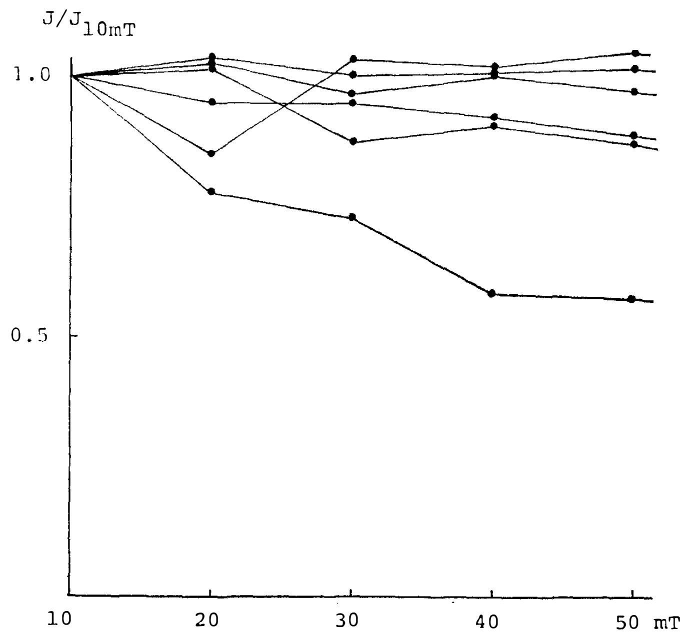

Fig. 2b. Variation of NRM strength with applied field, for 1550 nunatak dolerites (site 28).

magnetometer for weaker ones. Alternating field, smoothly decaying until vanished, was applied to the specimens which were tumbling in a magnetic shield about two axes perpendicular to each other. A usual demagnetization scheme is due to stepwise increase of the field by 10 mT until 60 mT, thereafter by 20 mT up to 100 mT.

A variety of granitic rocks, having unstable and weak NRM $<10^{-7}$ Am²/kg, gave only useless results in a lot of time-consuming experiments. They include gneiss, granites, granitic rocks in gneiss, granitic dike or vein and aplite vein. Pegmatite veins

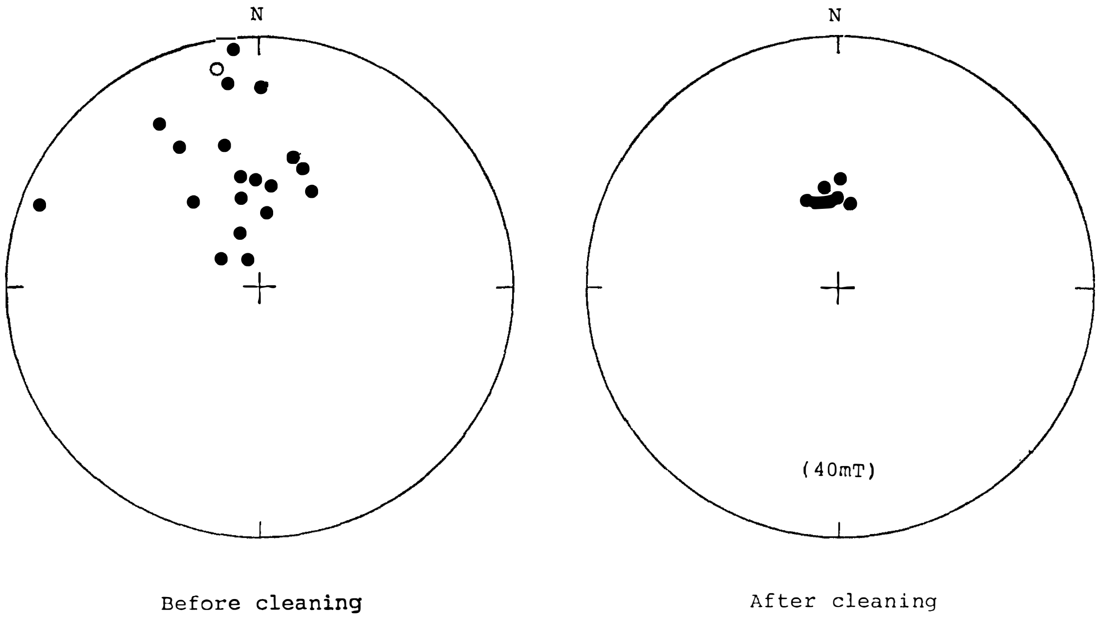

Fig. 3a. NRM directions before and after AF demagnetization, for Brattnipene dolerites (site 29).

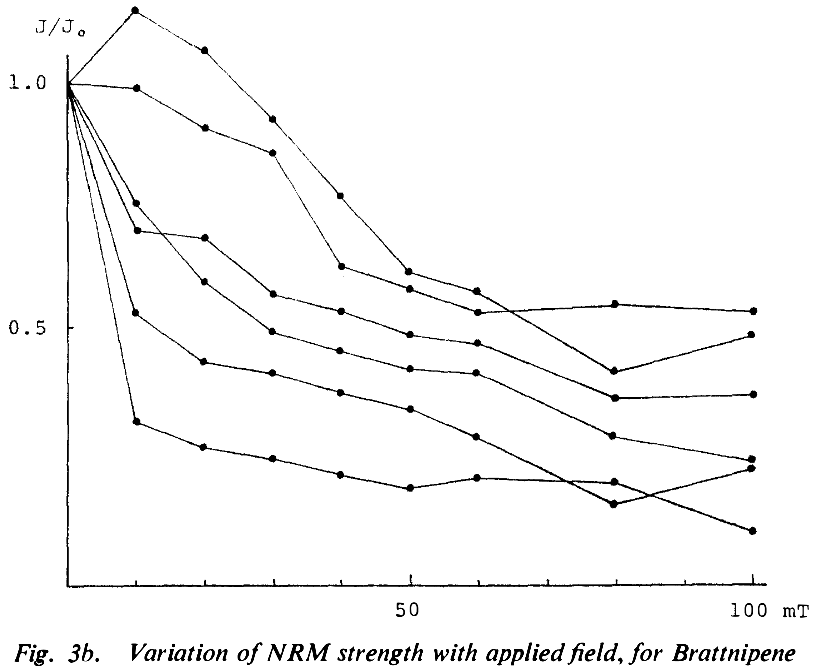

Fig. 3b. Variation of NRM strength with applied field, for Brattnipene dolerites (site 29).

and part of tonalites have also unstable NRMs and failed to give useful results, although their NRMs are rather strong. Some dolerites preserved scattering initial NRM directions even after demagnetization at 120 mT. Thermal demagnetization may work effectively to isolate useful components from them. Consequently clear convergence of NRMs was observed for only 82 samples (17%) from 8 sites. They are 1550 nunatak dolerites (site 28), Brattnipene dolerite (sites 29, 31), Lunckeryggen hornblendites (site 23) and syenites (site 25) and Nils Larsenfjellet tonalites (sites 10, 12–1, 14) and dolerites

Fig. 4a. NRM directions before and after AF demagnetization, for Brattnipene dolerites (site 31).

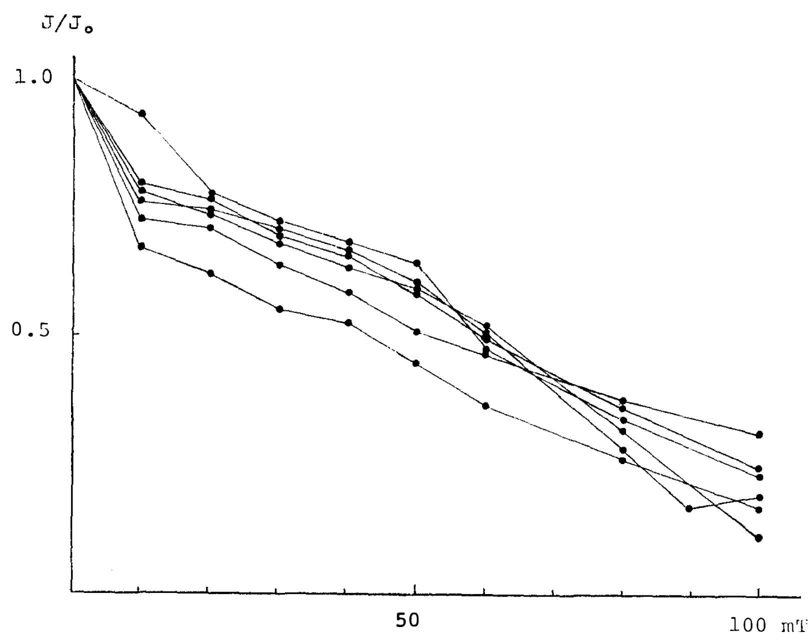

Fig. 4b. Variation of NRM strength with applied field, for Brattnipene dolerites (site 31).

(site 12–2), all having NRM strength more than 10^{-6} Am²/kg.

Results of AF demagnetization are described in the order from the northern to southern locality. The closest focusing of the NRM directions and the demagnetizing field that gave it are shown in figures of "After cleaning".

3.1. 1550 nunatak dolerites (site 28)

A focusing level of the NRM directions was considerably improved after demag-

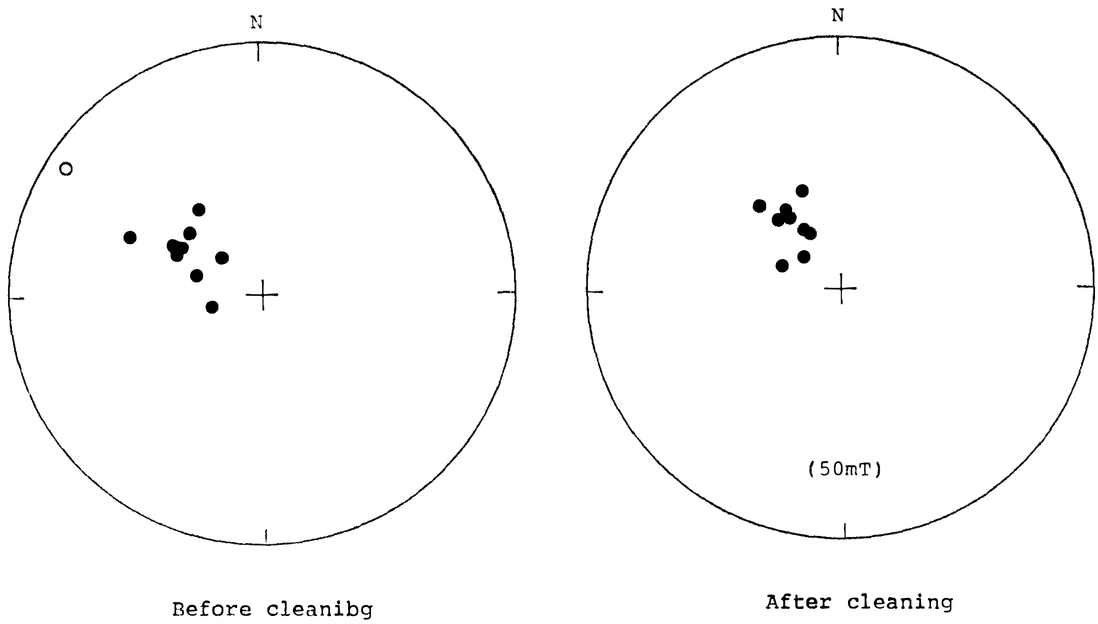

Fig. 5a. NRM directions before and after AF demagnetization, for Lunckeryggen syenites (site 25).

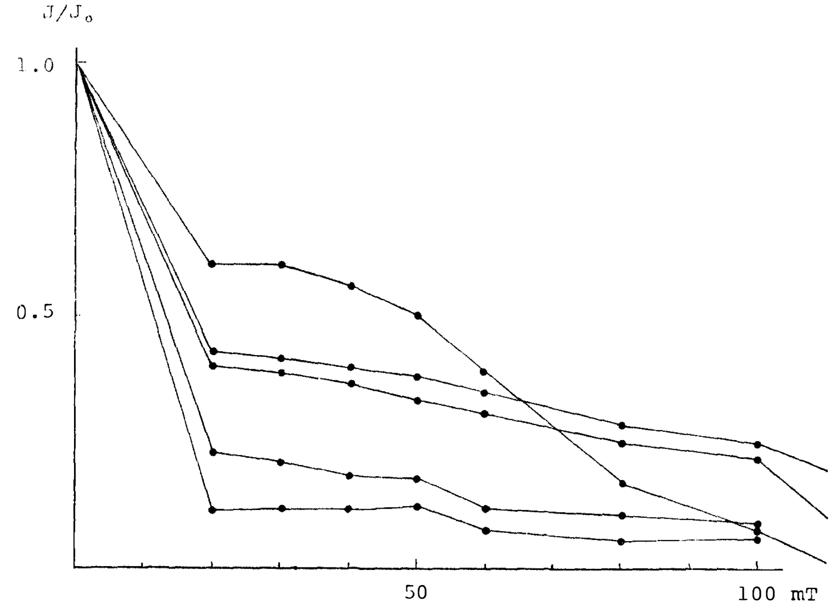

Fig. 5b. Variation of NRM strength with applied field, for Lunckeryggen syenites (site 25).

netization at 50 mT, following only a small decrease of NRM strength (Fig. 2). They are of normal polarity; Nils Larsenfjellet tonalites (site 12) is only another example of the normal polarity in the samples treated.

3.2. Brattnipene dolerites (sites 29, 31)

The dolerites (site 29) show a sharp convergence in their NRM directions after demagnetized at 40 mT. They left a considerable amount of remanence at high field

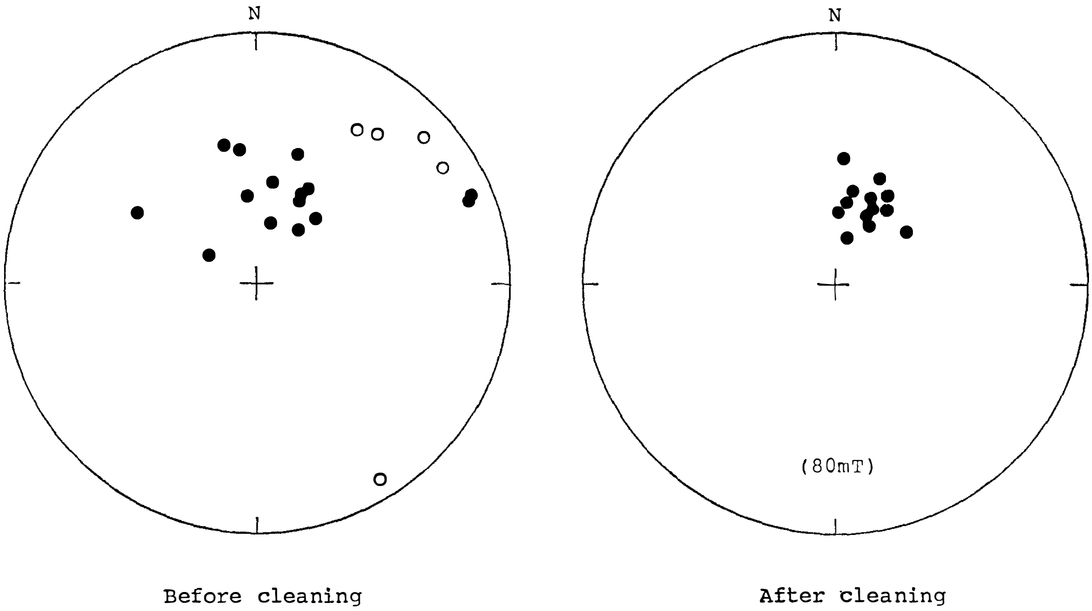

Fig. 6a. NRM directions before and after AF demagnetization, for Lunckeryggen hornblendite (site 23).

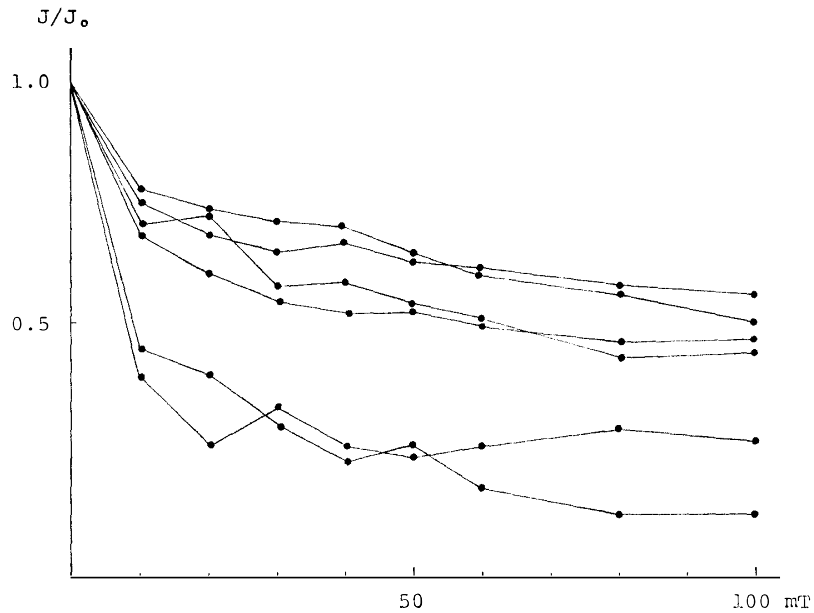

Fig. 6b. Variation of NRM strength with applied field, for Lunckeryggen hornblendite (site 23).

demagnetization up to 100 mT (Fig. 3).

The well clustered initial NRM directions of the dolerite (site 31) suffer a little change after the demagnetization at 80 mT, with a gradual decrease of the NRM strength to 1/3 of the initial values (Fig. 4).

3.3. *Lunckeryggen syenites (site 25) and hornblendite (site 23)*

In both cases, after a rapid decrease of the magnetically soft components around 20 mT, stable components were left behind showing a closer focusing of the NRM directions (Figs. 5, 6).

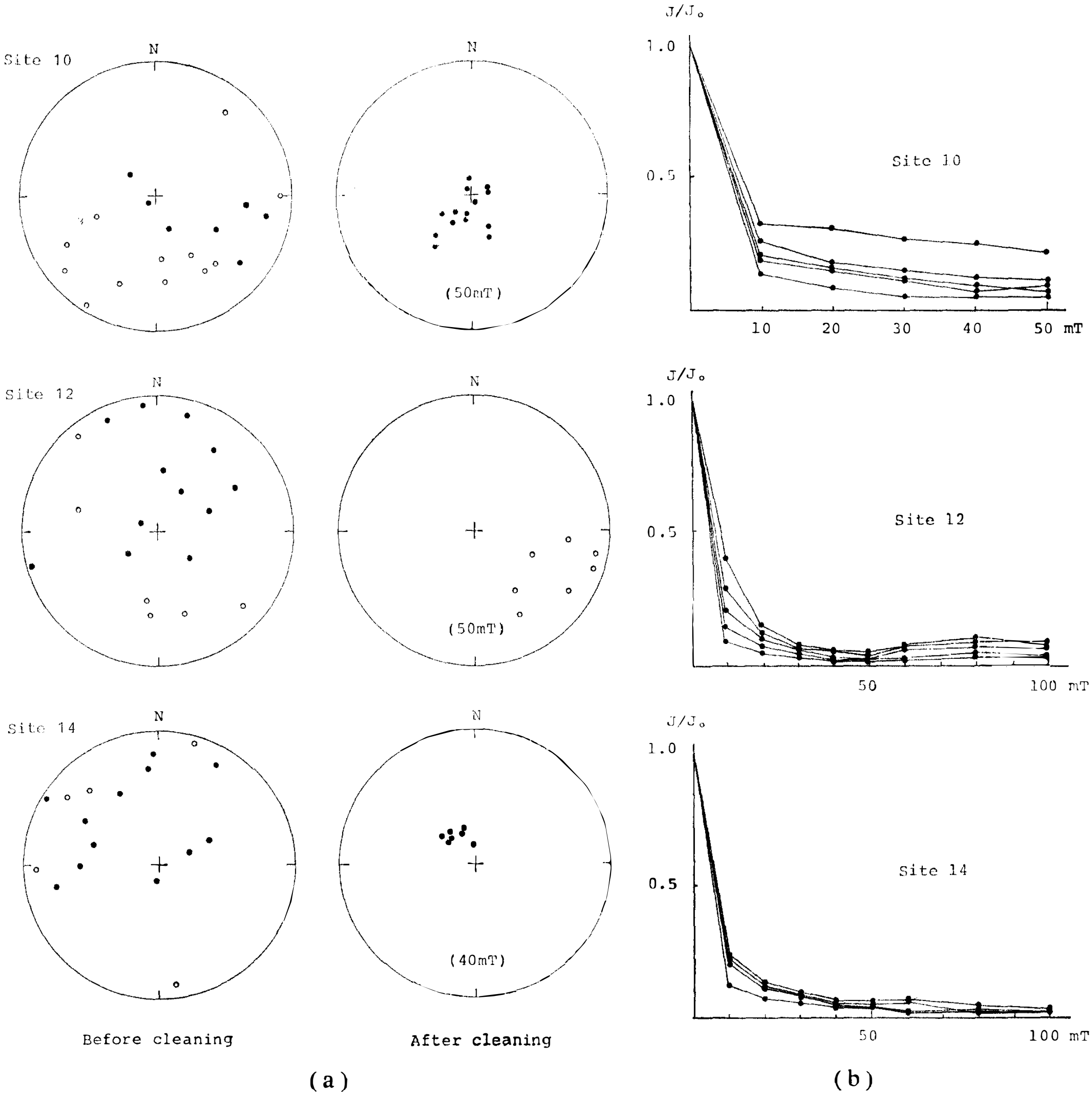

Fig. 7. (a) NRM directions before and after AF demagnetization, for Nils Larsenfjellet tonalites (sites 10, 12-1, 14). (b) Variation of NRM strength with applied field, for Nils Larsenfjellet tonalites (sites 10, 12-1, 14).

3.4. Nils Larsenfjellet tonalites (sites 10, 12–1, 14) and dolerite (site 12–2)

For the tonalites, a large amount of soft component was completely removed after treatment at 10 to 20 mT and consequently a marked convergence of the NRM directions was obtained (Fig. 7). The cleaned components of the tonalites (site 12–1) show the normal polarity.

The initial NRM directions of the dolerite (site 12–1) remain almost unchanged in

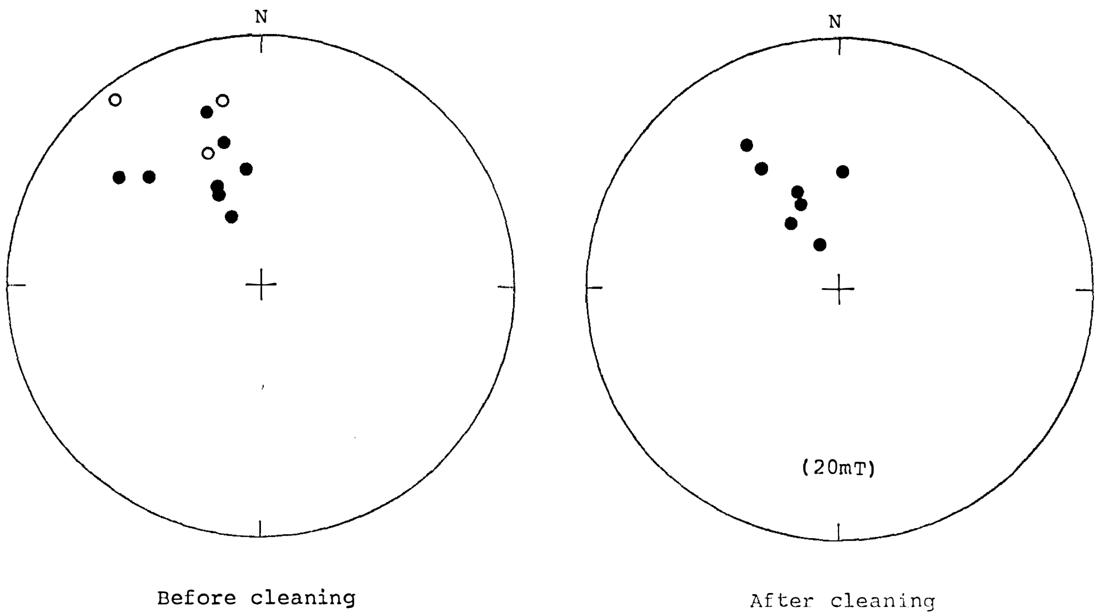

Fig. 8a. NRM directions before and after AF demagnetization, for Nils Larsenfjellet dolerites (site 12–2).

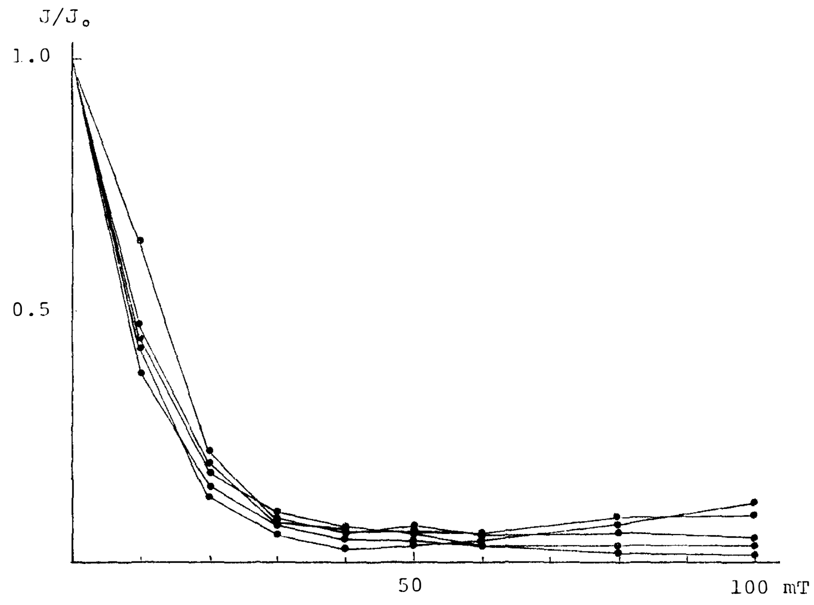

Fig. 8b. Variation of NRM strength with applied field, for Nils Larsenfjellet dolerites (site 12–2).

Table 2. Paleomagnetic elements from 1550 nunatak, Brattnipene, Lunckeryggen and Nils Larsenfjellet.

Locality (site)	Rock kind	I	D	k	θ_{95}	N	Lat.	Long.
1550 nunatak (28)	Dolerite	−56.9°	134.9°	28	11.7	7	24.6°S	14.3°W*
Brattnipene (29)	Dolerite	61.5	−5.8	112	5.3	8	25.6	19.5 E
(31)	Dolerite	67.7	−18.2	80	5.4	10	34.2	10.5 E
Lunckeryggen (23)	Hornblendite	61.1	23.7	59	5.4	13	25.5	43.8 E
(25)	Syenite	62.8	−38.8	71	6.1	9	29.5	6.5 W
Nils Larsenfjellet (10)	Tonalite	79.4	−78.2	17	15.1	14	60.4	21.5 W
(12)	Tonalite	−28.4	118.3	10	20.4	7	6.3	36.2 W*
(12)	Dolerite	51.4	−13.5	10	20.2	7	14.8	10.8 E
(14)	Tonalite	68.7	−34.7	112	5.7	7	36.6	3.2 W

I: Mean inclination; D: Mean declination (positive to east); k: Fisher's precision parameter; θ_{95}: Radius of a circle of 95% confidence; N: Quantity of samples; Lat.: Latitude of VGP; Long.: Longitude of VGP.
South seeking pole is denoted by (*).

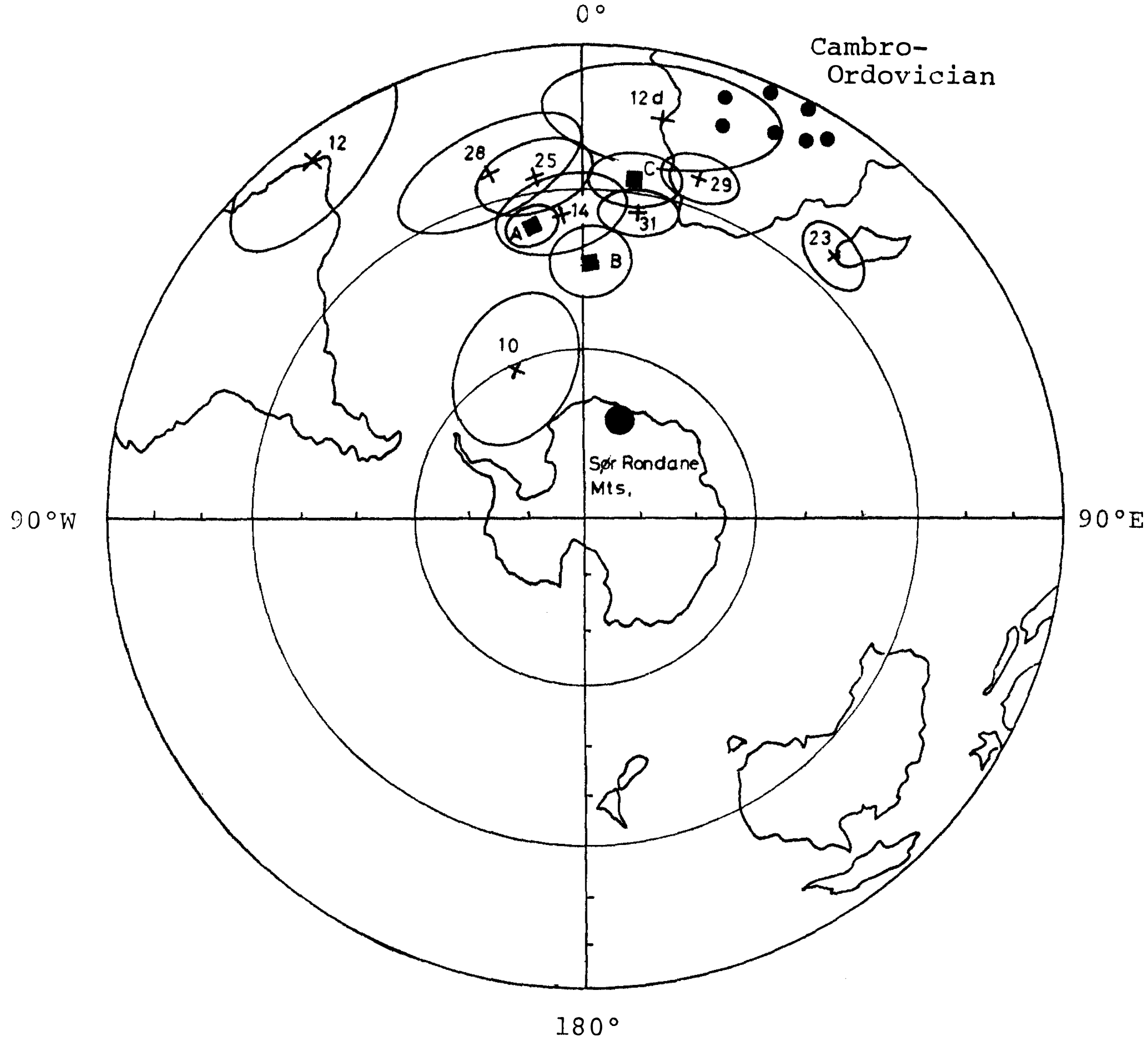

Fig. 9. VGPs of the Sør Rondane Mountains obtained in this study and those reported by others. Figures in brackets denote site numbers in this study. A and B were obtained by FUNAKI and TOKIEDA (1990) and C by ZIJDERVERD (1968).

the demagnetization up to 100 mT, even aftre a large amount of soft components have vanished at 30 mT (Fig. 8).

3.5. Paleomagnetic elements

Paleomagnetic elements were calculated from the cleaned NRM directions of the closest focusing (Table 2). The VGPs obtained are illustrated in Fig. 9 together with reported ones by FUNAKI and TOKIEDA (1990) and by ZIJDERVERD (1968).

4. Undeformed Single Structural Unit in the Sør Rondane Mountains and Reliability of Remanence

It is noted that several VGPs (sites 25, 28, 29, 31) are concentrated in a small area off the southwest coast of Africa combined with reported ones (A, B, C). Their localities are 1550 nunatak (site 28), Brattnipene (sites 29, 31), Lunckeryggen (sites 25, B), Pingvinane (site A), Vesthaugen (site C). They bound, except Lunckeryggen, some area in the northern side of the shear zone which runs from west to east through the Sør Rondane Mountains. The shear zone, extending eastward from Otto Borchgrevink, comes to an end just before reaching Lunckeryggen. There is no evidence of its further going through Lunckeryggen. This implies that the geological structure of Lunckeryggen can be dealt with as forming a single rigid unit with the northern area, because it was possibly little affected by a structural movement involved in the shear zone.

On the other hand, similar K-Ar ages of early Ordovician were reported from several rocks which yielded the marked concentration of the VGPs (TAKIGAMI and FUNAKI, 1991). They are 487 ± 8.6 Ma for the Pingvinane granite, 491.8 ± 8.8 Ma for the Lunckeryggen syenite, 482.1 ± 20 Ma for the Brattnipene dolerite and 488 ± 18 Ma for the 1550 nunatak dolerite.

Generally a close distribution of VGPs of some rocks having similar ages significantly augments paleomagnetic reliability of their remanence. This means also that the rocks concerned have experienced no relative movement.

In conclusion, we consider that the northern side of the shear zone in the Sør Rondane Mountains, including Lunckeryggen though southerly located, have behaved as an undeformed single structural unit, after the rocks had acquired the NRMs in early Ordovician.

5. Tilting Movement of the Sør Rondane Mountians

FUNAKI complied the paleomagnetic results reported from East Antarctica and calculated the Cambro-Ordovician VGPs, which are distributed around Central Africa as illustrated in Fig. 9. It is clear that the results from the Sør Rondane Mountains are significantly deviated beyond errors from those in other regions of East Antarctica, while they covered partly the similar ages in Ordovician. We explain these facts by the conclusion that the undeformed single structural unit of the Sør Rondane Mountains has possibly undergone some tilting movement relative to the rest mass of East Antarctica. Rough estimates of the tilting direction and angle would be N22°E and 15°.

The thick ice cover in Antarctica prevents confirming our consideration by direct field observation. According to a mineralogical study of the metamorphic rocks in the Sør Rondane Mountains (GREW *et al.*, 1989), the high pressure required for producing the observed specific minerals indicates that a great upheaval took place in this district. It is possible that such upheaval causes some tilting movements to explain the observed difference of the Ordovician VGPs from the Sør Rondane mountains and those from the rest mass of East Antarctica.

6. Interpretation of VGPs from Lunckeryggen Hornblendite

The hornblendite (site 23) yields its VGP near Madagascar, demonstrating a clear westerly shift from that of the syenite, a member of the tight cluster. The hornblendite and syenite came from the same area in Lunckeryggen and their sites are not far apart from each other. There is no field evidence in the area to indicate a local tectonic movement likely to cause such VGP shift. Both the syenite and hornblendite were possibly accompanied with the same volcanic activity, so we consider that the westerly shift of the hornblendite VGP arose from a spot reading of the geomagnetic variation when the hornblendite was embedded after the emplacement of the syenite, although age of the hornblendite is unknown.

7. Precambrian VGP and Possible Precambrian to Cambro-Ordovician APWP from Nils Larsenfjellet

Nils Larsenfjellet consists mainly of tonalites and dolerite dikes intruding them. They are apparently separated by the shear zone from its north side, which we consider to represent the undeformed single structural unit. We have no exact information whether or not Nils Larsenfjellet was actually affected by the shear zone. But it is safe to discuss paleomagnetic results from Nils Larsenfjellet independently from those of the north side.

In Nils Larsenfjellet, the VGPs show a large scattering; a K-Ar age of 662 ± 23 Ma is available only from the tonalites of site 10 (TAKIGAMI and FUNAKI, 1991). It is impossible to confirm reliability of magnetically cleaned remanences on the basis that they have similar ages and yield the analogous VGPs. The following discussion is somewhat speculative because it depends on only the magnetic cleaned data.

The Precambrian VGP (tonalites, site 10) is located at 60.4°S, 21.5°W, near Antarctica. Starting from this point, the VGPs from Nils Larsenfjellet seems to trace a smooth curve approaching to the Cambro-Ordovician ones of East Antarctica, subsequently passing along those of the tonalites (site 14) and the dolerite dike (site 12), with an exception of tonalites (site 12) showing a great departure at the eastern end of Brazil. We consider that this curve represents an apparent polarwander path (APWP) from Nils Larsenfjellet, and the departure of dolerite (site 12) arose from an unusual geomagnetic disturbance. The separated VGPs of the tonalites (sites 10, 12, 14) indicate that volcanic or metamorphic activity occurred at least three times since 662 Ma.

Thermal demagnetizations, other methods of the rockmagnetism and more age determinations are needed to verify these interesting problems.

Acknowledgments

We thank the leader of JARE-30, Prof. M. EJIRI, and also members of the Sør Rondane Mountains field survey for their help in our sample collections. We thank Messrs. R. AOKI, Y. OZASA, T. OHARA and M. NAKAMURA, students of Shimane University, for their laborious works in demagnetization experiments.

References

COLLINSON, D.W. (1983): Methods in Rock Magnetism and Palaeomagnetism: Techniques and Instrumentation. London, Chapman and Hall, 503 p.

FUNAKI, M. and TOKIEDA, K. (1990): Natural remanent magnetizations of granite and syenite from Pingvinane and Lunckeryggen in the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **4**, 67–79.

GREW, E.S., ASAMI, M. and MAKIMOTO, H. (1989): Preliminary petrological studies of the metamorphic rocks of the eastern Sør Rondane Mountains. Proc. NIPR Symp. Antarct. Geosci., **3**, 100–127.

KOJIMA, S. and SHIRAISHI, K. (1981): Note on the geology of the western part of the Sør Rondane Mountains, East Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **43**, 116–131.

PICCIOTTO, E., DEUTSCH, S. and PASTEELS, P. (1964): Isotopic ages from the Sør Rondane Mountains, Dronning Maud Land. Antarctic Geology, ed. by R.J. ADIE. Amsterdam, North-Holland, 570–578.

PICCIOTTO, E., DEUTSCH, S. and PASTEELS, P. (1966): Mesures d'ages par les methodes isotopiques de mineraux et de roches des monts Sør-Rondane. Expedition Antarctique Belge 1957–1958, Resultats Scientifiques, **7**, 233–266.

SHIRAISHI, K. and KAGAMI, H. (1989): Preliminary geochronological study of granulites from the Sør Rondane Mountains, East Antarctica—A comparison of Rb-Sr and Sm-Nd ages (abstract). Proc. NIPR Symp. Antarct. Geosci., **3**, 152.

TAKIGAMI, Y. and FUNAKI, M. (1991): ^{40}Ar-^{39}Ar and K-Ar ages for igneous and metamorphic rocks from the Sør Rondane Mountains, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **5**, 122–135.

TAKIGAMI, Y., KANEOKA, I. and FUNAKI, M. (1987): Age and paleomagnetic studies for intrusive and metamorphic rocks from the Sør Rondane Mountains, Antarctica. Proc. NIPR Symp. Antarct. Geosci., **1**, 167–177.

VAN AUTENBOUER, T. and LOY, W. (1972): Recent geological investigations in the Sør Rondane Mountains, Belgicafjella and Sverdrupfejlla, Dronning Maud Land. Antarctic Geology and Geophysics, ed. by R.J. ADIE. Oslo, Universitetsforlaget, 563–571.

ZIJDERVERD, J.D.A. (1968): Natural remanent magnetizations of some intrusive rocks from the Sør Rondane Mountains, Queen Maud Land, Antarctica. J. Geophys. Res., **73**, 3773–3785.

(Received February 27, 1991; Revised manuscript received April 23, 1991)