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PRELIMINARY REPORT ON PALEOMAGNETIC STUDY OF THE YAMATO MOUNTAINS (MASSIFS B AND C), EAST ANTARCTICA

Naoto ISHIKAWA[1] and Minoru FUNAKI[2]

[1] *School of Earth Sciences, IHS, Kyoto University, Sakyo-ku, Kyoto 606-8501*
[2] *National Institute of Polar Research, Kaga 1-chome, Itabashi-ku, Tokyo 173-8515*

Abstract: Paleomagnetic measurements were performed on granitic gneisses, syenites and granitic dike rocks from Massifs B and C of the Yamato Mountains in East Antarctica. The stable magnetic components carried by magnetite were isolated from granitic gneiss samples from two sites at Massif B and syenite samples from two sites at Massif C. The component directions are well grouped in each massif, but are different between the two massifs. The virtual geomagnetic pole (VGP) position of the gneisses is near the Cambrian, Silurian and upper Devonian segments of the apparent polar wander path (APWP) of East Gondwanaland, while that of the syenites is near the Ordovician segment. These comparisons are not supported by previous K-Ar age data, except the comparison between the gneiss pole and the upper Devonian segment of the APWP. The anisotropy of magnetic susceptibility (AMS) was also measured for samples at the four sites. The gneisses and syenites showed consistent magnetic fabrics within each massif. Especially, the K1 direction of the gneisses is almost parallel to the petrographical foliation. The following possibilities may be considered in order to explain the inconsistency between the VGP positions and the APWP of East Gondwanaland and the difference in the VGP positions between the gneisses and syenites: (1) differential tectonic movement between the two massifs and/or (2) the deviation of remanent acquisition in anisotropic rock or internal deformation in the rock bodies.

key words: paleomagnetism, AMS, the Yamato Mountains, East Gondwanaland

1. Introduction

Gondwanaland is one of the ancient supercontinents which existed in the Earth's history. Analyzing its formation process will shed light on our understanding of the cyclical formation of supercontinents. Paleomagnetic poles are useful for this purpose. Reliable paleomagnetic data suggest that Gondwanaland was formed at about 470 Ma (LI and POWELL, 1993); paleopoles from East Gondwanaland, which had acted as a coherent unit since about 1.0 Ga (DALZIEL, 1991, 1992; HOFFMAN, 1991; MOORRES, 1991; POWELL *et al.*, 1993), and from continental fragments of West Gondwanaland show good grouping at around that age in the Gondwanaland frame. However, the number of paleopoles is still small in Gondwanaland except in Australia (*e.g.*, VAN DER VOO, 1993).

East Antarctica, together with Australia and India, formed East Gondwanaland (*e.g.*, DALZIEL, 1992). We performed paleomagnetic work on the Lützow-Holm Bay area and the Yamato Mountains during the 35th Japanese Antarctic Research Expedition (JARE-35, 1993-1995). Late Proterozoic complexes are present in these areas; paleomagnetic data from them will give clues for clarifying the formation process of Gondwanaland. In this paper, we report preliminary paleomagnetic results for the Yamato Mountains.

2. Sampling

The Yamato Mountains are inland mountains located between 71°15′S and 72°05′S in latitude and 34°45′E and 36°55′E in longitude (Fig. 1), about 300 km from Syowa Station. The mountains extend for about 60 km north-south, and comprise seven massifs, named A, B, C, D, E, F and G, and several small nunataks. The mountains and the Belgica Mountains, which are about 200 km southeast of the Yamato

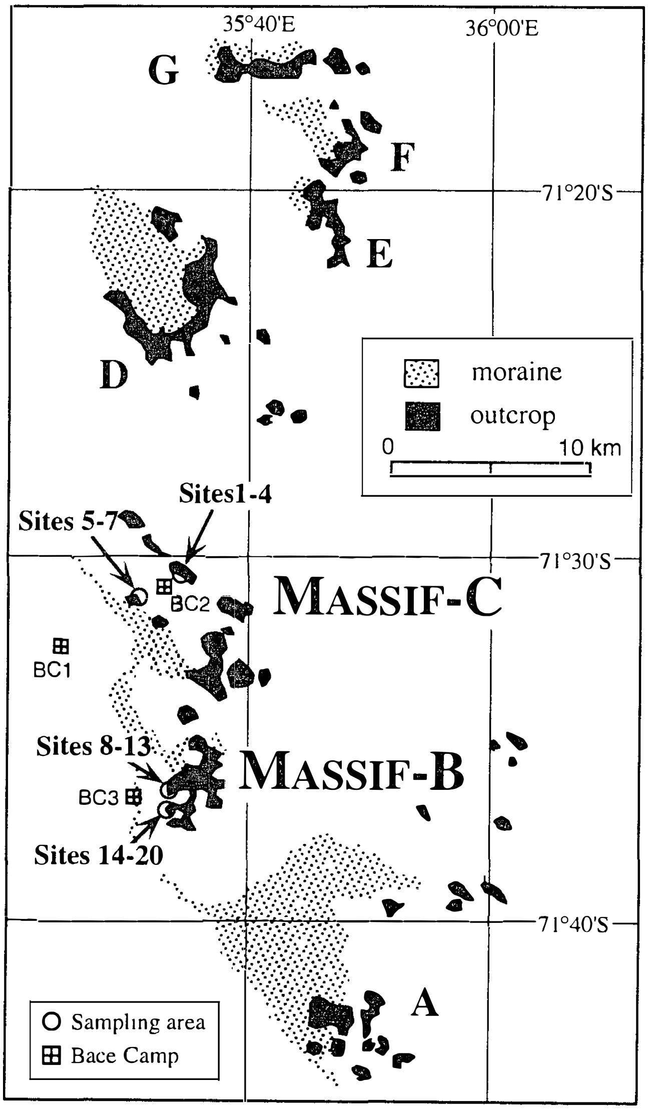

Fig. 1. Map showing the locations of Massifs B and C, Yamato Mountains, and paleomagnetic sampling sites.

Mountains, are considered one of the Late Proterozoic complexes in Queen Maud Land in East Antarctica, called the Yamato-Belgica complex (HIROI and SHIRAHASHI, 1986; HIROI *et al.,* 1991). The Yamato Mountains consist mainly of amphibolite and granulite facies metamorphic rocks and syenites (*e.g.,* HIROI *et al.,* 1991). A large number of granitic stocks and dikes and basic dikes intrude the basement rocks. A Rb-Sr whole-rock isochron age of about 720 Ma was obtained for the granulite facies rocks (SHIBATA *et al.,* 1986), which has been considered that of the granulite facies metamorphism (HIROI *et al.,* 1991). K-Ar and Rb-Sr ages of about 360 to 490 Ma have been also reported for the gneisses and igneous rocks (HIROI and SHIRAHASHI, 1986).

We performed paleomagnetic sampling on Massifs B and C from December 11 to 24, 1994 (Fig. 1). Four members and materials for this field work were transported using two airplanes. We established three base camps and moved on foot between the camps using two sledges for transportation of materials. Massifs B and C consist mainly of granitic gneisses of amphibolite facies and syenites (YANAI *et al.,* 1982). Previous K-Ar (whole rock) ages reported from these rocks are as follows: 368 ± 18 Ma for granitic gneiss and 359 ± 18 Ma, 363 ± 18 Ma and 400 ± 20 Ma for syenites (YANAI *et al.,* 1982). These ages appear to be younger than ages of the Lützow-Holm complex (~500–450 Ma; FRASER and MCDOUGALL, 1995). On Massif B, samples were collected at 14 sites from the Akakabe Bluff (12 sites of amphibolite-facies granitic gneisses and two of pegmatite and aplite intruding the granitic gneisses). On Massif C, we obtained samples at five sites from Tsuitate Rock (four of syenites and one of aplite) and at four sites from a nunatak (two of granitic gneisses and two of granitic dikes). A total of 213 cores were collected using an engine power core driller and oriented by a magnetic compass. A magnetic declination of 45.6°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 paleomagnetic standard size were cut out from each core for paleomagnetic analysis. The stability of the natural remanent magnetization (NRM) was assessed by thermal demagnetization. The NRM of each specimen was measured using a spinner magnetometer (Natsuhara Giken). Two pilot specimens from each site were first subjected to progressive thermal demagnetization experiments. Thermal demagnetization was performed in air using a noninductively wound electric furnace in a four-layer mu-metal magnetic shield; the internal stray field was less than 10 nT. The demagnetization steps were usually 80, 160, 200, 240, 280, 320, 360, 400, 440, 480, 500, 520, 540, 550, 560, 570 and 580°C. We tried to isolate the stable magnetic components of the NRM which were shown as a linear segment of vector end points decaying toward the origin on vector component diagrams (ZIJDERVELD, 1967). The remaining specimens at each site from which at least one pilot specimen provided such a stable component were also demagnetized progressively. During progressive thermal demagnetization, the bulk magnetic susceptibility of specimens was measured with a Bartington MS2 magnetic susceptibility meter after each demagnetization step in order to check magnetic mineralogical changes. Directions of the stable components were determined by applying least-square line fitting (KIRSCHVINK, 1980). The linear segments of vector end points were chosen by eye from demagnetization results, and 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^{-7} to 10^{-6} Am^2, while specimens of granitic and aplitic dikes had weaker intensities from 10^{-9} to 10^{-8} Am^2. Bulk magnetic susceptibilities of pilot specimens were on the order to 10^{-7} to 10^{-6} m^3/kg. During the progressive demagnetization, the bulk susceptibilities slightly increased at about 200° C, followed by gradual decreasing at higher temperature steps. The susceptibility changes were generally within about 10% of the initial values, indicating no significant alteration of magnetic mineralogy during thermal experiments. Soft magnetic components with negative inclination were generally erased from NRMs of pilot specimens in the temperature range from 80°C to 240°C or 360°C (Fig. 2). After removal of the soft components, additional stable components were found in NRMs of pilot specimens only from four sites, sites 1A and 2 for syenites in Massif C and sites 18 and 19 for granitic gneisses in Massif B. The stable components were isolated clearly in the demagnetization steps between about 440°C and 560°C, showing linear decay of vector end points approximately toward the origin of the vector component diagrams (Fig. 2a, b, c and d). NRMs of pilot specimens from all sites except the four sites consisted mainly of soft components. NRM intensities of those specimens decreased usually below about 20–30% of the initial values, and the specimens provided erratic behavior of direction after removal of the soft components (Fig. 2e and f). The pilot specimens of the four sites retained NRM intensities above 50% of initial values, generally 80 to 90%. The carrier of the stable component was considered titanomagnetite of low Ti content based on unblocking temperature of the component.

The remaining specimens of the four sites were demagnetized progressively. Several specimens did not provide stable components because of unstable or erratic magnetic behaviors of these specimens similar to those of the pilot specimens from the sites except for the four sites (Fig. 2). Finally, *in-situ* directions of the stable components from syenites in Massif C were obtained from seven specimens of site 1A and six of site 2, and those from granitic gneisses in Massif B were obtained from four of site 18 and three of site 19 (Fig. 3 and Table 1). The *in-situ* directions from syenites were well grouped, showing northward declinations and positive inclinations, while those from granitic gneisses have approximately northwestward declination with positive inclination (Fig. 3). Mean *in-situ* directions of Massifs C and B were calculated from 13 specimens of sites 1A and 2 and seven specimens of sites 18 and 19, respectively (Table 1). Structural correction was not performed on the mean directions because there was no geological information for preferable structural/tectonic correction.

Anisotropy of magnetic susceptibility (AMS) was also measured with a KLY-3S susceptibility meter for specimens of site 1A, 2, 18 and 19 except pilot ones. Initial mean susceptibilities (Km) of the syenite and granitic gneiss specimens was on the order of 10^{-6} to 10^{-5} m^3/kg (Table 2), which corresponded to the order of 10^{-4} to 10^{-3} SI if the volume of each specimen is assumed to be that of the standard paleomagnetic

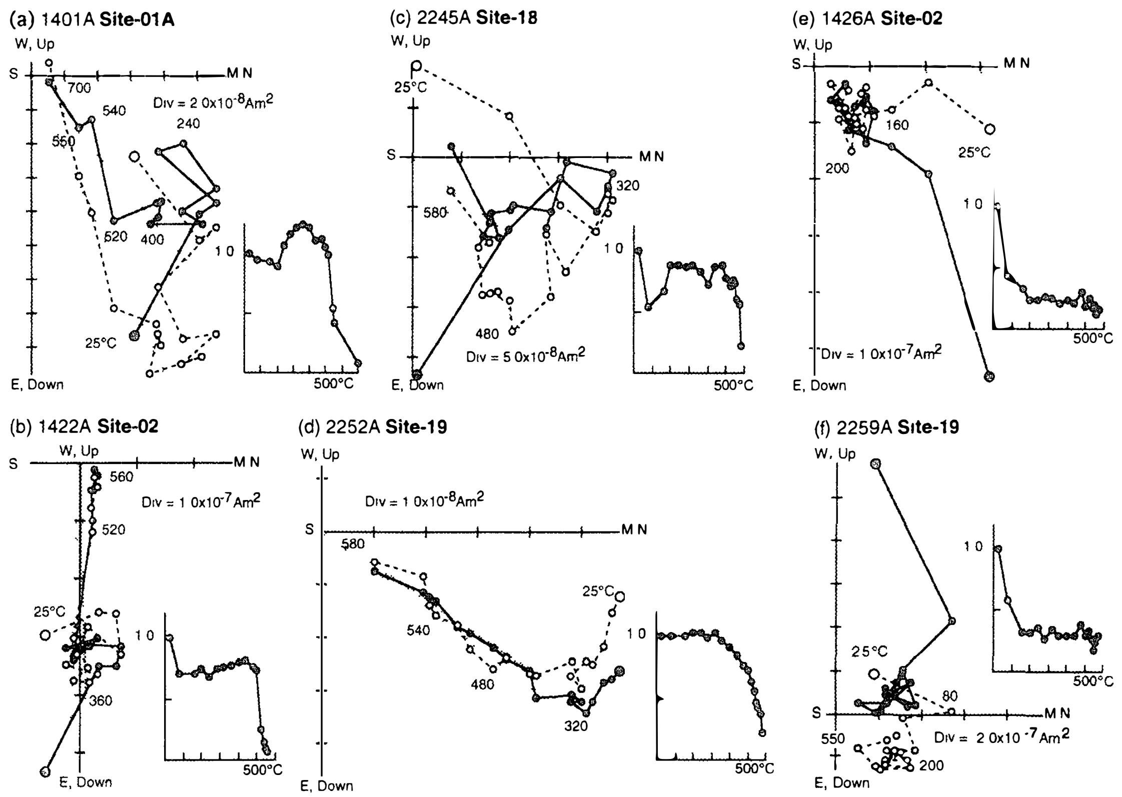

Fig. 2. Progressive demagnetization results shown on the vector component diagrams. Changes of normalized intensity are also shown. On the diagrams, solid and open circles are projections onto the horizontal and N-S vertical planes, respectively. M.N. denotes magnetic north. The magnetic declination (45.6° W) in the sampling area is not taken into account in this figure.

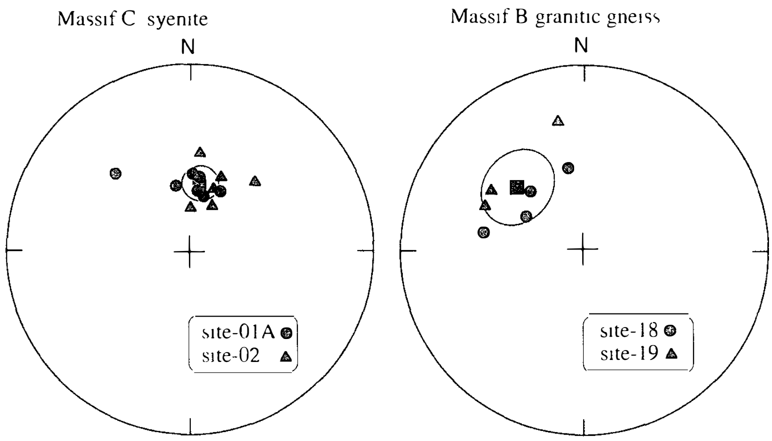

Fig. 3. Equal-area projections of stable magnetic components from sites 1A and 2 of syenites at Massif C, and from sites 18 and 19 of granitic gneisses at Massif B. A mean direction (square) with the 95% confidence limit for each massif is also plotted. Solid symbols are on the lower hemisphere.

Table 1. Paleomagnetic results.

Site	Rock	n	*In-situ* direction		α_{95} (°)	VGP position		A_{95} (°)
			D. (°)	I. (°)		Lon. (°E)	Lat. (°N)	
1A	syenite, Massif-C	7	−2.2	59.9	11.5			
2	syenite, Massif-C	6	21.5	58.8	11.3			
mean	[syenite, Massif-C]	13	9.0	59.9	7.9	43.4	−23.3	17.2
18	granitic gneiss, Massif-B	4	310.6	56.2	22.1			
19	granitic gneiss, Massif-B	3	316.2	39.6	38.8			
mean	[granitic gneiss, Massif-B]	7	313.4	49.2	16.4	−5.5	−17.6	19.5

n: the number of specimens. D., I. and α_{95}: declination, inclination and radius of 95% confidence circle of averaged *in-situ* direction, respectively. Lon., Lat. and A_{95}: longitude, latitude and radius of 95% confidence circle of averaged virtual geomagnetic pole (VGP) position, respectively.

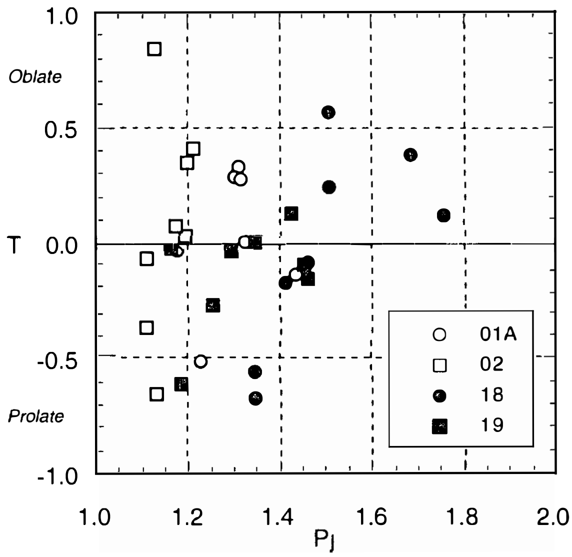

Fig. 4. Magnitudes of magnetic fabrics at sites 1A, 2, 18 and 19. A plot of the magnitude of the shape parameter, T, against the anisotropy degree, Pj.

specimen (11.1 cc). The susceptibility values indicated that the main carriers of AMS were ferrimagnetic minerals (TARLING and HROUDA, 1993). Anisotropy parameters and directions of magnetic fabrics are plotted in Figs. 4 and 5, respectively. The syenite specimens had the anisotropy degree, Pj (JELINEK, 1981) around 1.2, and had a variety of shape parameters, T (JELINEK, 1981). The magnetic fabrics of the granitic gneiss specimens showed a clear relationship between Pj and T; the shape of the magnetic fabric changed to prolate to oblate with increasing Pj. The Pj values of the granitic gneisses were higher than those of the syenites. Orientations of the principal susceptibility axes of the magnetic fabrics were different between the syenites and granitic gneiss (Fig. 5). The K1 directions were grouped with each other. The K1 directions of the syenites showed northeastward declinations with steep inclinations, while those of the granitic gneisses showed eastward declination with shallow inclination. The K2 and K 3 directions of site 1A were also grouped clearly. Those of sites 2, 18 and 19 were

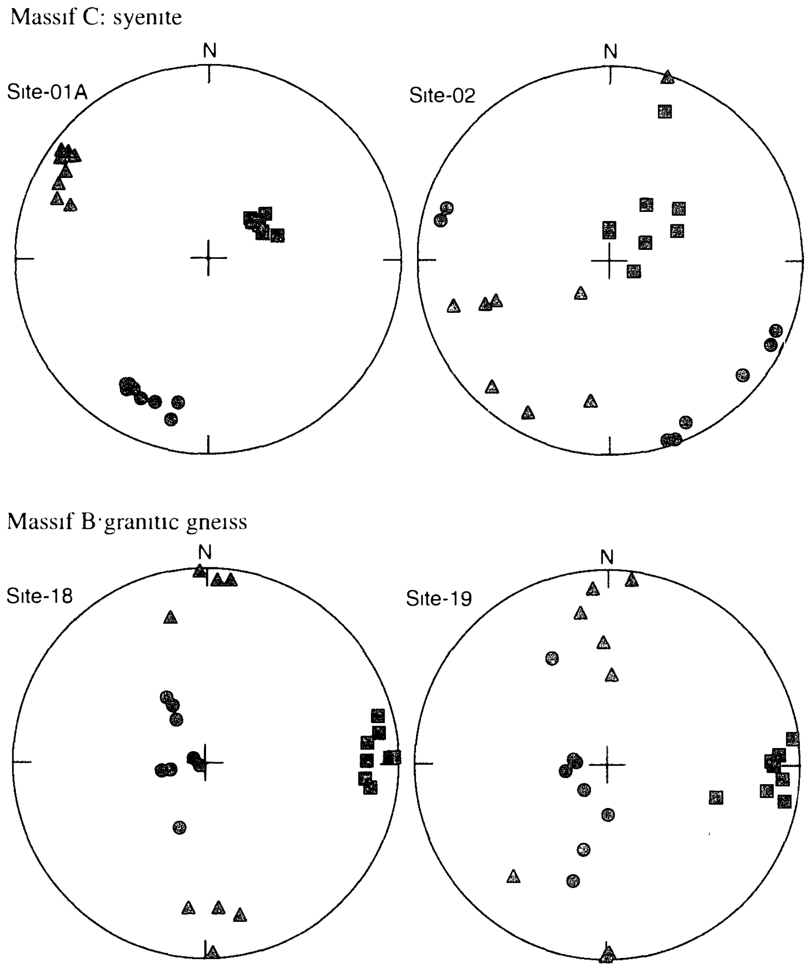

Fig. 5. Equal-area plots of directions of the principal susceptibility axes of magnetic fabrics. The directions of the maximum (K1), intermediate (K2) and minimum (K3) principal axes are plotted as squares, triangles and circles, respectively. Solid symbols are on the lower hemisphere.

Table 2. Anisotropy of magnetic susceptibility of sites 1A, 2, 18 and 19.

Site		1A	2	18	19
n		8	8	8	8
Km	mean(sd)	4.43E-06(1.40E-06)	4.61E-06(1.44E-06)	5.87E-06(3.59E-06)	5.15E-06(3.71E-06)
K1	mean(sd)	1.123(0.036)	1.069(0.017)	1.198(0.037)	1.145(0.046)
	direction	57.3°, 63.1°(3.2°)	40.2°, 65.0°(17.0°)	86.6°, 11.5°(6.6°)	93.1°, 14.6°(9.7°)
K2	mean(sd)	1.001(0.024)	1.004(0.019)	0.993(0.047)	0.984(0.014)
	direction	300.8°, 12.3°(6.1°)	223.1°, 27.2°(23.3°)	177.7°, 4.8°(13.8°)	3.6°, 12.1°(20.4°)
K3	mean(sd)	0.876(0.032)	0.928(0.023)	0.809(0.062)	0.871(0.046)
	direction	205.1°, 22.6°(5.8°)	130.8°, 1.7°(18.4°)	290.1°, 77.0°(13.1°)	77.0°, 72.8°(21.1°)

n: the number of specimens, Km: mean bulk susceptibility (m^3/kg), K1, K2 and K3: the maximum, intermediate and minimum principal susceptibility, respectively. mean: mean value, sd: standard deviation. direction: mean of direction of the principal axis, the first value is declination and the second one is inclination. The value in brackets is a radius of 95% confidence circle (α_{95}).

scattered approximately within planes normal to the K1 directions. Directions of megnetic fabrics at sites 18 and 19 were consistent.

4. Discussion

Virtual geomagnetic poles (VGPs) of the granitic gneisses at Massif B and the syenites at Massif C were calculated from *in-situ* component directions of specimens from sites 18 and 19 and from sites 1A and 2, respectively. The two VGPs are plotted in Fig. 6 with the apparent polar wander path (APWP) for East Gondwanaland between the Cambrian and Carboniferous (VAN DER VOO, 1993). Reliable paleomagnetic poles of around 500 Ma (450–550 Ma) from East Antarctica (VAN DER VOO, 1993; GRUNOW, 1995) are also shown. The VGP positions from the Yamato Mountains seem to be slightly different from 500 Ma paleopoles from East Antarctica. The VGPs

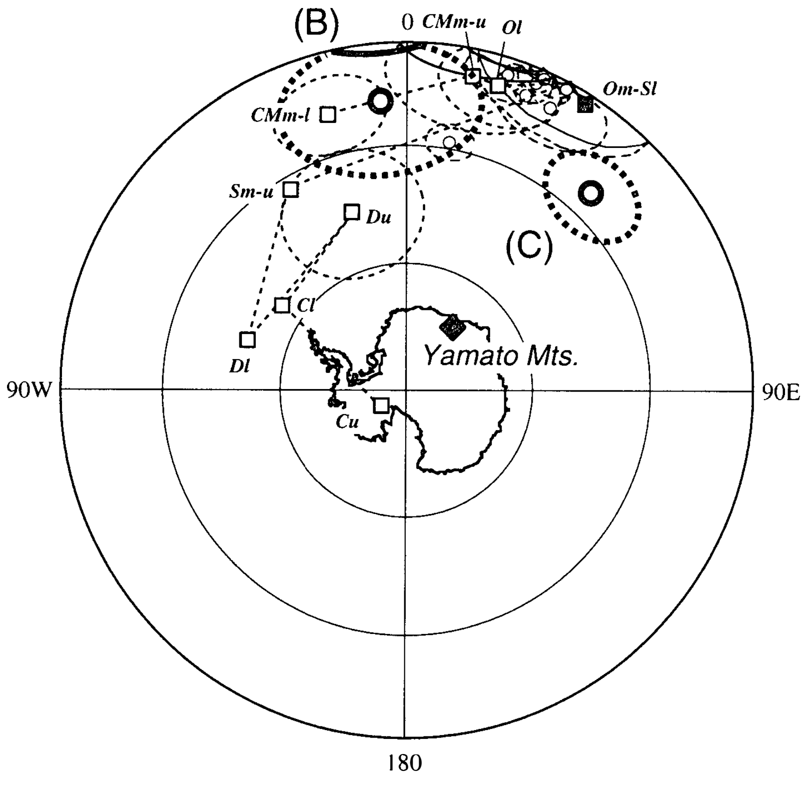

Fig. 6. Equal-area projection of VGP positions for Massifs B and C (large circles). Squares denote mean paleopoles for East Gondwanaland between Cambrian and Carboniferous (VAN DER VOO, 1993). The positions of the paleopoles are converted to those in the East Gondwanaland reference frame using parameters of POWELL et al. (1988) and shown in present-day Antarctica coordinates. Paleopoles of around 500 Ma in East Antarctica (VAN DER VOO, 1993; GRUNOW, 1995) are also plotted as small circles. Solid and open symbols are on the lower (northern) and upper (southern) hemispheres, respectively. Ovals around mean poles indicate 95% confidence limit (α_{95}). Paleopoles without α_{95} mean that the number of poles used in calculation of the mean is less than two or that α_{95} is larger than 60° (VAN DER VOO, 1993). C, D, S, O and CM: Carboniferous, Devonian, Silurian, Ordovician and Cambrian, respectively. l, m and u: lower, middle and upper, respectively.

of the gneiss and syenite are different; the VGP position of the gneiss is situated near the Cambrian, Silurian and upper Devonian segments of the APWP of East Gondwanaland, while that of the syenite is near the segment from Ordovician to Silurian. According to previous K-Ar age data, it appears that the VGP position of the gneiss is close to the upper Devonian pole of East Gondwanaland if the gneiss has been subjected to no significant tectonic movements. The other comparisons between the VGP positions and the APWP are not supported by the K-Ar age data. However, the segments of the APWP of East Gondwanaland between the middle Ordovician and Carboniferous, except the upper Devonian segment, have not been established yet because reliable paleomagnetic poles are few and/or they show large scatter (VAN DER VOO, 1993). Therefore, age estimation based on pole position is not available for this age range. Age dating of the granitic gneisses and syenites used in this work is necessary in order to clarify the APWP of East Gondwanaland.

The inconsistency between the VGP positions and the APWP, and the difference in the pole position between the gneisses and syenites, may be resolved through age dating. However, the following two possibilities which caused the inconsistency and the difference may also be implied: (1) differential tectonic movements occurred between the two massifs after the acquisition of remanence, and (2) the magnetic anisotropies affected the acquisition of remanence, or deformation in the rock bodies caused the difference in remanent direction, which resulted in the observed magnetic anisotropies.

The difference between the two VGP positions indicates a relative rotation of about 55° about a vertical axis between the two massifs. The amount of relative rotation seems to be close to the difference in the general trend of petrographical foliation between the two massifs. The foliation of granitic gneisses and syenites in Massif C trends generally in the NW-SE direction and dips 40° to 60°NE (YANAI *et al.*, 1982). The syenite at sites 1A and 2 has strike of N70°W with northward dip of 40°. In Massif B, the granitic gneisses in the northern part generally show NE-SW trending strikes of the foliation with northward dip, and the trend of the foliation changes to the N-S to NE-SW direction with eastward dip in the southern part. At sites 18 and 19 at the southern part of Massif B, the foliation which we measured trends about N50°E and dips 45°SE. The difference in the trend of the foliation may imply possibility (1). There is, however, no remarkable tectonic boundary between the two massifs, although an E-W trending thrust fault with northward dip is found near the boundary between syenites and granitic gneisses in the southern part of Massif C (YANAI *et al.*, 1982).

The granitic gneisses show a higher degree of AMS than the syenites (Fig. 4), and their K1 axes are closer to the petrographical foliation planes (Fig. 7). The magnetic fabrics of the granitic gneisses may be more related to the formation of the petrographical foliation. COGNÉ (1988) indicated that thermoremanent magnetization acquired by deformed rocks can be deflected by AMS from the magnetic field direction. Rock samples he analyzed were strained granitic rocks, and their magnetic anisotropy percentages were 15 to 31%. The granitic gneisses in this study have higher anisotropy percentages (20 to 70%). Possibility (2) must be verified in order to interpret the remanence of the granitic gneisses.

In summary, this study has revealed the existence of the stable magnetic components carried by magnetite in NRMs of granitic gneisses of two sites at Massif B and

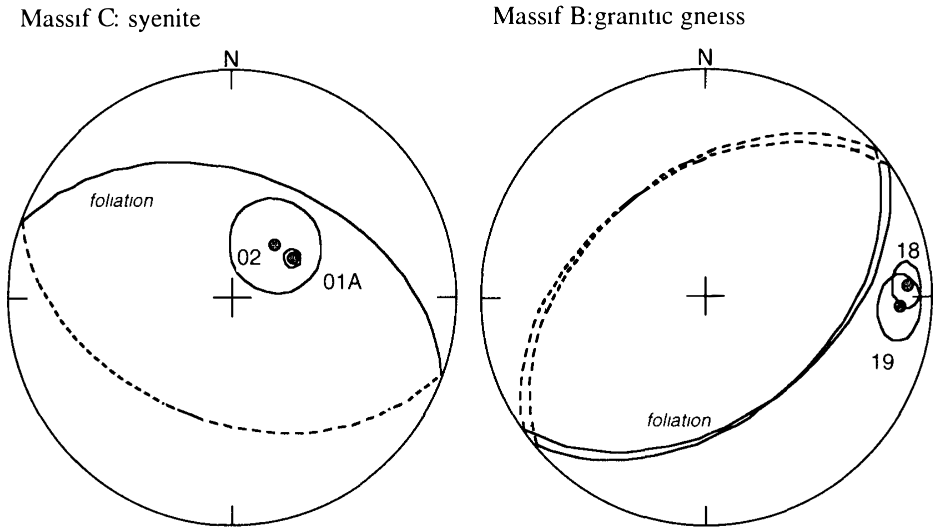

Fig. 7. Equal-area projections of the mean directions of the maximum principal axes from sites 1A, 2, 18 and 19. Orientations of petrographical foliation planes are also shown as great circles. The foliation at sites 1A and 2 are after YANAI *et al. (1982). The foliations at sites 18 and 19 were measured at their sites in this field work.*

those of syenites of two sites at Massif C. The VGP positions of the gneisses and syenites are different. The pole position of the gneisses is near the Precambrian, Silurian and upper Devonian segments of the APWP of East Gondwanaland, while that of the syenites is near the Ordovician segment. These comparisons are not supported by previous K-Ar age data except for the comparison between the gneiss pole and the upper Devonian segment of the APWP. Although age dating is necessary to explain the inconsistencies between the VGP positions and the APWP and the difference in the location of VGP between the gneisses and syenites, two possibilities may also be implied from geological structures in massifs and AMS analysis: these phenomena may be caused by (1) differential tectonic movement between the two massifs, and/or (2) the acquisition of remanence in anisotropic rock or deformation in the rock bodies.

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