Proc. NIPR Symp. Antarct. Geosci., **10**, 79–91, 1997

PRELIMINARY REPORT ON PALEOMAGNETIC STUDY OF ROCKS FROM THE MT. RIISER-LARSEN AREA IN ENDERBY LAND, EAST ANTARCTICA

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Abstract: Paleomagnetic samples were collected at eight sites from granulites of the Archean Napier Complex and dolerite dikes intruding the complex in the Mt. Riiser-Larsen area in Enderby Land, East Antarctica. Progressive demagnetization results indicate the presence of two magnetic components: the low-stability (L) and high-stability (H) components. A principal carrier of the H component is fine-grained magnetite, while the L component may be carried by coarser titanomagnetite. L components with steep negative inclination were remarkably observed in both granulite and dolerite samples. The characteristic L component is considered as a viscous remanence (VRM) in the recent geomagnetic field. A complete overprint of the VRM is observed in samples from one granulite site. The H components of two dolerite sites have positive inclinations, and their virtual geomagnetic pole positions are situated near the segment of the apparent polar wander path between 1.0 and 1.2 Ga for Australia in the East Gondwanaland frame. This may imply that the formation of East Gondwanaland can be dated back to about 1.2 Ga, if the intrusions of the dolerite dikes was related to the Amundsen dike activity in the Napier complex. The H component direction determined at one granulite site is inconsistent with other component directions, implying the possibility that the remanence might have been acquired before the intrusion of the dolerite dikes.

key words: paleomagnetism, the Napier Complex, the Amundsen dikes, East Gondwanaland

1. Introduction

The formation of supercontinents, amalgamation and dispersal of continental fragments, have been repeated several times in the Earth's history. This is one of the important themes for our understanding geodynamic system of the Earth. Gondwanaland is a good research target for investigating the formation process of supercontinents. Gondwanaland, which has been dispersing since about 180 Ma (*e.g.*, STOREY, 1995), has been considered to have formed at about 500 Ma (*e.g.*, LI and POWELL, 1993). Before the "Gondwanaland" period, it is considered that fragments of Gondwanaland were distributed in different frames at about 1.0 Ga, forming a Neoproterozoic supercontinent (DALZIEL, 1991, 1992; HOFFMAN, 1991; MOORRES, 1991), termed Rodinia by MCMENAMIN and MCMENAMIN (1990).

The East Antarctica Precambrian shield is one of the key continents of Gondwanaland. East Antarctica, accompanied by Australia and India, formed East

Gondwanaland, which is considered to have acted as a coherent unit through the break-up of Rodinia and subsequent formation of Gondwanaland (*e.g.*, DALZIEL, 1992). The coherence of East Gondwanaland has been assessed by means of paleomagnetism. Paleomagnetic poles are useful in estimating the ancient distribution of continents. Reliable paleomagnetic poles between about 1.0 and 0.5 Ga from East Gondwanaland seem to form one path, which support the coherency of East Gondwanaland (POWELL *et al.*, 1993). However, the number of reliable poles is still rare in East Gondwanaland except Australia (LI and POWELL, 1993). There are only three poles before 700 Ma in East Gondwanaland: two poles of 730 Ma from India and Australia and one pole of 1.0 Ga from Australia (POWELL *et al.*, 1993). In East Antarctica, there is no reliable pole except those around 500 Ma.

The Napier Complex in Enderby Land (Fig. 1) is one of the Archean nuclei in East Antarctica (BLACK *et al.*, 1992), and consists of high-grade metamorphic rocks of granulite facies. The initial formation of felsic crust in the complex is considered to have occurred at about 3.9 Ga (BLACK *et al.*, 1986). Three major events of deformation (D) and metamorphism (M) have been identified in the complex: D1-M1 at 3.0 Ga, D2-M2

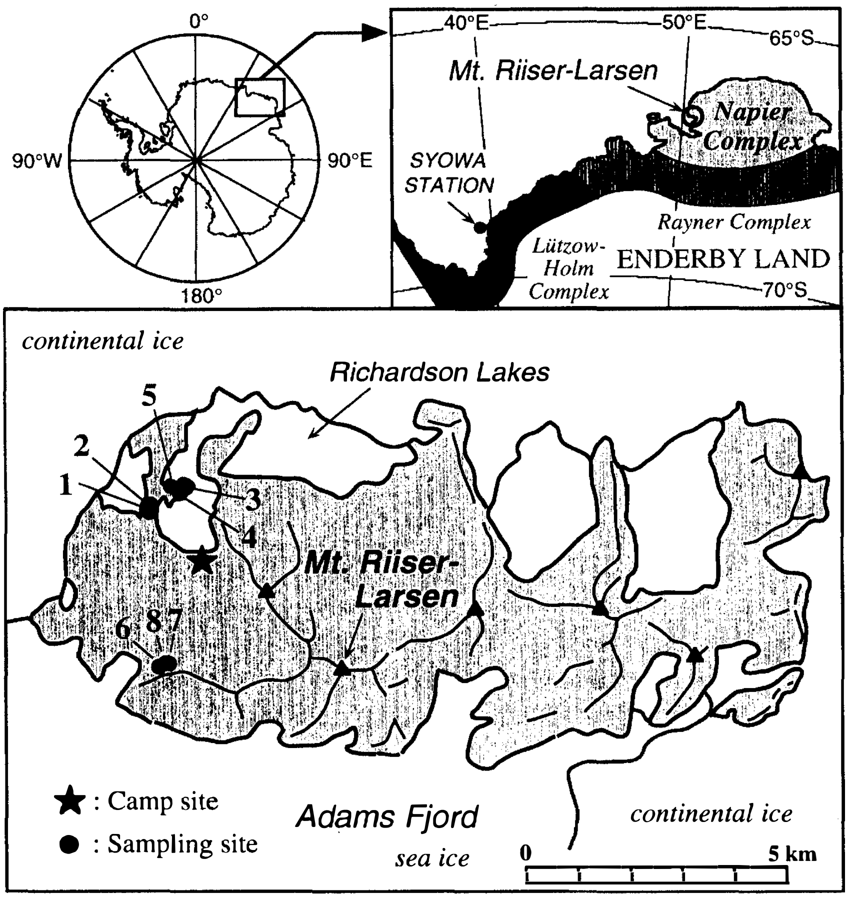

Fig. 1. Map showing paleomagnetic sampling sites in the Mt. Riiser-Larsen area. This sketch map is modified from MAKIMOTO et al. (1989b). The index map showing Precambrian metamorphic complexes is after HIROI et al. (1991).

at 2.9 Ga and D3-M3 at 2.5–2.4 Ga (TINGEY, 1991; BLACK *et al.*, 1992). The metamorphic conditions of these events were very high-grade; 900–980°C and 0.7–1.0 GPa during M1 and M2, 650–700°C and 0.5–0.8 GPa at M3. The Napier Complex experienced fracturing and shearing at about 1.0 Ga, probably related to the deformation/metamorphism activity of the Rayner Complex. Intrusion of mafic dikes also occurred in the complex; intrusions of metatholeiites including high-Mg type at 2.35 Ga and tholeiite dikes, the Amundsen dikes, at about 1.2 Ga (SHERATON and BLACK, 1981). Although initial information was erased from the complex through the three intense deformation/metamorphism events, the granulites and the mafic dikes intruding the complex are expected to have useful paleomagnetic information at least since 2.4 Ga.

Mt. Riiser-Larsen is located on the coast of Amundsen Bay in Enderby Land (Fig. 1), and the Napier Complex is exposed around the mountain. During the 35th Japanese Antarctic Research Expedition (JARE-35, 1993–1995), paleomagnetic sampling was performed in the region west of the Mt. Riiser-Larsen area on February 24 and 25, 1995 (Fig. 1). FUNAKI (1984, 1988) reported paleomagnetic results from ten granulite samples collected in the Mt. Riiser-Larsen area. In this paper, we will report preliminary paleomagnetic results, especially stable magnetic components isolated in natural remanent magnetizations (NRMs) of granulite and dolerite samples.

2. Sampling

Samples were collected at eight sites (Fig. 1): sites 1, 2, 3, 4 and 5 (66°45'S, 50°40'E) at rock bodies cropped out in the moraine around Richardson lake, and sites 6, 7 and 8 (66°46.5'S, 50°40'E) on the north-facing slope of the western ridge of Mt. Riiser-Larsen. Granulite-facies metamorphic rocks were sampled at sites 1, 2, 3, 4 and 8. According to petrological descriptions of MAKIMOTO *et al.* (1989a), the sampled granulites seem to correspond to felsic gneiss (sites 1, 2, 3 and 4) and quartzites (site 8). Intense mylonitization is clearly observed in thin sections of granulites from sites 1, 2, 3, and 4. Dolerite samples were collected from dikes at sites 5, 6 and 7. The strike and dip of the contact plane were N24.5°E and 85°E for site 5, N44.5°E and 80°NW for site 6, and N43.5°W and 87°NE for site 7. Igneous textures are observed in thin sections of samples from these sites, but the textures of site 5 is less clear. The dolerites of site 5 also appeared to have been subjected to shearing. A total of 82 cores were collected using a engine power core driller and oriented by a magnetic compass. A magnetic declination of 55.5°W is expected in the sampling area on the basis of the International Geomagnetic Reference Field 1995.

3. Paleomagnetic Analysis and Results

One to three specimens of standard size were cut out from each core for paleomagnetic analysis. The stability of NRM was assessed by thermal and alternating-field (AF) demagnetization. The NRM of each specimen was measured using mainly a spinner magnetometer (Natsuhara Giken) at Kyoto University and a three-axis cryogenic magnetometer (2G Enterprises) at NIPR for very weakly magnetized specimens. Two or three pilot specimens from each site were first subjected to progressive demagnetization experiments by the thermal and AF methods. The remaining specimens were also demagnetized progressively by the demagnetization method which was more effective to isolate magnetic components from NRMs of the pilot specimens. Bulk magnetic susceptibility of pilot specimens was measured with a Bartington MS2 magnetic susceptibility meter after each thermal demagnetization step in order to check magnetic mineralogical changes. Strong-field thermomagnetic experiments (1.0 T) were performed on one or two rock chips from each site in vacuum condition less than approximately 4×10^{-2} Pa using a vibrating sample magnetometer (Riken denshi) at NIPR.

Component directions were determined by applying least-square line fitting (KIRSCHVINK, 1980) to linear segments of vector end points chosen by eye from demagnetization results plotted on vector end-point diagrams (ZIJDERVELD, 1967). The least-square line fitted to the linear segment decaying toward the origin of the diagram was anchored to the origin. The component directions were plotted on equal-area nets. Site-mean directions for the component directions and associated statistical parameters were calculated after FISHER (1953).

Initial NRM intensities of the majority were on the order of 10^{-8} to 10^{-6} Am^2, while specimens from site 4 had weak intensities around 10^{-9} Am^2. In general, NRMs were characterized by two unblocking temperatures of about 300–360°C and 500–580°C and by the median demagnetization field (MDF) lower than 10 mT (Fig. 2). Bulk susceptibilities of pilot specimens did not change remarkably during thermal demagnetization, indicating that there was no significant alteration of magnetic mineralogy. Most of the progressive demagnetization results indicated that the existence of two magnetic components (Fig. 2); a low-stability (L) component was removed in demagnetization steps below 200–400°C and approximately 10 mT, and a high-stability (H) component was isolated in the demagnetization range up to 550–580°C and 20–60 mT after removal of the L component. Both thermal and AF demagnetization for pilot specimens from the same core generally provided the same magnetic components. Specimens from sites 1 and 2 also showed other magnetic components at intermediate thermal demagnetization levels between approximately 200°C and 500°C, referred to intermediate-stability (I) components (Fig. 2). The stabilities of NRMs varied at each site, especially granulite sites. Unstable directional changes were also observed after removal of the L components, which prevented the isolation of the H components from many specimens. Pilot demagnetization results from site 8 showed erratic directional changes of magnetization above 300°C and 10 mT (Fig. 2). About 90% of the initial NRMs of pilot specimens were erased by 300 or 360°C thermal demagnetization, and MDFs of the NRMs were less than 5 mT. Although linear segments of vector end points not decaying toward the origin were observed, remaining specimens from site 8 were not subjected to demagnetization experiments.

Strong-field thermomagnetic results indicated a Curie temperature of magnetite (Fig. 3). Although the presence of pyrrhotite or Ti-rich titanomagnetite may be inferred from the unblocking temperature of NRM around 300°C, there is no remarkable evidence for such minerals in the thermomagnetic curves. The H component with high blocking temperature and coercivity is thus considered to be carried principally by Ti-poor titanomagnetite or pure magnetite of fine grain size. Such minerals of coarser grain size may be possible carriers of the L components, probably in addition to the I component,

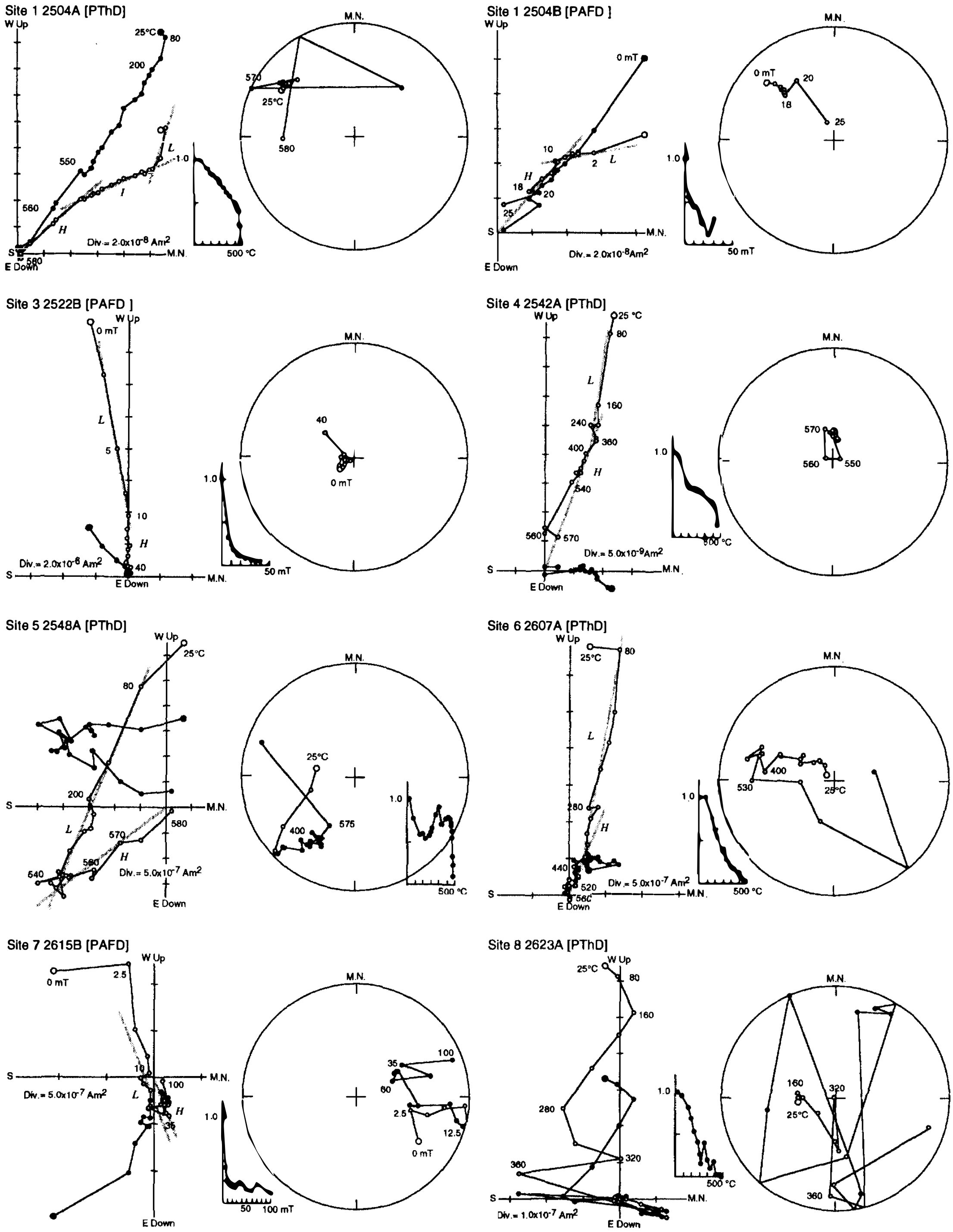

Fig. 2. Progressive demagnetization results shown on the vector end-point diagrams and equal-area nets. Changes of normalized intensity are also shown. PThD and PAFD denote thermal and AF demagnetization, respectively. On vector end-point diagrams, solid and open circles are projections onto the horizontal and N-S vertical planes, respectively. L, I and H denote low-, intermediate- and high-stability components, respectively. On equal-area nets, solid (open) symbols are on the lower (upper) hemisphere. M.N. denotes magnetic north. The magnetic declination (55.5°W) in the sampling area is not taken into account in this figure. Sites 1, 3, 4 and 8: granulite. Sites 5, 6 and 7: dolerite.

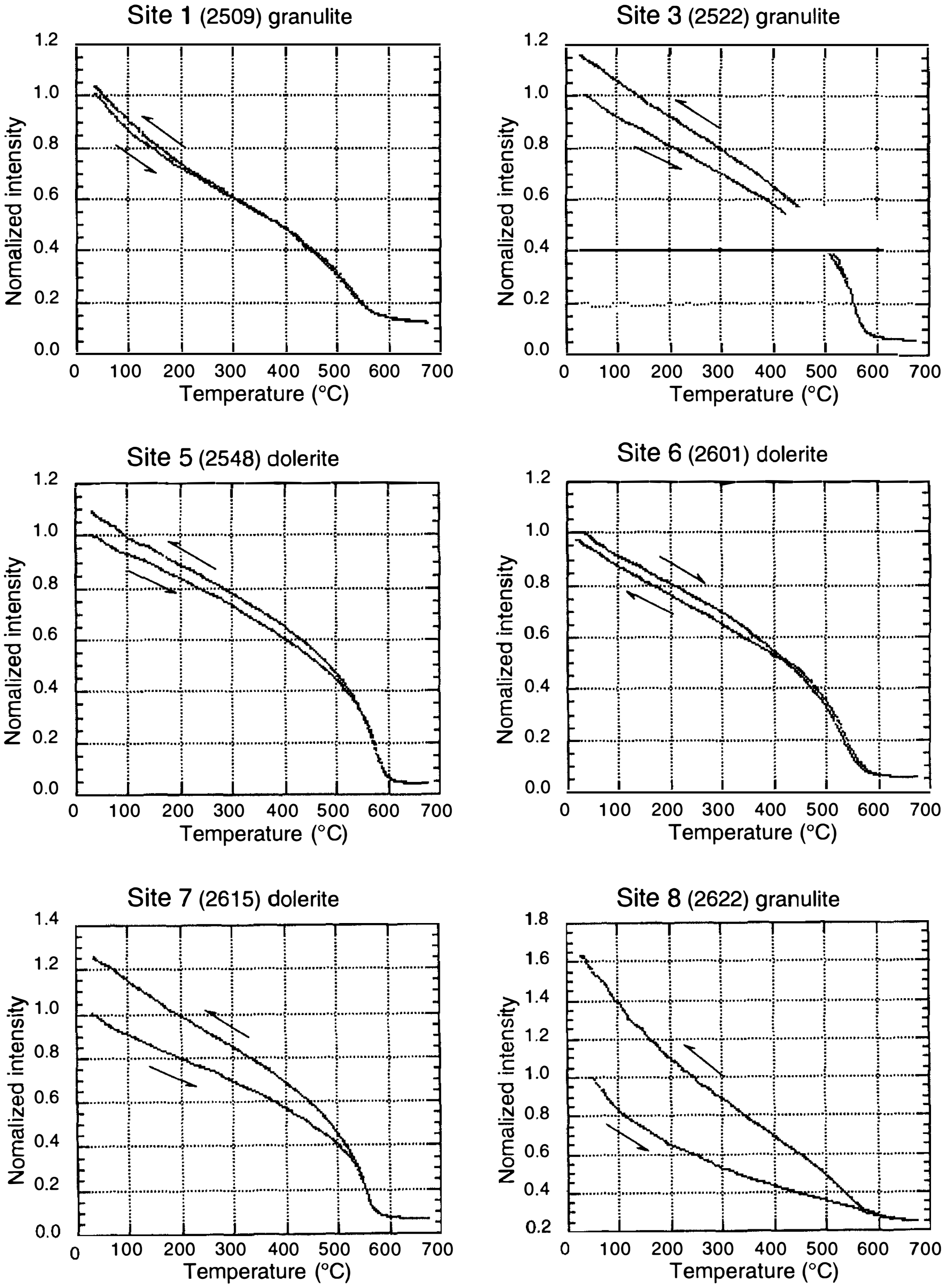

Fig. 3. Strong-field thermomagnetic curves.

because these components were erased in low AF demagnetization steps below about 10 mT and the MDFs of the total NRMs were generally lower than 10 mT. Some samples showed an increase of magnetization in the cooling run (Fig. 3), suggesting formation of magnetite in the heating. The newly formed magnetite may be due to thermal alteration of maghemite or iron sulfide. The possibility remains that maghemite or pyrrhotite carries the L and/or I components.

Site-mean directions of magnetic components isolated in specimens of the seven

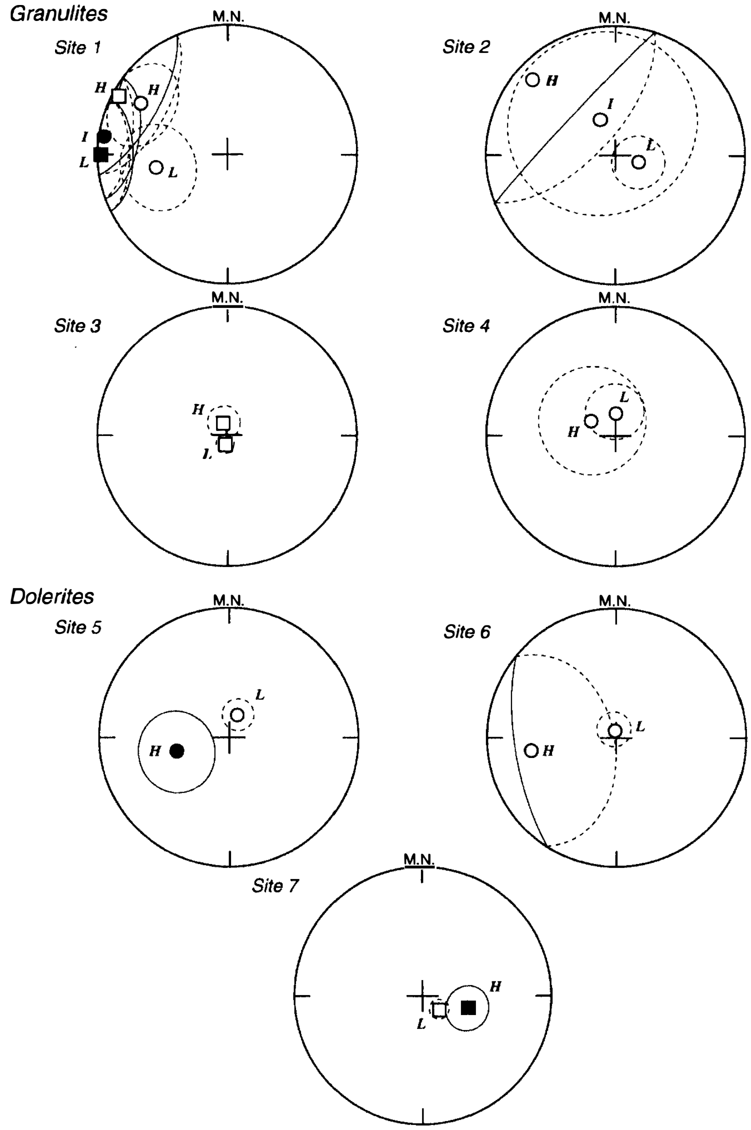

Fig. 4. Equal-area projections of site mean directions of magnetic components listed in Table 1. M.N. denotes magnetic north. Circles and squares indicate the components isolated by thermal and AF demagnetization, respectively. L, I and H are the low-, intermediate- and high-stability components, respectively. Solid (open) symbols are on the lower (upper) hemisphere. Ovals around the directions indicate the 95% confidence limit.

sites except site 8 are shown in Fig. 4 and listed in Table 1. The L component directions are well grouped within each site. The L components of six sites except site 1 have steep negative inclination, indicating normal polarity, while those of site 1 show moderate inclination with normal polarity. The I and H component directions are less grouped within each site, and those from sites 2, 4 and 6 have α_{95} larger than 30°. The site mean of the H component directions from site 3 is close to the L component direction. The H component directions of sites 5 and 7 (dolerites) show positive inclination. The I and H component directions of site 1 have shallow inclination, and are different from the component directions of other sites.

Table 1. Paleomagnetic results from the Mt. Riiser-Larsen area.

Site No.	demag. level	comp	n/N	*In-situ* direction Dec.(°)	Inc.(°)	α_{95}(°)	k	VGP(south pole) Lat.(°S)	Lon.(°E)
1	AF 2-8	L	10/10	214.3	1.5	25.9	4.4	−19.8	87.4
	AF 8-20	H	9/10	243.3	−3.2	37.9	2.8		
	TH 80-200	L	6/7	204.3	−43.1	26.1	7.5	3.6	72.6
	TH 200-500	I	6/7	223.0	3.1	28.0	6.7	−18.3	96.6
	TH 530-580	H	5/7	245.1	−22.4	23.6	11.4	1.3	113.4
2	TH 80-200	L	5/8	50.4	−75.0	17.3	20.5	68.2	331.8
	TH 200-500	I	5/8	281.8	−64.4	61.7	2.5		
	TH 500-560	H	4/8	257.2	−14.2	65.5	2.9		
3	AF 2-10	L	10/10	139.9	−83.5	5.9	68.3	56.0	35.9
	AF 10-20	H	7/10	290.0	−81.5	11.1	30.3	66.8	93.7
4	TH 80-400	L	5/9	301.7	−74.8	18.2	18.6	65.0	124.7
	TH 400-540	H	4/9	248.6	−71.5	35.0	7.9		
5	TH 80-240	L	6/10	324.6	−74.6	10.5	41.9	73.7	143.9
	TH 400-570	H	9/10	199.9	54.0	24.8	5.3	−55.8	80.6
6	TH 80-320	L	8/10	287.5	−84.3	11.2	25.5	67.6	80.0
	TH 360-520	H	4/10	205.5	−33.1	55.2	3.8		
7	AF 2-10	L	11/12	74.8	−75.8	6.3	52.9	60.1	349.8
	AF 20-60	H	9/12	51.0	59.5	14.2	14.2	−23.9	271.1
Low-stability component									
Mean(sites 2, 3, 4, 5, 6 and 7)				4.1	−84.8	10.6	40.6	76.6	47.6
								(A_{95}=20.6°, K=11.5)	

Notes: demag. level: levels of thermal (TH) and alternating field (AF) demagnetizations included in least-square line fitting (°C for TH and mT for AF). comp: stable magnetic components isolated. L, I and H represent the low-, intermediate- and high-stability components, respectively. n/N: the number of specimens used in calculation (n) and subjected to demagnetization (N). Dec. and Inc.: declinations and inclinations of site mean directions in *in-situ* coordinate, respectively. α_{95} and A_{95}: the radius of 95% confidence limit for site mean directions and a mean pole, respectively. k and K: precision parameters. VGP: virtual geomagnetic pole positions (south poles) calculated from *in-situ* site mean directions with α_{95} smaller than 30°.

4. Discussion

Figure 5 shows *in-situ* site mean directions of the L, I and H components with α_{95} smaller than 30°. The positions of virtual geomagnetic poles (VGPs) are calculated from these *in-situ* directions on the assumption that each component was acquired in an ancient normal polarity period of the geomagnetic field (Table 1).

The L component directions with steep negative inclination make a tight cluster (Fig. 5). A mean of site-mean directions from the six sites is D=4.1°, I=−84.8°, α_{95}=10.6° and k=40.6 in *in-situ* coordinate, and a pole position (south pole) of the characteristic L component is 76.6°S and 47.6°E. FUNAKI (1988) obtained stable remanent magnetizations from five granulite specimens of the Napier Complex. The *in-situ* mean direction of the remanences of FUNAKI (1988) and its pole position (F: Fig. 6) are consistent with the direction and pole position of the characteristic L component in this work, respectively (Figs. 5 and 6). FUNAKI (1988) considered that the stable remanence was acquired in the final intensive deformation event at 2.5–2.4 Ga (the D3 deformation event). However, the characteristic L component is determined from both granulite (sites 2, 3, and 4) and dolerite samples (sites 5, 6 and 7). It is thus suggested that the characteristic L component is the secondary remanence acquired after the intrusion of the dolerite dikes. The *in-situ* directions of these L components are close to the expected direction of the geocentric axial dipole field in the Mt. Riiser-Larsen area (Fig. 5) and the 95% confidence limit of the L component pole includes the geographical south pole (Fig. 6). The characteristic L component is probably a viscous remanence (VRM) imparted in the recent geomagnetic field. The *in-situ* direction and its pole position of the H component of site 3 are close to those of the characteristic L component, respectively (Figs. 5 and 6), implying a complete overprint of this secondary component on NRMs of site 3.

The H components of dolerite sites (sites 5 and 7) show positive inclination in *in-situ* coordinates (Fig. 5). These H components carried by fine-grained magnetite are probably primary remanences acquired in the emplacement of the dikes. Structural cor-

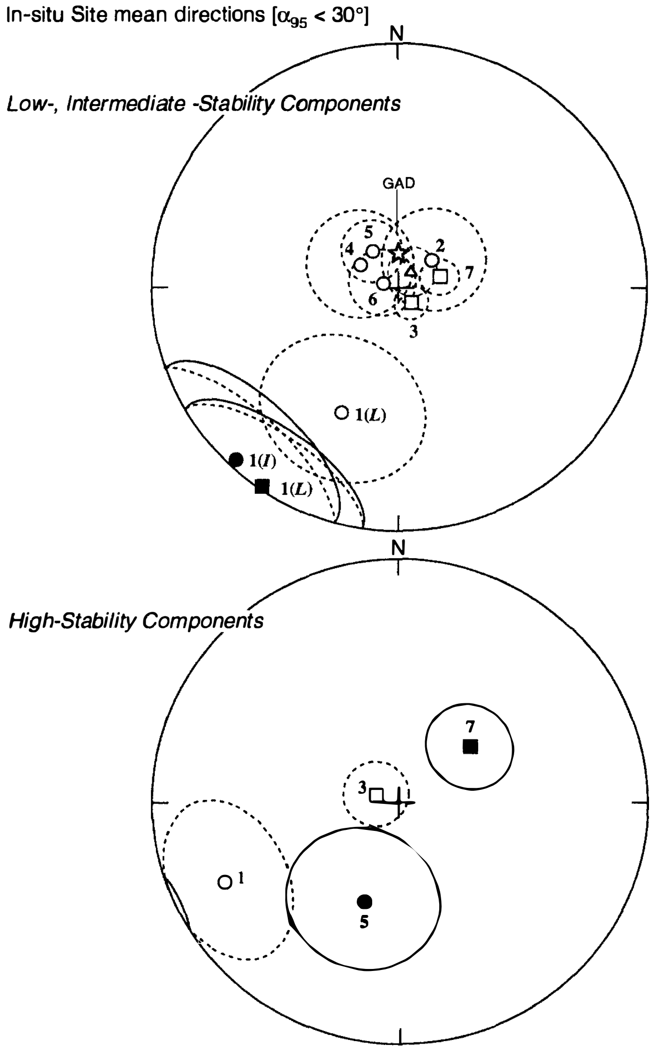

Fig. 5. Site-mean directions of stable magnetic components with α_{95} smaller than 30° plotted on equal-area nets with α_{95} circles of confidence. Circles and squares are defined as in Fig. 4. Numerals denote site numbers. The star represents the geocentric axial dipole field direction (GAD) expected in the sampling area. The triangle is the direction of FUNAKI (1988). Solid (open) symbols are on the lower (upper) hemisphere.

rection is not performed on these directions because these dolerite dikes have nearly vertical contact planes. The apparent polar wander path (APWP) for East Gondwanaland between about 0.5 and 1.0 Ga (POWELL *et al.*, 1993; GRUNOW, 1995) and that for Australia before 1.0 Ga (IDNURM and GIDDINGS, 1988; TANAKA and IDNURM, 1994; IDNURM *et al.*, 1995) are shown in the East Gondwanaland reference frame (Fig. 6). The VGPs of the H

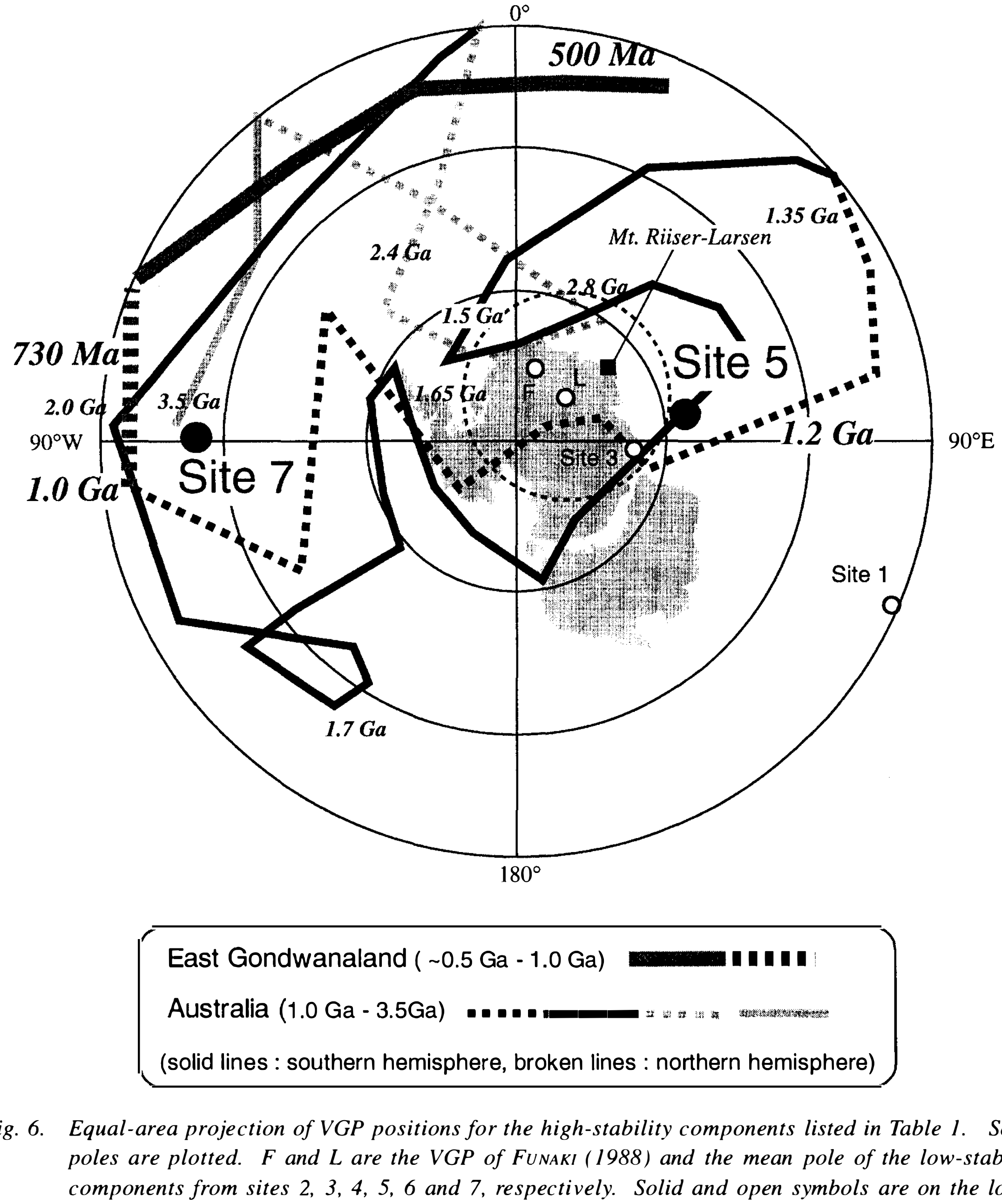

Fig. 6. Equal-area projection of VGP positions for the high-stability components listed in Table 1. South poles are plotted. F and L are the VGP of FUNAKI (1988) and the mean pole of the low-stability components from sites 2, 3, 4, 5, 6 and 7, respectively. Solid and open symbols are on the lower (northern) and upper (southern) hemispheres, respectively. The thick line is the APWP for East Gondwanaland between about 0.5 and 1.0 Ga (POWELL et al., 1993; GRUNOW, 1995). The thin line is the APWP for Australia before 1.0 Ga (IDNURM and GIDDINGS, 1988; TANAKA and IDNURM, 1994; IDNURM et al., 1995). These APWPs are converted to the paths in the East Gondwanaland reference frame using parameters of POWELL et al. (1988) and shown in present-day Antarctica coordinates. Solid (broken) segments of the paths are on the southern (northern) hemisphere.

components from the dolerite sites are situated near the segment of the APWP of Australia between 1.0 and 1.2 Ga (Fig. 6). K-Ar ages of 1.40 and 1.22 Ga are obtained from mafic dike rocks in the Mt. Riiser-Larsen area (UENO, 1995), and are similar to the age of the Amundsen dikes (1.19 ± 0.2 Ga; SHERATON and BLACK, 1981). If the emplacement of the dolerite dikes at the two sites was related to the igneous activity of the Amundsen dikes, the VGP positions of the dolerite dikes may indicate that East Antarctica and Australia had formed East Gondwanaland at the time of the Amundsen dike igneous activity, implying the possibility that the formation of East Gondwanaland can be dated back to about 1.2 Ga. In order to clarify this possibility, it is indispensable to obtain more paleomagnetic poles from the Amundsen dikes.

In-situ directions of the L, I and H components from site 1 are different from both the H component directions of dolerite dikes and the characteristic L component direction (Fig. 5). Demagnetization and thermomagnetic results indicate that the H component of site 1 may also be carried by fine-grained magnetite, which can maintain stable remanence over a long geological period. The possibility may be inferred, at least, for the H component that this component had been acquired before the igneous activity of the dolerite dikes, possibly the Amundsen dike activity at about 1.2 Ga. This H component of site 1 might have been acquired associated with the final intense deformation/metamorphism event (the D3-M3 event) of the Napier Complex. In order to clarify the meaning of the H component direction, it is necessary to assess the effect of deformation on the remanent direction through magnetic anisotropy measurements, as well as to obtain more paleomagnetic data from granulites of the Napier Complex.

5. Conclusions

Paleomagnetic measurements were performed on samples from granulites of the Archean Napier Complex and dolerite dikes intruding the complex collected at eight sites in the Mt. Riiser-Larsen area in Enderby Land, East Antarctica. Progressive demagnetization experiments revealed the presence of two magnetic components, the low-stability (L) and high-stability (H) components, in most of these samples. Demagnetization and strong-field thermomagnetic results indicate that the principal carrier of the H component is fine-grained magnetite, while the L component may be carried by titanomagnetite of coarser grain size. The L component directions of seven sites are well grouped within each site, and site-means of the components from six of the seven sites make a cluster with steep negative inclination. The characteristic L component direction is consistent with the geocentric axial dipole field direction expected in the sampling area, and is thus considered as a VRM in the recent geomagnetic field. The H component directions grouped within each site are determined at two granulite and two dolerite sites. The H component directions of two dolerite sites show positive inclination. VGP positions were calculated from the *in-situ* directions on the assumption that each H component of the dolerite dike was acquired in an ancient normal polarity period of the geomagnetic field. The VGPs are situated near the segment of the APWP between 1.0 and 1.2 Ga for Australia in the East Gondwanaland reference frame. It may be implied that the formation of East Gondwanaland can be dated back to about 1.2 Ga, if the emplacement of the dolerite dikes was related to the Amundsen dike activity in the Napier complex. The H component direction of one granulite site is close to the directions of the characteristic L component, implying a complete overprint of the VRM. On the other hand, the H component of the other granulite site shows different direction from either the characteristic L component direction or the H component directions of dolerites, and might have been acquired before the intrusion of dolerite dikes.

Acknowledgments

We express our sincere thanks to the members of JARE-35 and -36 and the crew of icebreaker Shirase during 1994–1995 season for giving us the opportunity for this field survey and their helpful support. Assistance of Mr. M. Kawakubo in the field work is also appreciated. I wish to thank Drs. Y. Kawano and M. Arita for their helpful geological information on the study area. Dr. H. Shinjoe is also thanked for his support in microscopic observation.

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(Received March 10, 1997; Revised manuscript accepted June 9, 1997)