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Paleomagnetic study of the Mount Riiser-Larsen area in Enderby Land, East Antarctica

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Abstract: Paleomagnetic analyses were performed on samples of two sites from felsic gneiss of the Archaean Napier Complex and two sites from a dolerite dike (Amundsen dikes) in the Mt Riiser-Larsen area in Enderby Land, East Antarctica As a result of progressive demagnetization experiments, directions of the high-stability (H) components, carried probably by fine-grained magnetite, were determined for one dolerite and two gneiss sites Among the three sites, gneiss samples at the two sites were found to be magnetically anisotropic, while magnetic fabrics at the dolerite site indicated the possibility that the fabrics are of primary origin Based on the results of demagnetization experiments and magnetic anisotropy measurements, the H component direction of one dolerite site was regarded as a primary one Virtual geomagnetic poles of two sites form the dolerite dikes in this study and Ishikawa and Funaki (1998) appeared to be situated near the segment of the apparent polar wander path between 1 0 and 1 2 Ga for Australia in the East Gondwanaland frame It might be implied that East Antarctica and Australia formed East Gondwanaland at the time of igneous activity of the Amundsen dikes

key words paleomagnetism, East Gondwanaland, Mt Riiser-Larsen area, the Amundsen dike, the Napier Complex

1. Introduction

The Mt Riiser-Larsen area in Enderby Land, East Antarctica, is underlain by granulite-facies metamorphic rocks of the Archaean Napier Complex The formation of the initial crust of the Napier complex occurred at about 3 9 Ga and the complex was subjected to metamorphic events characterized by ultra high temperature at 2 8 and 2 4 Ga (Black *et al*, 1986, Motoyoshi, 1998) In the area, unmetamorphosed dolerite dikes, the Amundsen Dikes, are also distributed (Ishizuka *et al*, 1998) The age of the dolerites is 1190 Ma (Sheraton and Black, 1981) We have performed paleomagnetic and rock-magnetic investigations on old rocks in the area to obtain reliable paleomagnetic information for clarifying the formation process of supercontinents, especially Gondwanaland, before 1 0 Ga (Ishikawa and Funaki, 1997, 1998) In this paper, we will report new paleomagnetic results from the Mt Riiser-Larsen area and discuss directional data including the data of Ishikawa and Funaki (1998)

2. Paleomagnetic analysis

A geologic team of the summer party of the 38th Japanese Antarctic Research Expedition (JARE-38) collected the samples analyzed in this paper Large rock blocks were taken at four sites (66°46 5′S, 50°43′S, Fig 1), two sites from a dolerite dike (sites A and B) and two from felsic gneiss of the Napier Complex (sites C and D) The dolerite dike was vertical with strike of 70°E relative to magnetic north Sites C and D of felsic gneiss were about 20 m away from the dolerite dike The strike of layering of the gneiss was 8°W relative to magnetic north with dip angle of 8° toward the west A magnetic declination of 55 5°W is expected at the sampling area on the basis of the International Geomagnetic Reference Field 1995 Two blocks oriented by a magnetic compass were sampled at each site Ten specimens of paleomagnetic standard size were prepared from each block in the laboratory

Stability of natural remanent magnetization (NRM) of the samples was assessed by progressive demagnetization experiments using the thermal (TH) and alternating-field (AF) methods Two pilot specimens from each site were subjected to the demagnetization experiment Suitable demagnetization methods for isolating stable magnetic components were determined based on pilot demagnetization results Eight specimens among the remaining specimens from each site were demagnetized progressively by a suitable method The NRM was measured on a superconducting magnetometer (Model 760R) of 2G Enterprises at Kyoto University These measurements were performed in a shield room,

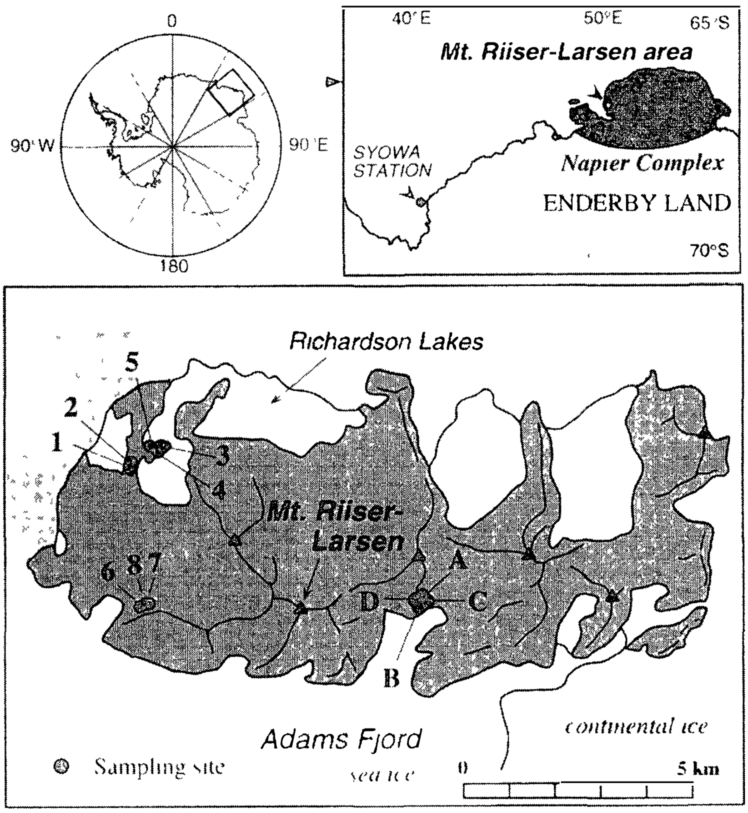

Fig 1 Map showing sampling sites in the Mt Riiser-Larsen area

in which a stray field was less than 1×10^{-6} T around the space for measuring

Anisotropy of magnetic susceptibility (AMS) was also measured with a KLY-3S susceptibility meter (AGICO Inc) at Kyoto University Ten specimens from each site were subjected to AMS measurements before demagnetization experiments The anisotropy degree (Pj) and shape parameter (T) of a susceptibility ellipsoid were calculated after Jelinek (1981)

3. Results

Pilot AF demagnetization results indicated that NRMs are composed mainly of soft magnetic components with low coercivity NRM intensities became less than 10% of the initial value for dolerite specimens (sites A and B) and less than 30% for gneiss ones (sites C and D) at the demagnetization step around 10 mT, followed by unstable magnetic behavior of NRMs in higher demagnetization steps (Fig 2a, d) Pilot TH demagnetization results indicated the presence of two magnetic components (Fig 2), which are referred to a low-stability (L) and high-stability (H) components after Ishikawa and Funaki (1997) The L components were isolated in the demagnetization range from 80°C or 160°C to 240°C or 500°C After the isolation of the L component, specimens from sites A and C clearly provided H components in the higher temperature range, especially at 500–560°C, the H component showed a linear trend of vector end-points decaying toward the origin of the demagnetization diagrams (Fig 2b, e) On the other hand, demagnetization behaviors of sites B and D showed considerable overlapping of unblocking temperatures of the L and H components (Fig 2c, f), which prevented clear isolation of the H component as a linear trend of vector end-points in some cases NRM intensity of gneiss samples (sites C and D) became less than 20% of the initial value after demagnetization of the L component at about 300°C, followed by unstable behaviors of NRMs in higher demagnetization steps in some cases Based on the demagnetization results, NRMs of the samples are carried mainly by magnetites of large grain size, which have the L components. The carrier of the H component is probably finer magnetite grain

The remaining specimens were subjected to progressive TH demagnetization experiments. Directions of the L and H components were determined by applying least-square line fitting (Kirschvink, 1980) to linear segments consisting of more than three vector end points. The origin of the diagram was included for determining the H component direction Component directions with maximum angular deviation less than 10° were used in calculating site mean directions of the components The site mean directions in in-situ coordinates are listed in Table 1. The directions with α_{95} smaller than 30° were considered reliable in this study and plotted on Fig 3 with the data of Ishikawa and Funaki (1998)

Initial mean mass susceptibilities of dolerite specimens (sites A and B) were about 2–3×10^{-5} m^3/kg and those of gneiss (sites C and D) were on the order of 10^{-6} m^3/kg Those values corresponded to volume susceptibilities of 10^{-3} to 10^{-2} SI The susceptibility values indicated that the main carriers of AMS are ferrimagnetic minerals (Tarling and Hrouda, 1993) Anisotropy parameters and directions of magnetic fabrics are plotted in Figs 4 and 5, respectively Dolerite specimens of sites A and B showed Pj values almost below 1 2, and oblate magnetic fabrics dominantly (Fig 4) Felsic gneisses of sites C and

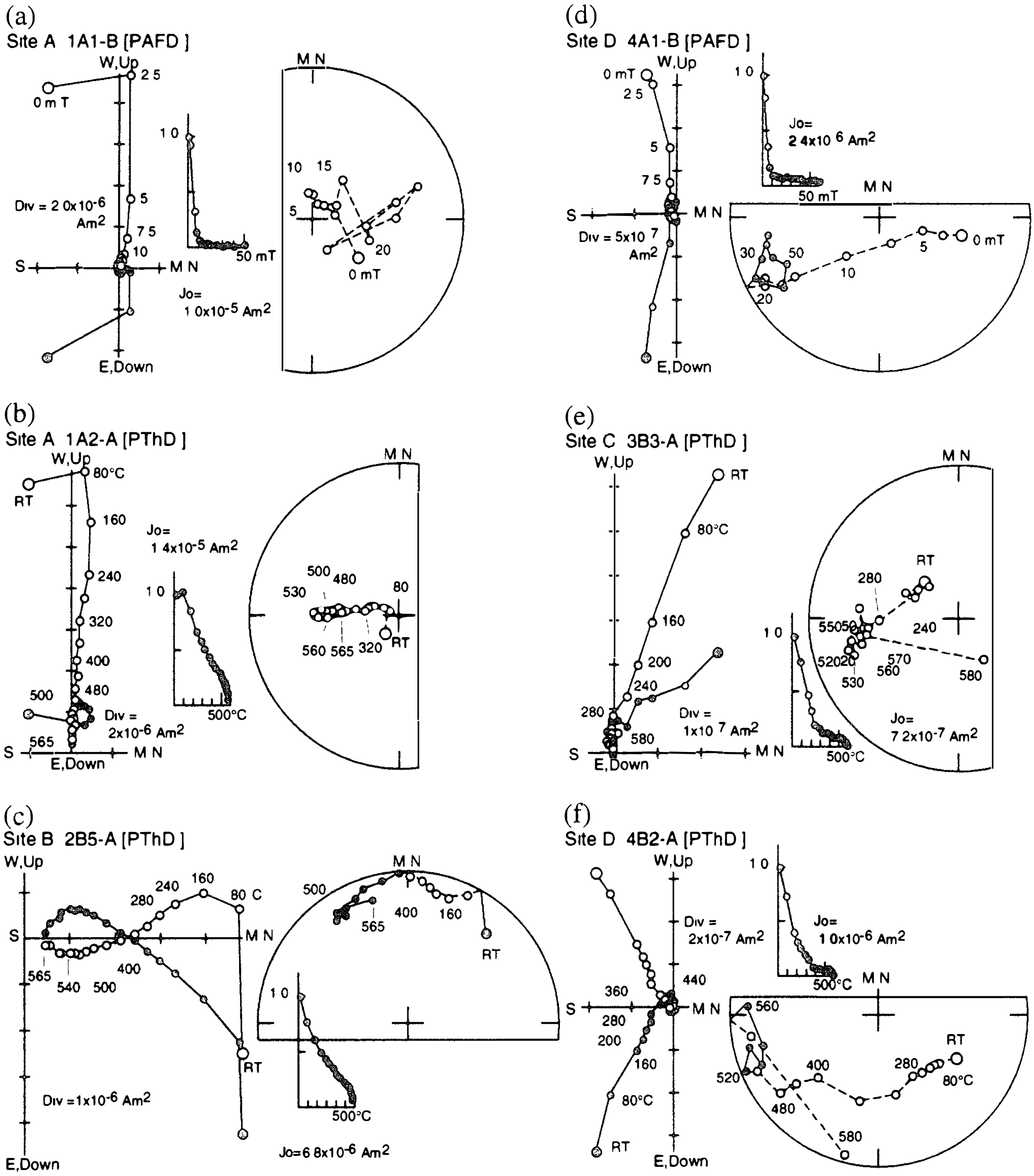

Fig 2 Progressive demagnetization results shown on vector end-point diagrams and equal-area nets Changes of normalized intensity are also shown PThD and PAFD denote thermal and AF demagnetization, respectively On vector end-point diagrams, solid and open circles are projections onto the horizontal and N-S vertical planes, respectively On equal-area nets, solid (open) symbols are on the lower (upper) hemisphere M N denotes magnetic north

D had Pj values of about 1 2-1 3, slightly higher than the dolerite specimens, and tended to show weaker oblate or prolate magnetic fabrics in comparison with the dolerite ones The prolate magnetic fabrics with higher Pj values were remarkable in specimens from site D (Fig 4) Magnetic foliations of dolerite sites (sites A and B) intersected contact planes of the dike (Fig 5) Magnetic fabrics of gneisses (sites C and D) yielded clusters of the

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 Lat (°S)	Lon (°E)
A	TH	160-440	L	10/10	0 3	−72 0	8 5	33 5	80 2	−128 3
	TH	520-560	H	10/10	216 0	−33 9	18 7	7 6	−0 6	84 6
B	TH	160-500	L	10/10	347 1	−42 4	12 0	17 3	47 0	−146 6
	TH	540-570	H	10/10	264 3	9 1	30 6	3 5	−6 5	137 3
C	TH	80-280	L	10/10	317 1	−56 7	9 0	29 8	51 9	169 4
	TH	400-540	H	8/10	228 7	−29 8	17 2	11 4	0 2	97 0
D	TH	80-240	L	10/10	48 7	−55 0	11 7	18 1	48 2	−62 7
	TH	480-540	H	5/10	191 3	11 7	23 8	11 3	−16 9	62 5
Low-stability component										
mean		10 sites			359 9	−70 1	10 0	24 3	79 3	51 7
	(sites 2, 3, 4, 5, 6, 7, A, B, C and D)							(A_{95} = 14 3°, K = 12 4)		

Notes demag level, levels of thermal (TH, °C) demagnetizations included in least-square line fitting, comp, stable magnetic components isolated L and H represent the low- 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* coordinates, respectively, α_{95}, radius of 95% confidence limit, k, precision, VGP, virtual geomagnetic pole positions (south poles), A_{95} and K, radius of 95% confidence limit and precision parameter of a mean VGP, respectively A mean direction of the L component directions was calculated using the data of this study and Ishikawa and Funaki (1998)

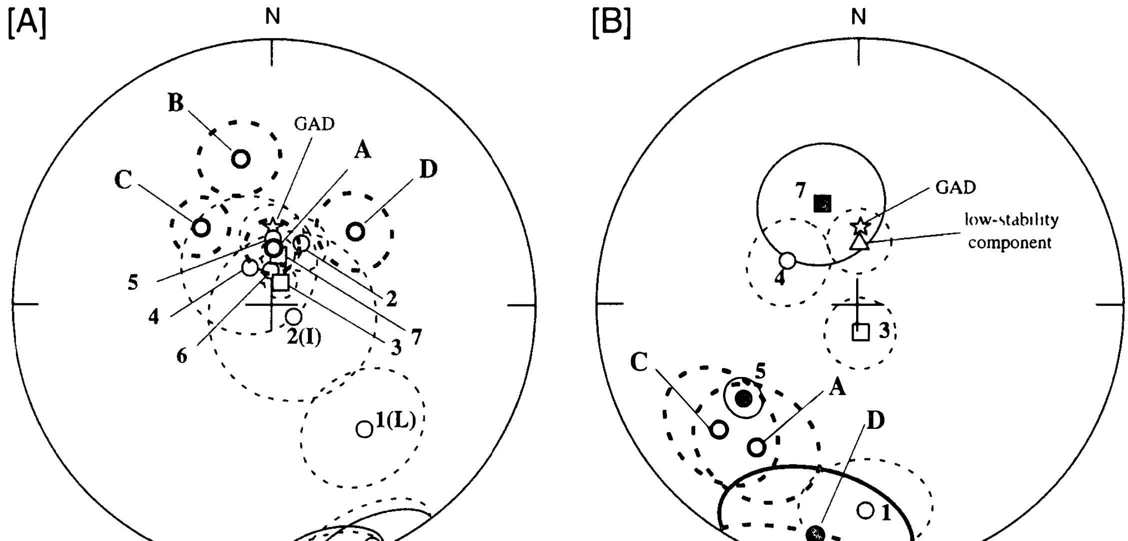

Fig 3 Equal-area projections of site-mean directions of low-stability (A) and high-stability (B) components from sites A, B, C and D The mean directions with α_{95} smaller than 30° are plotted The directions of low- and intermediate-stability components and high-stability components of Ishikawa and Funaki (1998) are also shown in (A) and (B), respectively L and I denote low and intermediate stability components, respectively Circles and squares indicate components isolated by thermal and AF demagnetization, respectively Solid (open) symbols are on the lower (upper) hemisphere Ovals around the directions indicate 95% confidence limits The star represents the geocentric axial dipole field direction (GAD) expected in the sampling area

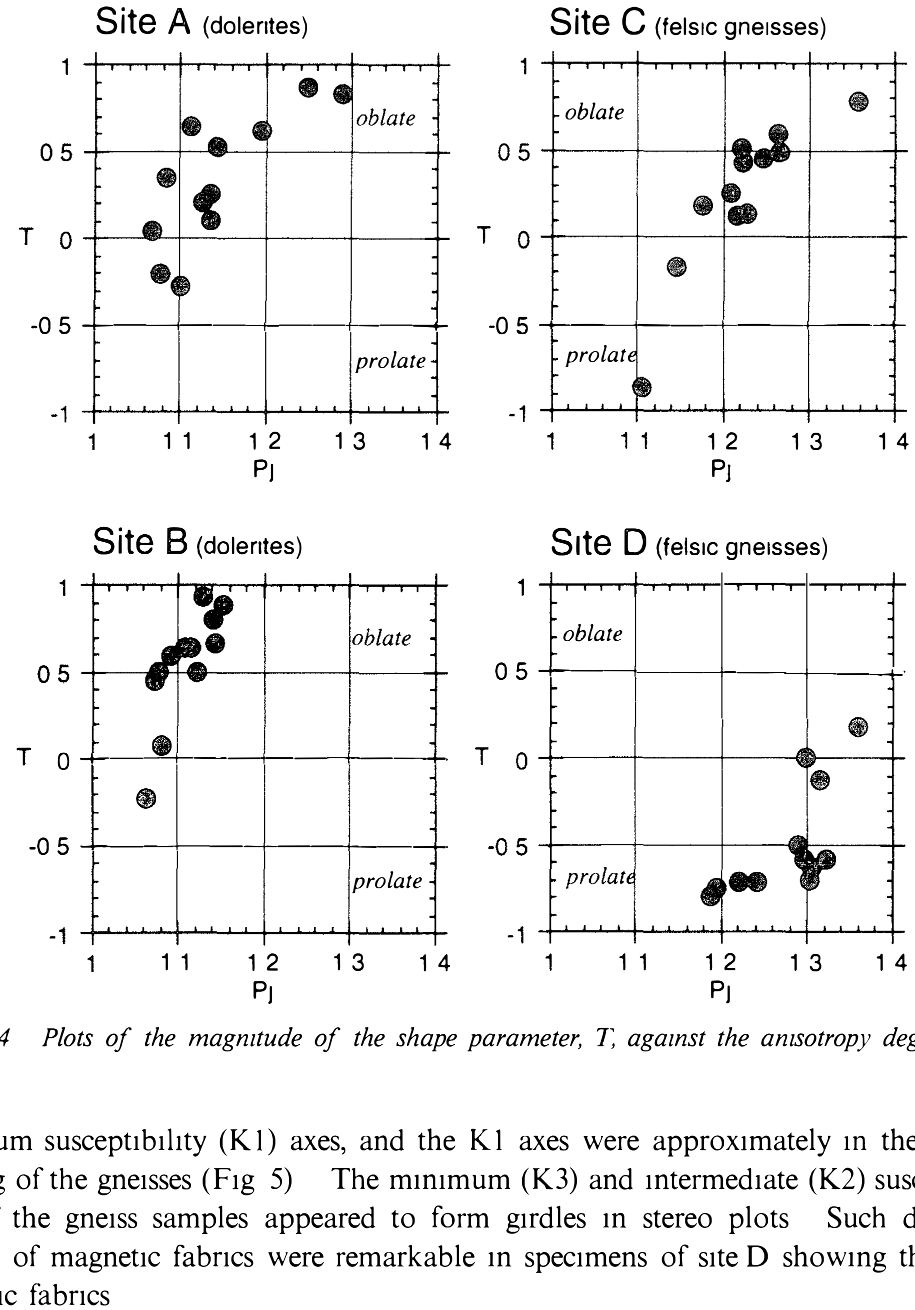

Fig 4 Plots of the magnitude of the shape parameter, T, against the anisotropy degree, Pj

maximum susceptibility (K1) axes, and the K1 axes were approximately in the plane of layering of the gneisses (Fig 5) The minimum (K3) and intermediate (K2) susceptibility axes of the gneiss samples appeared to form girdles in stereo plots Such directional features of magnetic fabrics were remarkable in specimens of site D showing the prolate magnetic fabrics

4. Discussion

The L components of the four sites in this study have negative inclinations with northward declinations (Fig 3) The L component directions are almost consistent with those of Ishikawa and Funaki (1998) It is thus considered that the L components are of viscous remanence origin in the recent geomagnetic field as discussed in Ishikawa and Funaki (1998) The mean of the L component directions from the 10 sites of this work and Ishikawa and Funaki (1998) is $D=-0\ 2°$, $I=-70\ 1°$, $\alpha_{95}=10\ 0°$ and $k=24\ 3$ (Table 1)

Among the H components (Fig 3), it was suspected for those of sites 3 and 4 (felsic

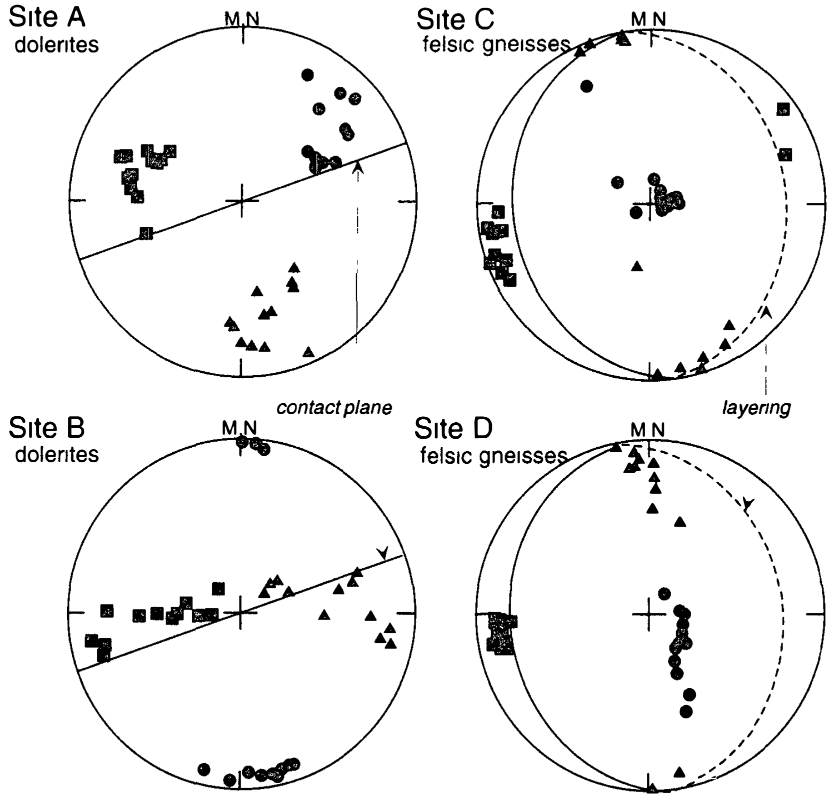

Fig 5 Equal-area plots of directions of the principal susceptibility axes of magnetic fabrics The directions of the maximum (K1), intermediate (K2) and minimum (K3) principal axes are plotted as squares, triangles and circles, respectively M N denotes magnetic north

gneisses) that the influence of the L component is not erased completely because the two H component directions are close to the L component direction (Ishikawa and Funaki, 1998) Samples of sites 1 (felsic gneiss) and 5 (dolerite) showed the effect of deformation through microscopic observations and AMS measurements (Ishikawa and Funaki, 1998) It was thus inferred that the H component directions of sites 1 and 5 may be affected by deformation and/or the magnetic anisotropy observed in those samples As a result, Ishikawa and Funaki (1998) suggested the possibility that the H component of site 7 is of primary origin

The magnetic fabrics of sites C and D (felsic gneisses) show the strong relationship to the layering of the gneisses. The magnetic fabrics may be primary ones associated with the formation of the gneisses In order to interpret the H component directions of sites C and D, it is indispensable to clarify the relationship of internal structures of the samples to their magnetic fabrics and the H component directions The magnetic fabrics possibly affected the acquisition of the H component, and/or deformation in the gneisses, which resulted in the observed magnetic fabrics, and probably caused alteration in the H component directions Furthermore, the H component direction of site C overlaps that of site A (dolerites) It is implied that the H component of site C was produced by the thermal effect of the dolerite dike

Demagnetization results of site A samples (dolerite) indicate that fine-grained magnet-

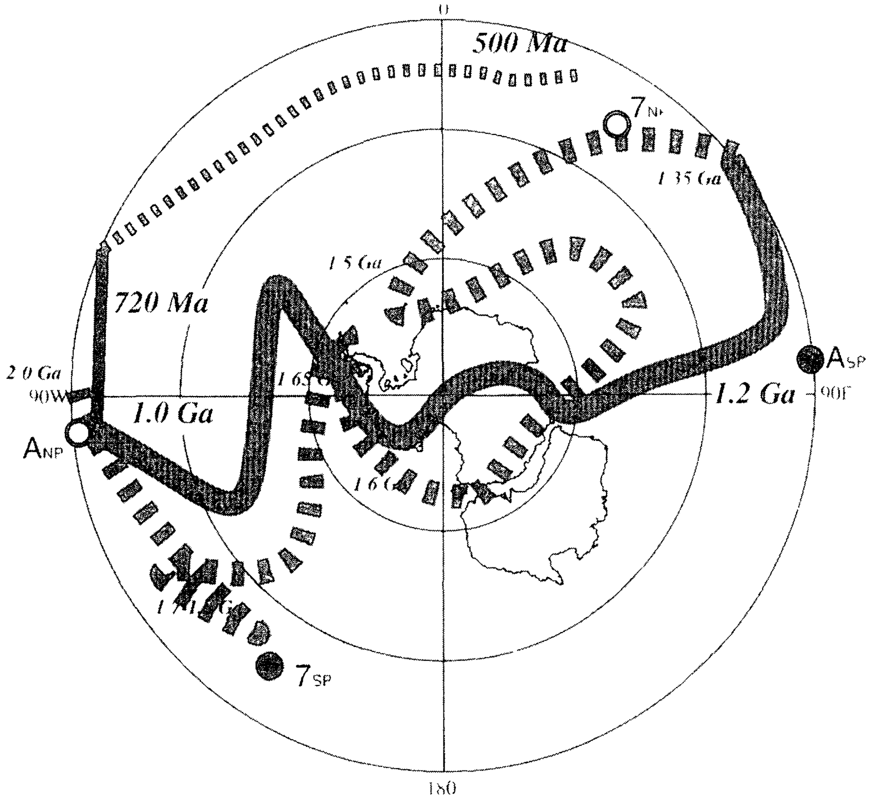

Fig 6 Equal-area projection of VGP positions for the high-stability components from sites 7 and A NP and SP denote north and south poles, respectively Solid and open symbols are on the lower (northern) and upper (southern) hemispheres, respectively The thin line is the APWP for East Gondwanaland between about 0 5 and 1 0 Ga (Powell et al, 1993, Grunow, 1995) The thick line is the APWP for Australia between 1 0 and 2 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 northern (southern) hemisphere

ites is the principal carrier of the H component at site A Magnetic fabrics of site A (Fig 5) showed the magnetic foliation crossing the contact plane of the dike, which can be interpreted as magnetic fabrics representing the flow of magma during formation of the dike The magnetic fabrics are possibly of primary origin although it is noticed that the degree of anisotropy appears to be slightly high (Fig 4) The H component of site A is a candidate, which can be regarded as a primary remanence The H component direction of site A is different from that of the other dike (Site 7) The difference can be interpreted at the difference in paleoposition of the Napier complex at the emplacements of the two dikes and/or in polarity of the two components The two H component directions appear to show an anti-parallel relationship approximately, which may imply the latter case It is suggested that igneous activity of dolerite dikes (Amundsen dikes) in the Mt Riiser-Larsen area ranged over a long period

Virtual geomagnetic poles (VGPs) of sites A and 7 are plotted in Fig 6 South and north poles of the two sites are shown because we cannot determine the polarities of the

H components 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 also shown in the East Gondwanaland reference frame (Fig 6) Sheraton and Black (1981) presented 1 19$\pm$0.2 Ga as the age of the Amundsen dikes Takigami *et al* (1998) obtained an age of about 0 8 to 1 0 Ga with the ^{40}Ar-^{39}Ar geochronological method from samples of site 7. According to those age data, the south pole of VGP for site 7 appears to be situated near the segment of the APWP of Australia between 1 0 and 1 1 Ga (Fig 6), and either the south or north pole for site A is located near the segment of the APWP between 1 0 and 1 2 Ga (Fig 6) These VGP positions of the dolerite dikes might have implied that East Antarctica and Australia had already formed East Gondwanaland at the time of igneous activity of the Amundsen dikes East Gondwanaland, consisting of East Antarctica, Australia and India, has been considered to have acted as a coherent unit through the break-up of Rodinia and subsequent formation of Gondwanaland between about 1.0 Ga and 500 Ma (Dalziel, 1991, 1992, Hoffman, 1991, Moorres, 1991) Reliable paleomagnetic poles between about 1 0 and 0 5 Ga from East Gondwanaland seem to form one path, which supports 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) The VGP data of the Amundsen dikes in this study might have support the coherency of East Gondwanaland and may imply the possibility that the formation of East Gondwanaland can be dated back to the time of the Amundsen dike activity

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