—研究論文—
Scientific Papers

Natural Remanent Magnetization of the Napier Complex in Enderby Land, East Antarctica

Minoru FUNAKI*

東南極，エンダービーランド，ナピーアコンプレックスの自然残留磁気

船 木 實*

要旨：東南極大陸ナピーアコンプレックスから採集された約38億年前の岩石試料について，古地磁気学的研究を行った．得られた10個の試料のうち，5個は交流消磁と熱消磁に対して安定であったが，残りの5個の試料は不安定であった．安定な残留磁気を持つ試料は，主に単磁区ないし擬単磁区構造を持つ磁鉄鉱である．

変成年代などを考慮すると，ナピーアコンプレックスは25億年前の地球磁場を記憶し，冷却速度が遅かったため，地球磁場の変動も記憶している．最も信頼できる残留磁気の方向は，480°C の熱消磁で得られ，その方向は，伏角−82.9°，偏角 39.3° で，これから計算される古地磁気極は，南緯 75.0°，東経 14.5° である．

Abstract: Paleomagnetic studies were performed with the oldest rocks reported (about 3800 m.y.), collected from the Napier Complex in East Antarctica. Five specimens have stable NRM against AF and thermal demagnetizations, but other five have unstable one. The main NRM carriers in the former specimens are pure magnetite of single-pseudosingle domain structure. The Napier Complex was remagnetized completely in the amphibolite facies metamorphism 2500 m.y. ago. Since the cooling rate of the Complex was very slow at that time, it recorded the changing geomagnetic field. The most reliable NRM direction obtained is −82.9° inclination and 39.3° declination by thermal demagnetization to 480°C, and the corresponding VGP position is calculated to be latitude 75.0°S and longitude 14.5°E.

1. Introduction

Although geological and geochronological aspects of the Napier Complex, Enderby Land, East Antarctica, have been reported (*i.e.* GREW and MANTON, 1979), indicating that this is one of the oldest crust of the world, no paleomagnetic studies of the Complex have been reported up to the present.

During the 23rd Japanese Antarctic Research Expedition, H. MATSUEDA and Y. MOTOYOSHI of the geological team collected ten oriented rock samples from the coast of Amundsen Bay with an engine core drill for paleomagnetic investigations.

2. Geology of Napier Complex

The Napier Complex consists of pyroxene granulite, orthopyroxene-quartz-feldspar gneiss, quartzite and granitiferous gneisses (GREW and MANTON, 1979). Ac-

* 国立極地研究所．National Institute of Polar Research, 9–10, Kaga 1-chome, Itabashi-ku, Tokyo 173.

cording to the geological and geochronological studies (BLACK and JAMES, 1983) of the Complex, an initial acidic igneous crust was formed at 3700–3800 m.y. (U-Pb in zircon data supported by Rb-Sr determination age), and then was subjected to three phases of metamorphism and some dyke intrusions as follows:

Metamorphism	D1	3100 m.y.	:	Granulite facies metamorphism
	D2	2900	:	Granulite facies condition
	D3	2450–2500	:	Upper amphibolite to granulite
Dyke intrusions		2350±45, 1190±20	:	Tholeiite dykes intrusion
		1000	:	Granulite-facies tectonothermal event in the adjacent Rayner Complex
		520	:	Minor pegmatite
		482±3	:	Small alkaline dyke

HARLEY (1983) reported the available pressure-temperature-time models of the Napier Complex using granulites which display a variety of exsolution, recrystallization and corona textures. His conclusions are:

(a) The peak metamorphic conditions during the first and second major deformation phases (D1 and D2) were found to be 900–950°C, 7–10 k bar and 3100–3000 m.y. ago.

(b) Locally, the minimum crustal thickness must have been of the order of 30 km.

(c) Subsequent to the peak granulite facies metamorphism, D3 occurred at 650–700°C, 5–8 k bar and 2500 m.y. ago.

ELLIS (1983) estimated from the metamorphism conditions that the Napier Complex granulites were crystallized at 8–12 k bar and 900–1000°C on a local scale. MCCULLOCH and BLACK (1983) reported the metamorphism ages as 3050±210 and 2500 m.y. from $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ isotopic determination.

3. Characteristics of NRM

From all core samples, 2 specimens of 1 inch in length and diameter were cut out for tests of natural remanent magnetization (NRM) against AF and thermal demagnetizations. The magnetic field intensity in AF and thermal demagnetizer is less than 100 and 20 γ respectively.

The AF demagnetization tests were done with 10 specimens of group A (AF 1, 2... 5) and B (AF 6, 7... 10) in steps of every 50 Oe up to 500 Oe. The representative AF demagnetization results of the group A specimens are shown in Fig. 1a. The demagnetization characteristics of normalized intensities are essentially similar to one another for these specimens; the original intensities, $6.0–8.8 \times 10^{-5}$ emu/g, changing relatively steep from 0 to 150 Oe for all specimens, and then gradually to 500 Oe for AF1 and AF3 and to 300 Oe for AF2 specimens. The value of MDF (median demagnetization field) is about 150 Oe, for all specimens. Therefore, these specimens have soft and hard components of magnetizations before the demagnetization to 150 Oe, and their values of original intensities are almost same.

The AF demagnetization curves of the group B specimens are shown in Fig. 1b. The original intensities of 3 representative specimens are $5.0–74 \times 10^{-3}$ emu/g with less

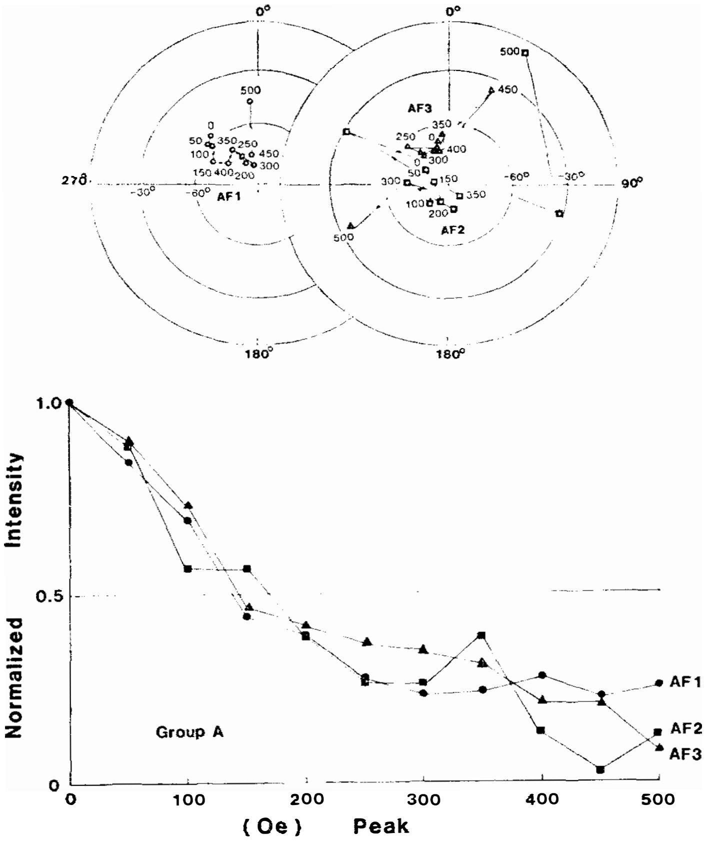

Fig. 1a. *AF demagnetization curves of NRM for group A specimens.*

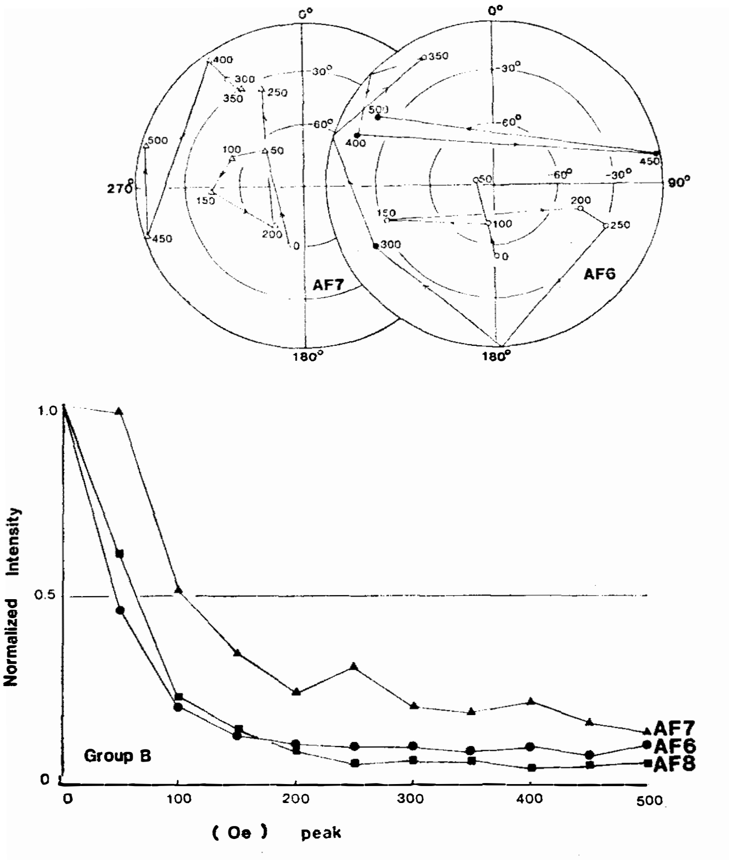

Fig. 1b. *AF demagnetization curves of NRM for group B specimens.*

than 100 Oe MDF. These intensities are demagnetized by more than 70% from the original value at 150 Oe. The directional changes of AF6 and 7 specimens are fairly unstable even in weak demagnetization fields as shown in Fig. 1b. The same characteristic occurs with AF8 specimen. Therefore, the specimens of group B are not able to have reliable stable remanent magnetization.

The thermal demagnetization test has been applied to the all specimens of group A from 30 to 580°C in steps of 50°C. The demagnetization results of two representative directions and five intensities change curves are shown in Fig. 2. The specimens number, TD 1 . . . 5 correspond in order to the specimens of AF 1 . . . 5, which were used to the AF demagnetization tests. The original intensities of TD 1 . . . 5 are in the range of $5.7–9.1 \times 10^{-5}$ emu/g. These intensities are demagnetized steeply between 30, 180 and 480 to 580°C, but smoothly from 180 to 480°C. The smooth demagnetization area may be divided into two parts at 330°C; the curve of the first half decreases but that of the other half increases gradually. The directional NRMs do not change markedly from 80 to 480°C for all specimens, but they become scattered against thermal demagnetization at 530 to 580°C.

From these demagnetization tests, one may conclude that every specimen of group A has very soft and hard magnetic components. The soft magnetic components, responsible for more than a half of the original intensity, can be demagnetized almost completely by AF and thermal demagnetizations up to 150 Oe and 180°C respectively. The hard magnetic components are stable at least up to 300 Oe and 480°C. However,

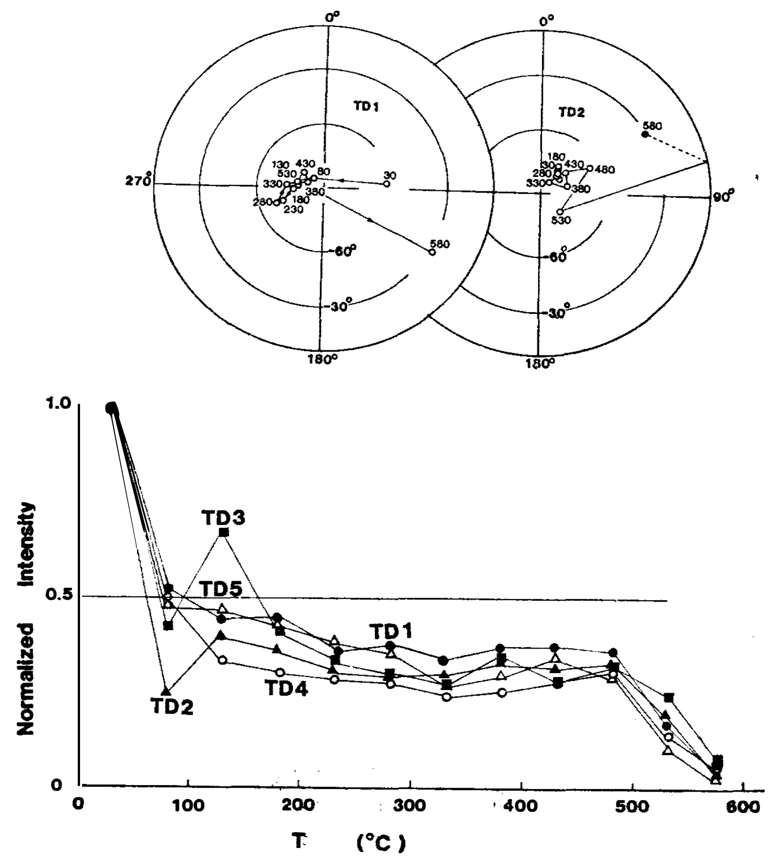

Fig. 2. Thermal demagnetization curves of NRM for group A specimens

the group B specimens exhibited only unstable magnetization even in a weak demagnetization field.

4. Basic Magnetic Properties and Mineralogy

Thermomagnetic curves (Fig. 3) were obtained with a vibrating sample magnetometer, at 1.1×10^{-2} Pa pressure, by applying magnetic field intensity of 10 k Oe and heating and cooling rate of 200°C/h. The saturation magnetizations before heating at 10 k Oe are 0.43 emu/g for the group A specimens and 4.83 emu/g for the group B ones.

The thermomagnetic curves from the group A specimens are irreversible, presenting a clearly defined Curie point of magnetite at 580°C and a small gradual natural change around 400°C. The saturation magnetization after the first run heating is increased by about 13% at room temperature. In the cooling curve, the magnetite Curie point only is clearly observed. The second run thermomagnetic curves of these specimen are consistent with the first run cooling curves. A magnetization change around 400°C in the first run heating curve may be due to the chemical alteration of maghemite or iron sulfide. The thermomagnetic curves of the group B specimens are reversible with only one clearly defined Curie point at 580°C. Therefore, the magnetic mineral in these specimens is only magnetite.

The magnetic hysteresis curves were also measured with a vibrating sample magnetometer at room temperature, the saturation magnetization (I_S), the saturation remanent magnetization (I_R), the coercive force (H_C) and remanent coercive force (H_{RC}) being determined from these curves. The data for the groups A and B specimens are listed in Table 1. The values of I_S indicate the amount of magnetic minerals in the specimens. According to the thermomagnetic analysis, the magnetization of the

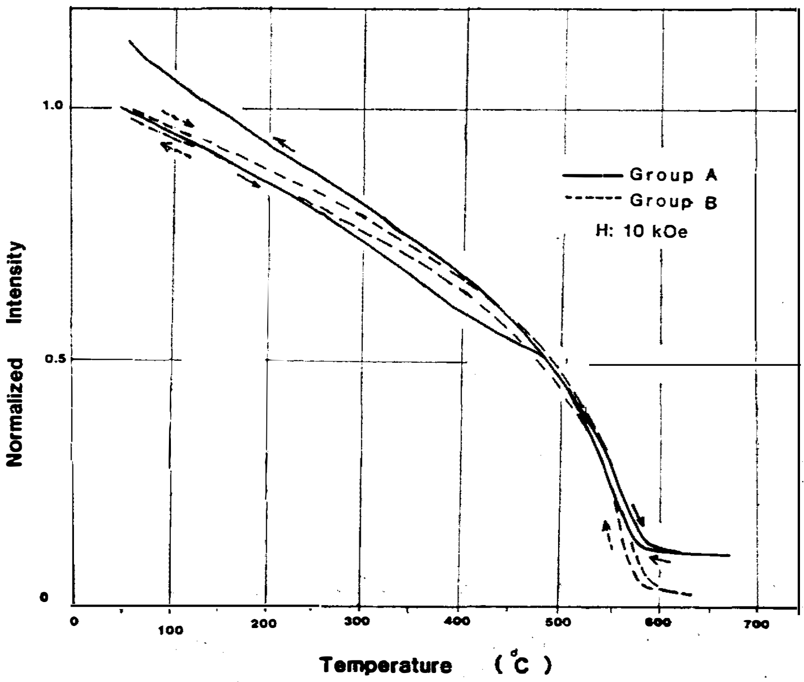

Fig. 3. Thermomagnetic curves of the 1st run cycle for groups A and B.

Table 1. Basic magnetic hysteresis data of representative samples of groups A and B specimens.

Group	I_S (emu/g)	I_R (emu/g)	H_C (Oe)	H_{RC} (Oe)	I_R/I_S	H_{RC}/H_C
A	0.31	0.048	113	332	0.155	2.9
B	4.53	0.245	55	194	0.054	3.5

groups A and B specimens are essentially due to magnetite and a small amount of other magnetic minerals. Since the saturation magnetization of magnetite (I_S(Mt)) is 92 emu/g at 24°C, its content in a specimen (V_A, V_B) is calculated as $V = I_S/I_S$ (Mt). The amounts of magnetite for the groups A and B specimens were found to be 0.34 and 4.92 wt% respectively.

As shown in Table 1, the values of I_R/I_S and H_{RC}/H_C are 0.16 and 2.9 for the group A and 0.054 and 3.5 for the group B specimens respectively. According to the relationships of the magnetic hysteresis properties and the domain structures investigated by DAY *et al.* (1977), the above values indicate that the specimens of groups A and B are single–pseudosingle domain and pseudosingle–multi domain structures.

The specimens of groups A and B acquired SIRM and ARM in the test of stability against AF demagnetization up to 1300 Oe. A steady magnetic field $\bar{h}$ // +z, is given for SIRM test. The acquisition of ARM is carried out in $\bar{h}$ = 0.44 Oe of steady magnetic field with $\tilde{H}$ = 1300 Oe peak of the alternating magnetic field, $\bar{h}$ // $\tilde{H}$ // +z. The stability sequences of these specimens against AF demagnetization are in the order ARM > NRM > SIRM for the group A specimens, and SIRM > ARM > NRM for the group B specimens. JOHNSON *et al.* (1975) examined the stability of ARM and SIRM of fine-grained (<0.2 μ in diameter) and coarse-grained (210–250 μ in diameter) magnetites against AF demagnetization. Their results show that ARM is stabler than SIRM for fine-grained magnetite and that it is less stable than SIRM for the coarse-grained one. It seems, therefore, that the specimens of group A contain reasonably fine-grained (possibly single–pseudosingle domain structure) magnetite while that of group B coarse-grained (pseudosingle–multi domain structure) magnetite.

Polished thin sections of a group A specimen were prepared for reflected-light microscopic observations and electron probe microscopic analyses (EPMA). In this specimen, magnetite, ilmenite and iron sulfide grains were observed as opaque minerals. These minerals are present in small aboundance and only in small grain size, less than 20 μ in diameter. Exsolution of ilmenite or magnetite structures is not observed on the surface of the magnetite grains at 1000 magnifications. The results of EPMA analyses for these opaque minerals show that magnetite (Fe_3O_4), ilmenite ($FeTiO_4$), pyrite (FeS_2) and pyrrhotite (Fe_7S_8–FeS) are included in the group A specimen. The chemical compositions of two different grains correspond only to magnetite associated with TiO_2 and Cr_2O_3 in small percentages, 0.340 and 1.978 wt% respectively.

5. Mean Natural Remanent Magnetization

The intensities and the directions of NRM before and after AF demagnetization by an optimum demagnetizing field of 150 Oe were measured for all 10 specimens of

Table 2. Paleomagnetic results by AF demagnetization of pyroxene granulite from Napier Complex.

Group	N	Demag.	In ($\times 10^{-4}$ emu/g)	Inc	Dec	K	α_{95}	pLat	pLon
A	5	0	0.75	−76.5°	302.9°	26	15.0°	—	—
		150	0.38	−84.8	329.4	48	11.1	74.9°S	71.3°E
B	5	0	36.79	−80.0	85.2	8	27.4	—	—
		150	10.24	−82.7	279.9	7	29.0	—	—

the Amundsen Bay area. The results are shown in Table 2, in which, N: sample number, In: mean intensity of NRM, Inc and Dec: mean inclination and declination of NRM, K: precision parameter, α_{95}: radius of 95% confidence, pLat and pLon: paleolatitude and paleolongitude of virtual geomagnetic pole (VGP).

The distributions of directional NRM of the group A specimens lead to a good cluster by AF demagnetization; the K and the α_{95} values change from 26 to 48 and from 15.0 to 11.1° respectively. The original mean directional NRM shifts by 9.1° in spherical coordinates, with resulting values Inc = −84.4° and Dec = 329.4°, by the demagnetization. The value of In decreases by about 50% from 0.75 to 0.38×10^{-4} emu/g. In the case of the group B specimens, however, the In value decreases by 28% from 36.79 to 10.24×10^{-4} emu/g and the original distributions of NRM are scattered by the AF demagnetization. Consequently, a reasonable VGP position is calculated for the group A specimens as pLat = 74.9°S and pLon = 71.3°E, as is shown in Fig. 4.

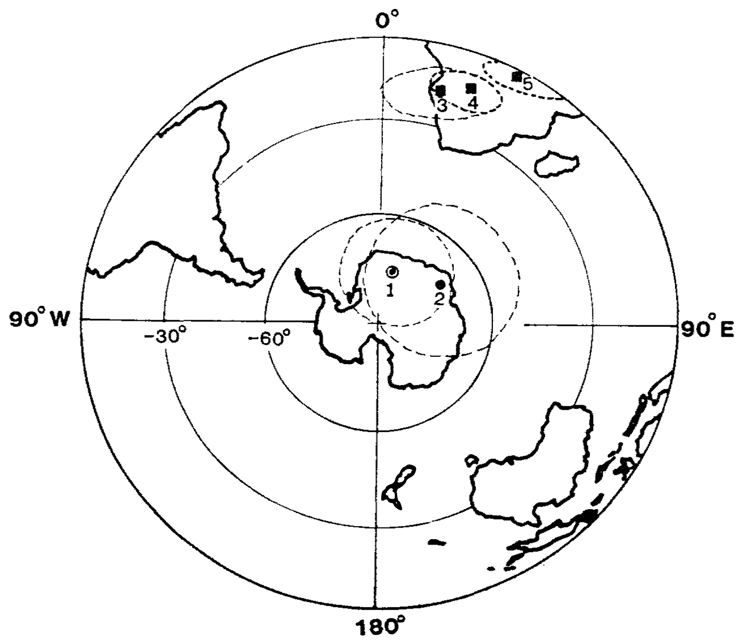

Fig. 4. VGP positions from early Paleozoic to Archeozoic ages.
1. Present work (thermal demagnetization at 480°C), 2. Present work (AF demagnetization at 150 Oe), 3. EMBLETON and ARRIENS (1973), 1000 m.y. ago, Vestfold Hills, 4. FUNAKI (1982), Cambro-Ordovician age, McMurdo Sound, 5. MCQUEEN et al. (1972), Cambro-Ordovician age, Mirny Station.

Table 3. Change of the average NRM of 5 samples against thermal demagnetization for pyroxene granulite from Napier Complex.

T (°C)	In ($\times 10^{-5}$ emu/g)	Inc	Dec	K	α_{95}	pLat	pLon
30	6.50	−78.3°	201.5°	4	43.5°	45.4°S	62.5°E
80	2.98	−85.0	289.3	12	22.1	68.2	77.0
130	3.13	−77.0	322.5	21	16.8	75.3	125.7
180	2.65	−82.3	340.2	32	13.5	79.9	81.3
230	2.37	−84.4	339.5	28	14.5	76.8	68.2
280	2.26	−85.0	316.0	27	14.8	72.7	74.8
330	2.06	−85.4	331.1	33	13.3	74.3	67.5
380	2.23	−85.9	5.6	55	10.3	75.0	47.9
430	2.28	−85.8	41.6	63	9.6	72.4	32.5
480	2.32	−82.9	39.3	86	8.2	75.0	14.5
530	1.19	−83.1	314.6	54	10.4	73.5	87.3
580	0.36	13.3	196.5	—	—	—	—

T: Temperature (°C), In: Mean intensity, Inc: Mean inclination, Dec: Mean declination, K: Precision parameter, α_{95}: Radius of 95% confidence circle about mean direction, pLat: Paleolatitude, pLon: Paleolongitude.

All specimens of group A with stable NRM have been tested by stepwise thermal demagnetization at every 50°C from 30 to 580°C. The results are shown in Table 3. The values of In are demagnetized steeply from 30 to 130°C and from 530 to 580°C, but from 180 to 480°C they are almost consistently 30–40% of the initial value. Although the mean directional NRM is different between neighboring steps of the thermal demagnetization, it does not exceed 3° at temperatures from 170 to 480°C. The mean directions from 180 to 280°C are almost parallel to that of the AF demagnetization up to 150 Oe; the angle of the differential vectors between both directions are less than 2.8°. Therefore it may be concluded that the soft magnetic components, *i.e.* IRM and VRM, are almost completely demagnetized up to 180°C and the hard components survive at least to 480°C against thermal demagnetization. The values of K and α_{95} suggest that the individual directions gather in the center of the mean direction up to 480°C, but they start to scatter from 530°C up. Therefore, the NRM obtained at 480°C thermal demagnetization would have been the most reliable geomagnetic field direction when the Amundsen Bay area was finally metamorphosed at the age of 2500 m.y. The calculated VGP position and the 95% confidence are shown in Table 3 and illustrated in Fig. 4.

6. Discussion

As mentioned above, the Napier Complex had experienced two times of granulite (D1 and D2) and one time of amphibolite (D3) facies metamorphism, and then four times of dyke intrusions (BLACK and JAMES, 1983). Since the estimated temperature of final metamorphism D3 would be 650–700°C, it exceeds the magnetite Curie point of 580°C. As a consequence, the acquired magnetizations at D1 and D2 metamorphisms must have been fully remagnetized at that time. On the other hand, the thermal influences resulting from dyke intrusions to the granulite body would be limited along the dykes. According to CARSLAW and JAEGER (1959), if a completely molten dyke at 1100°C intruded into a granite body, the maximum temperature of the granite does not exceed 200°C at a point at a distance of the dyke thickness from its surface. Since there is no evidence of dyke intrusions around the sampling area, their thermal influences can be neglected. Therefore, the granulite of the Napier Complex should have recorded the geomagnetic field when the Complex was finally metamorphosed 2500 m.y. ago.

The angular deviation between the VGP positions obtained from AF and thermal demagnetization results is 7.2°, as shown in Fig. 4, but they cannot be fully separated from each other since they present very close α_{95} values. However, the VGP positions change almost systematically by thermal demagnetization from 180 to 480°C as shown in Table 3. The thermal demagnetization results of group A suggest that the TRM was acquired from the magnetite Curie point 580 to 480°C, so that the Complex might have been magnetized mainly during that temperature range. We conclude that the Napier Complex recorded the changing geomagnetic field during the slow cooling period, being magnetized mainly from 580 to 480°C, in the D3 metamorphism. Since the Complex was metamorphosed under the conditions of high temperature and pressure (650–700°C and 5–8 k bar respectively, HARLEY, 1983), it must have been heated at a fairly deep part of the crust.

EMBLETON and ARRIENS (1973) reported a VGP position of the Archean age (1000 m.y.) from the Vestfold Hills (68.5°S, 78.0°E) in East Antarctica. They obtained the mean direction of NRM as −42.5° in inclination and 107.5° in declination with α_{95} value 11°. The calculated VGP position from this NRM direction is latitude 17°S and longitude 13°E, as shown in Fig. 4 (number 3). This position is very close to the Cambro-Ordovician VGPs obtained from East Antarctica (Fig. 4, numbers 4 and 5), reported from the McMurdo Sound (FUNAKI, 1982) and Mirny Station (MCQUEEN *et al.*, 1972) respectively. It is important to observe that the VGP position of Amundsen Bay is completely different from that of the VGP of the early Paleozoic and the VGP of 1000 m.y. ago.

7. Conclusion

The granulite specimens including fine-grained magnetite (group A) collected from the Napier Complex present a stable NRM against AF and thermal demagnetizations, but for specimens including large-grained magnetite (group B) the magnetization is not stable. The NRM carriers are magnetite and pyrrhotite for group A and magnetite for group B. However, the contribution of pyrrhotite is much smaller than that of magnetite in group A. The domain structures of magnetite are single–pseudosingle and pseudosingle–multi domain for groups A and B respectively. The Napier Complex was remagnetized when it was finally metamorphosed in the amphiborite facies metamorphism 2500 m.y. ago, mainly in the cooling stage from 580 to 480°C. As the Complex cooled down slowly from 480 to 230°C, it may have recorded the changing geomagnetic field. This explains why the VGP obtained from AF demagnetization at 150 Oe differs by 17° from that obtained by thermal demagnetization at 480°C. So the most reliable VGP position at the age of 2500 m.y. ago may be latitude 75.0°S and longitude 14.5°E as obtained by thermal demagnetization to 480°C. This position is very different from the VGPs reported for Proterozoic and lower Paleozoic ages in East Antarctica.

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