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Magnetic fabric analysis of deformed rocks in the Riiser-Larsen Main Shear Zone, East Antarctica

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Abstract: Anisotropy of magnetic susceptibility (AMS) in deformed rocks in the Riiser-Larsen Main Shear Zone (RLMSZ) was analyzed in order to demonstrate the changes in rock magnetic properties due to deformation. Sixty-nine samples were collected at six sites from sheared gneisses and sheared dolerites. Experimental results of stepwise acquisition of isothermal remanence, demagnetization of a composite IRM and thermomagnetic measurement indicate the presence of Ti-poor titanomagnetite. Pyrrhotite also occurs characteristically in specimens with mylonitic textures. Magnetic foliations of AMS for the mylonite at three sites show good agreement with mylonitic foliation at each site. The mylonites showed enhancement of anisotropy degree from protoliths, indicating overprinting of the original magnetic fabrics. Their maximum susceptibility axes are well defined within each site, and dip about 50–60° northward. The magnetic lineation probably indicates the maximum stretching direction in the RLMSZ.

key words: Mt. Riiser-Larsen, mylonite, rock magnetism, anisotropy of magnetic susceptibility, pyrrhotite

1. Introduction

Anisotropy of magnetic susceptibility (AMS) offers a fast, precise and non-destructive way to quantify average alignments of minerals in a small rock sample. It is widely recognized that AMS is useful for obtaining the invaluable strain history of deformed rocks (Borradaile, 1988; Borradaile and Henry, 1997). AMS has actually been utilized in many fabric studies in shear zones to determine finite strain values and geometries (Goldstein, 1980; Goldstein and Brown, 1988; Rathore, 1985). It is, however, noted that some disagreements between magnetic tectonic orientations have been reported (*e.g.* Ruf *et al*., 1988). Response of AMS fabrics to strain can be affected by many factors including state of initial magnetic anisotropy (Ruf *et al*., 1988), kind and size of magnetic minerals that control AMS (Housen *et al*., 1995) and strain-related recrystallization (Borradaile, 1988). This implies the importance of

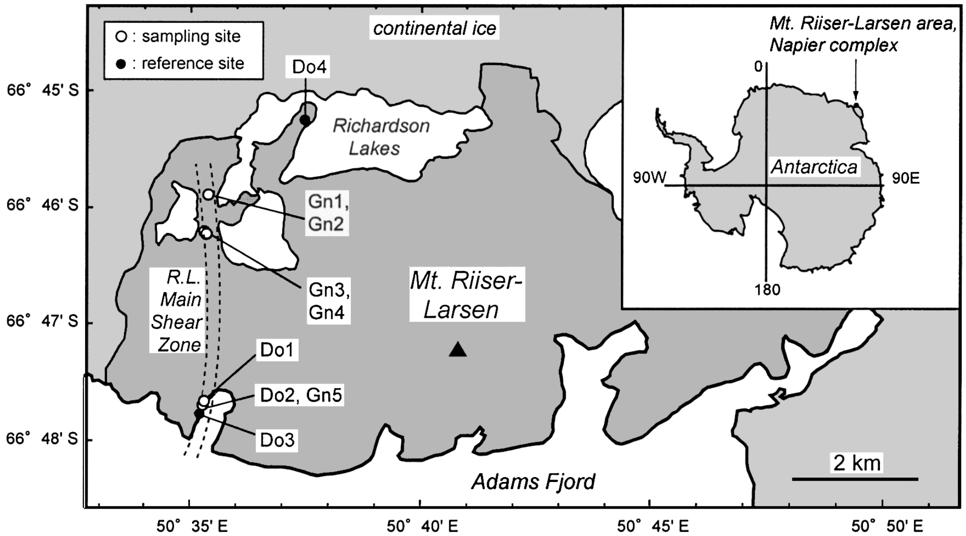

Fig. 1. Locality map showing the sampling sites in the Mt. Riiser-Larsen area. Modified from Ishizuka et al. (1998). Undeformed dolerites were sampled from the reference sites to evaluate the original magnetic features of dolerites.

Fig. 2. The Riiser-Larsen Main Shear Zone. The black part in the center is the sheared dolerite. Site Do1 is near side in this photo. The scale is 1 m long.

clarifying the changes in magnetic properties due to deformations when we use AMS parameters as strain indicators.

In this study, AMS analysis was carried out for the deformed rocks in the main shear zone in the Mt. Riiser-Larsen area, Enderby Land, East Antarctica (Fig. 1). The Mt. Riiser-Larsen area is the largest bedrock exposure in the Archean Napier Complex, which is one of the oldest continental blocks in the world (Motoyoshi, 1998). In this area, granulite-facies metamorphic rocks and unmetamorphosed Proterozoic intrusive rocks are present (Ishikawa *et al*., 2000). Ishikawa and Yuse (2004) suggested that there are at least three stages of shear zone formations in this area. The latest N-S shears develop along pre-existing mafic dikes that are suggested to have intruded at 1.2 Ga (Suzuki *et al*., 2000). The most significant N-S shear zone is referred to as "Riiser-Larsen Main Shear Zone (RLMSZ)" (Ishizuka *et al*., 1998) as shown in Fig. 1. In the RLMSZ, gneisses and dolerites underwent ductile deformation and show mylonitic textures (Fig. 2). Ishikawa and Yuse (2004) suggested that there is west-side-up relative movement of the RLMSZ based on microstructures with monoclinic symmetry.

We present the result of rock magnetic analysis including AMS for deformed rocks in the RLMSZ. The main purpose of this study is to demonstrate changes in magnetic minerals and AMS parameters related to the deformation, and thereby to estimate the maximum stretching lineation in the RLMSZ.

2. Sampling and rock magnetic analysis

The samples were collected in summer field research in the Mt. Riiser-Lasen area during the 42nd Japanese Antarctic Research Expedition (JARE-42). We used samples from sheared gneisses and dolerites at six sites in the RLMSZ, and also undeformed dolerite samples at the reference sites to evaluate original magnetic features of dolerites (Fig. 1). Six to 13 oriented core samples or hand samples were collected at each site. The core orientations were determined using a magnetic compass. Magnetic declination is expected to be 57.5°W on the basis of the international geomagnetic reference field 2000. Individual cylindrical specimens 25 mm in diameter and 22 mm long were prepared in a laboratory for rock magnetic experiments.

Ishikawa and Funaki (1998) reported the results of rock magnetic experiments including AMS for sites Gn3 and Gn4. Measurements for the rest of the sites in the RLMSZ were carried out in this study. AMS values were measured using a Kappabridge KLY-3S (AGICO Inc.) before any other rock magnetic experiments. AMS can be described in terms of an ellipsoid with three orthogonal principal axes, designated the maximum (K1), intermediate (K2) and minimum (K3) susceptibility axes, respectively. Jelinek (1978)'s statistical tensor has been employed to yield the site mean directions and the 95% confidence ellipse of each principal axis. The major AMS parameters examined in this study are the mean susceptibility:

$$K_m = (\mathrm{K1} + \mathrm{K2} + \mathrm{K3})/3, \quad (1)$$

and the corrected anisotropy degree and shape parameters (Jelinek, 1981):

$$Pj = \exp\{2[(n_1 - n_m)^2 + (n_2 - n_m)^2 + (n_3 - n_m)^2]\}^{1/2}, \quad (2)$$

$$T = (2n_2 - n_1 - n_3)/(n_1 - n_3), \quad (3)$$

where, $n_1 = \ln K_1$, $n_2 = \ln K_2$, $n_3 = \ln K_3$, $n_m = (n_1 + n_2 + n_3)/3$.

After alternating field demagnetization of NRM with a maximum field of 100 mT, at least 2 specimens from each site were subjected to cumulative acquisition of IRM up to 2 Tesla using a pulse magnetizer (Magnetic Measurements Ltd). For the same specimens, stepwise thermal demagnetization of a composite IRM was carried out (Lowrie, 1990). The three IRM components were orthogonally imparted at 2.5 T (Hard), 0.4 T (Medium) and 0.12 T (Soft) fields. To check Curie temperatures (T_c) and magneto-mineralogical reactions, thermomagnetic measurements were carried out for a bulk rock chip of about 50–100 mg from each site. The measurements were run in air under an applied field of 0.7 Tesla, with heating and cooling rates of 8°C/min, using a magnetic balance (Eiko Electric Ltd).

3. Sample descriptions

The original lithologies of the sampled rocks in the RLMSZ are either dolerite or gneiss (Table 1). Sheared gneisses were sampled at Sites Gn1 and Gn2 in the northern part of the RLMSZ (66°46′S, 55°35′E) as shown in Fig. 1. At Site Gn1, intensely sheared felsic gneiss showed dark mylonitic textures and low-strain lenses of leucocratic gneisses. Samples were collected from both parts. The strike and dip of the mylonitic foliation is near N-S and vertical. Sites Gn3 and Gn4 are located at 66° 46′S, 50° 35′E; the descriptions for these sites were given as Sites 1 and 2 in Ishikawa and Funaki (1998). Sheared dolerites were sampled at Sites Do1 and Do2 in the southern part of the shear zone (66°58′S, 50°35′E). Felsic gneiss at Site Gn5 was sampled in the same location as Site Do2 across the dike contact. The outcrop at Site Do1 is shown in Fig. 2. The strike and dip of the mylonitic foliation at these sites is N11°E and 75°N.

Microscopic observations revealed that all of the samples appear to have been more or less subjected to shearing. Textures of the deformation considerably differ from site to site depending on the original lithology and on the location in the shear zone.

Table 1. Magnitude and orientation of the principal axes of the site means of the AMS ellipsoids (Jelinek, 1978).

Site	Rock	n	K_m 10^{-7} m^3/kg	$\tau 1$	Dec. deg.	Inc. deg.	$\tau 2$	Dec. deg.	Inc. deg.	$\tau 3$	Dec. deg.	Inc. deg.
Do1	Ds	7	169.78	0.378	351.9	50.2	0.344	220.9	173.5	0.278	327.6	6.5
Do2	Ds	11	158.57	0.374	365.4	60.6	0.330	212.4	26.6	0.297	116.5	11.5
Gn1	Gs	10	14.94	0.371	311.4	34.5	0.330	201.2	26.6	0.299	82.6	43.8
Gn2	Gs	9	5.80	0.359	351.7	14.3	0.348	248.5	41.9	0.293	96.2	44.6
Gn3 (1)*	Gs	7	2.26	0.342	3.7	13.8	0.332	263.2	36.5	0.325	110.8	50.2
Gn4 (2)*	Gs	13	17.82	0.382	21.0	49.7	0.328	175.1	37.3	0.290	275.2	12.9
Gn5	Gs	9	248.59	0.364	205.2	1.6	0.326	112.3	61.5	0.310	296.1	28.5

Notes: * Site name in Ishikawa and Funaki (1998); Ds and Gs denote sheared dolerite and sheared gneiss, respectively. n is the number of specimens used to define the mean; K_m is the mean low-field susceptibility magnitudes for every site; $\tau 1$, $\tau 2$, $\tau 3$ are the normed mean principal susceptibilities; Dec. and Inc. are the declination and inclination for each mean susceptibility axis, respectively.

Mylonitic textures characterized by intensive grain size reduction were dominant in samples from dolerites at Sites Do1 and Do2 and gneiss at Site Gn1. The gneisses at Sites Gn2–5 often show the coexistence of original and strain related fabrics. The felsic gneiss at Site Gn5 shows only a few cracks and has no evidence of ductile deformation. Based on these observations, we classify these rocks into two types: mylonite (Sites Do1, Do2 and Gn1) and deformed gneiss (Sites Gn2–5). The dolerite at the reference site (Do3) has a porphyritic texture with phenocryst of clinopyroxene and plagioclase, showing no evidence of deformation.

4. Results

4.1. Anisotropy of magnetic susceptibility

Degree of anisotropy against mean low-field susceptibility is plotted in Fig. 3. Most dolerite and sheared dolerite specimens (Sites Do1–4) have susceptibility of about 1×10^{-5} m^3/kg. The sheared gneisses (Sites Gn1–5) have much lower susceptibility, on the order of 10^{-7} and 10^{-6} m^3/kg, but the sheared gneiss at Site Gn2 has exceptionally high susceptibility. The mylonites at Sites Do1 and Do2 show higher mean Pj than those for undeformed dolerites. The mylonite at Site Gn1 also has higher mean Pj than those of the other deformed gneisses. Only Site Gn5 has weak Pj, generally less than 1.1.

Shape parameters for the mylonites (Fig. 4A) and sheared gneisses (Fig. 4B) generally range from oblate to prolate ranges. Positive correlation between Pj and T might be present only at Sites Do1 and Gn4. Gneiss specimens with weak anisotropy

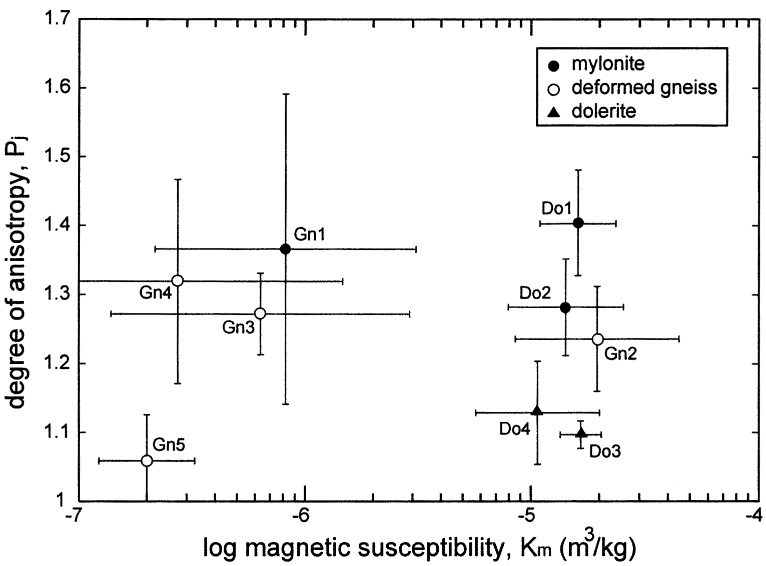

Fig. 3. Plots of the arithmetical mean of the corrected anisotropy degree, Pj, against the magnetic susceptibility, K_m, with their standard deviation. Open circle: deformed gneiss, solid circle: mylonite, solid triangle: dolerite.

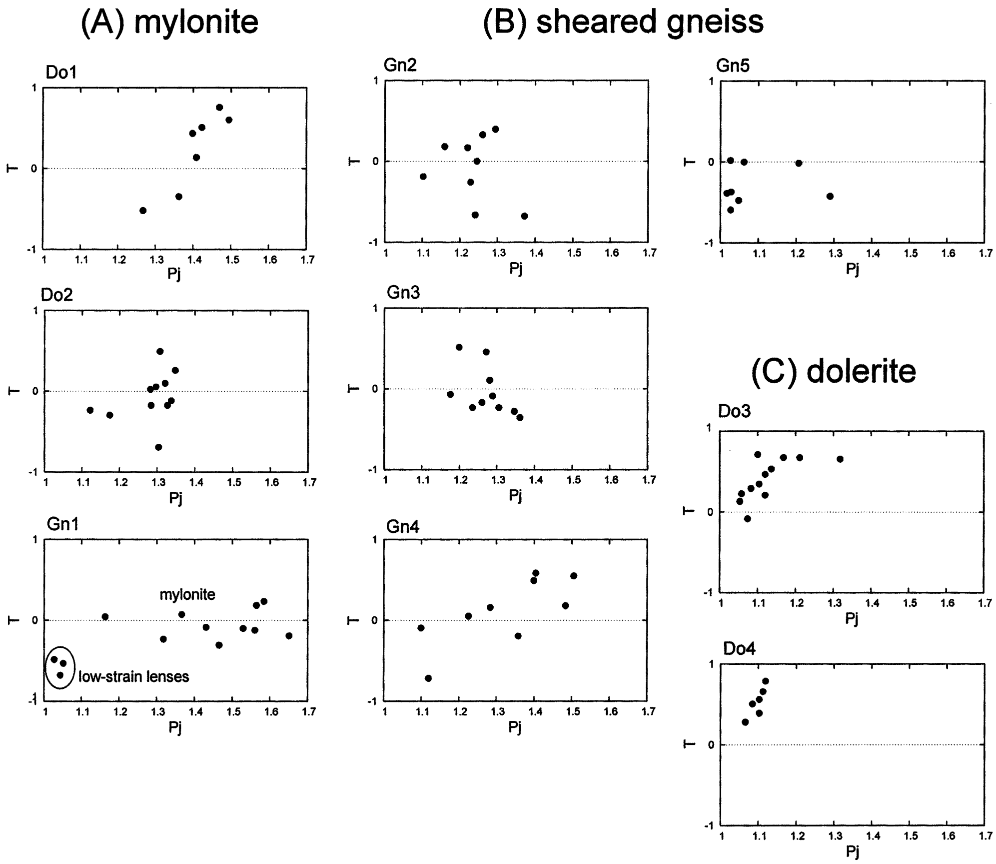

Fig. 4. Plots of the magnitude of the shape parameter, T, against the anisotropy degree, Pj.

(Pj < 1.1) tend to have a prolate susceptibility ellipsoid. Site Gn1 shows changes in its AMS parameters from low strain lens to mylonite. The Pj of the mylonite parts ranges from 1.2 to 1.7, indicating variable magnitude of strain even at the same site. The undeformed dolerites show more oblate susceptibility ellipsoids and lower Pj values than deformed dolerite (Fig. 4C).

Orientations of the principal susceptibility axes are shown in Fig. 5, and AMS parameters for the mean susceptibility ellipsoids are listed in Table 1. The specimens from mylonites show generally well grouped principal susceptibility axes at each site (Fig. 5A). Their magnetic foliations, defined by the planes through K1 and K2 axes, are sub-parallel to the observed mylonitic foliations. Their mean magnetic lineations dip about 50° northward at Sites Do1 and Gn1, and about 60° at Site Do2. The principal axes of some specimens at Sites Gn3 and Gn4 point in similar directions to those of mylonites (Fig. 5B). They are, however, slightly deviated away from the shear foliation, and the K1 axes are ill defined at Site Gn4. The magnetic foliations of Sites Gn2 and Gn5 disagree with the shear foliation of the RLMSZ.

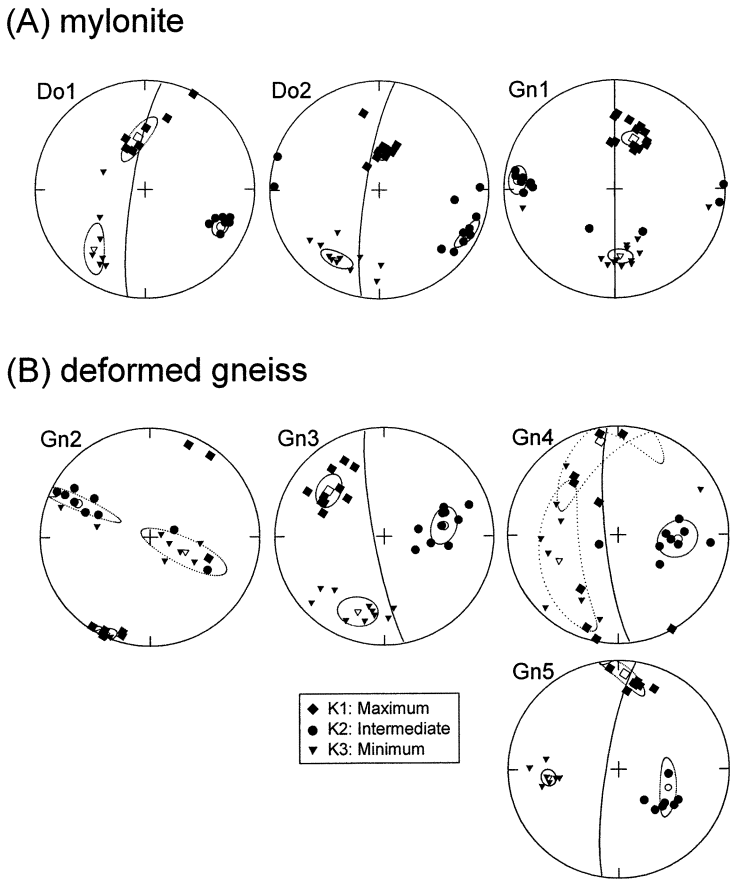

Fig. 5. Equal-area plots showing the directions of the principal AMS axes for each specimen (solid symbols). The K1, K2 and K3 axes are plotted on the lower hemisphere as squares, triangles and circles, respectively. Open symbols are the directions of the principal axes of the site mean ellipsoid with 95% confidence ellipse (Jelinek, 1978). Great circle indicates the plane of the shear foliations. (a) mylonites, (b) deformed gneisses.

4.2. Magnetic mineralogy

Results of the IRM acquisition experiments showed that all specimens are close to their saturations below 1 T (Fig. 6). Mylonites at Sites Do1 and Gn1 show the changes in gradient at about 100 mT and further increase in IRM until about 500 mT (Fig. 6A), indicating the presence of two magnetic minerals with low and high saturation fields. The results of the demagnetization experiments also indicate 2 maximum unblocking temperatures of 360°C and 590°C. They are probably carried by monoclinic pyrrhotite (Fe_7S_8) and Ti-poor titanomagnetite, respectively. The mylonite at Site Do2 and the deformed gneisses (Fig. 6B) shows monotonous acquisition of IRM until 200 mT. The results of the progressive demagnetization show the maximum unblocking temperatures between 560°C and 590°C, mainly in the soft IRM component, and slight decrease in the

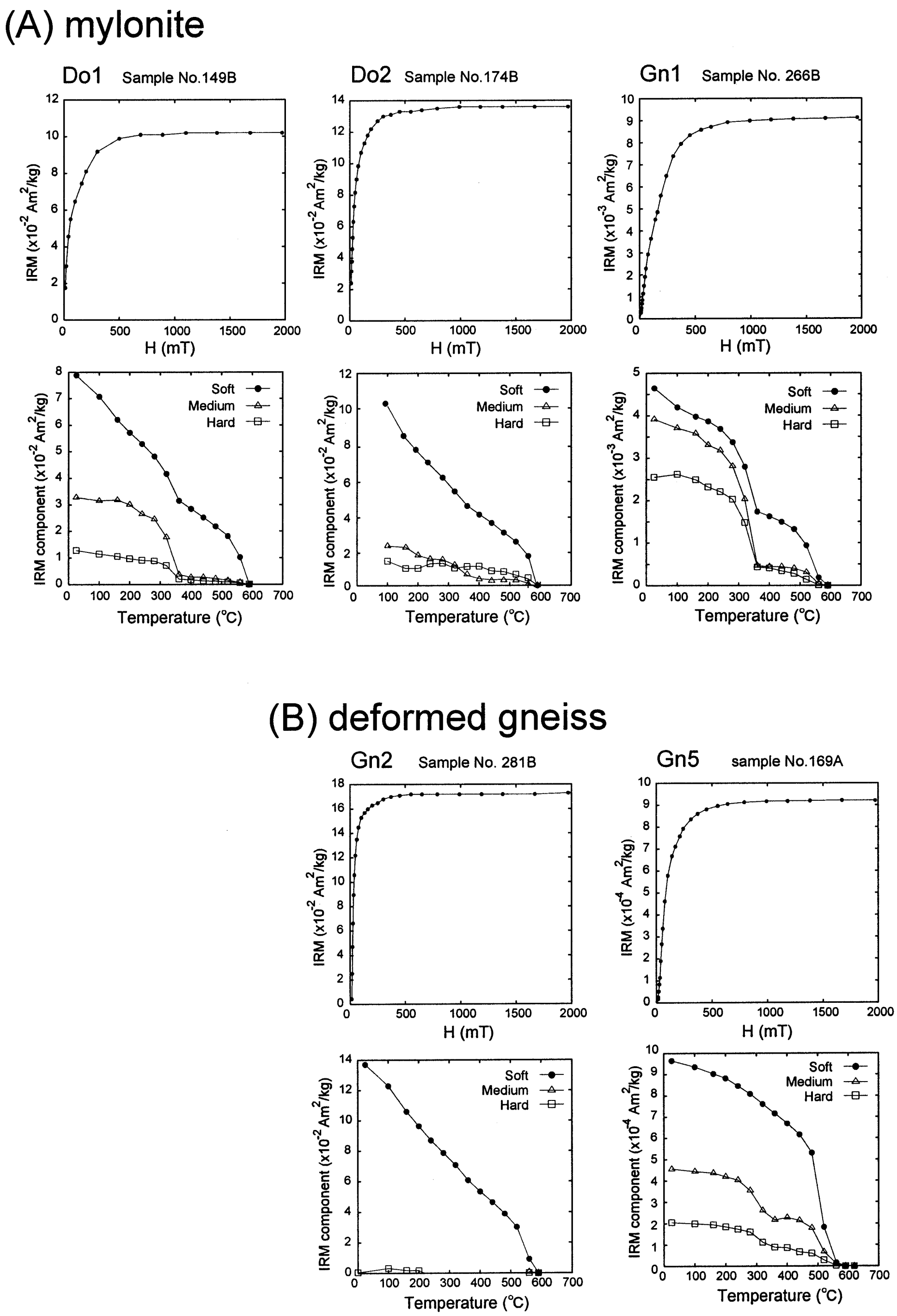

Fig. 6. Results of the isothermal remanence (IRM) acquisition experiments, and stepwise thermal demagnetization of the composite IRM. Each component of the IRM was produced by applying a different DC field of 2.4 T (hard), 0.4 T (medium) and 0.12 T (soft) to the three perpendicular axes of a specimen.

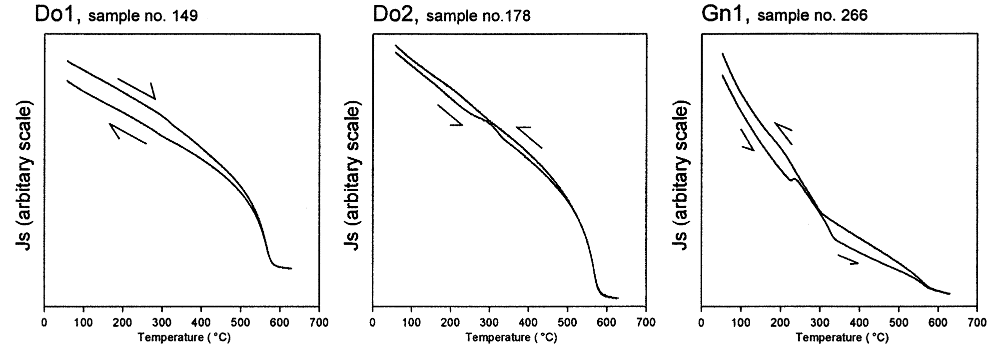

Fig. 7. Typical results of strong-field thermomagneitc experiments for the mylonites.

medium IRM component at 360°C. These indicate that the specimens contain Ti-poor titanomagnetite as their main magnetic mineral, and to a lesser extent, pyrrhotite.

Typical thermomagnetic curves for mylonite samples are shown in Fig. 7. The observed Tc between 570°C and 580°C corresponds to Ti-poor titanomagnetite. Site Gn1 also shows an increase in magnetization at about 230°C, indicating λ-transition of hexagonal pyrrhotite (Fe_9S_{10}). The ferrimagnetic phase of the hexagonal pyrrhotite was preserved below 200°C under rapid cooling conditions. Indication of pyrrhotites is also shown for Site Do1 and Do2 as slight changes in the magnetization around 300°C in the heating curves.

5. Discussion

The presence of pyrrhotite in the RLMSZ is indicated in the mylonites by the several rock magnetic experiments. The observed T_c at about 330°C is slightly higher than that of typical monoclinic pyrrhotite (320°C). Such higher T_c of pyrrhotite might be explained by modification of ordering in Fe vacancies due to substitution of ions such as oxygen (Rochette, 1990). Occurrence of sulfide minerals in the shear zone is often associated with fluid activities (Rochette, 1987). The deformed gneisses in this study have magnetite as their main magnetic mineral. Previous rock magnetic studies of dolerites and gneisses in this area have not reported the presence of pyrrhotite either (Ishikawa and Funaki, 1998, 2000). This fact supports the idea that pyrrhotite occurs locally in shear zones, especially in rocks with mylonitic textures.

The relatively high susceptibilities for the mylonites within dolerites imply that their AMS is mainly controlled by ferromagnetic minerals (Tarling and Hrouda, 1993), while the AMS of the most deformed gneiss samples can be controlled by both paramagnetic and ferromagnetic minerals. Ishikawa and Funaki (1998) inferred that the AMS at Sites Gn3 and Gn4 are probably controlled by magnetite based on the result of hysteresis measurements. Because the mylonite specimens at Site Gn1 have generally higher susceptibilities than those at Sites Gn3 and Gn4, their AMS is also suggested to be controlled by magnetic minerals, namely magnetite and/or pyrrhotite.

Primary magnetic fabrics in dolerite dikes or sills generally show an oblate susceptibility ellipsoid and relatively low anisotropy degree of Pj, less than 1.2 (*e.g.* Ishikawa and Funaki, 2000; Elming and Mattsson, 2001). This is consistent with the AMS parameters in undeformed dolerites in this study. The AMS in the sheared dolerites with the high anisotropy degree clearly shows the enhancement of AMS due to strain, and thereby indicates complete overprinting of the original magnetic fabric. The contrast of the anisotropy degrees between mylonite and low-strain lens also infers overprinting of the magnetic fabric.

The magnetic foliations of the mylonites in the RLMSZ well reflect the mylonitic foliations, just as in the previous AMS studies in mylonite zones (Goldstein, 1980; Goldstein and Brown, 1988; Rathore, 1985). In contrast, the principal axes of the deformed gneisses are ill defined or inconsistent with the shear foliations. This may be due to incomplete or transitional magnetic fabrics from original to tectonic fabrics as suggested by Goldstein (1980). It is also known that magnetic lineation in the mylonite zone often agrees with the maximum stretching direction, although disagreements have also been reported (Ruf *et al*., 1988). We believe that the magnetic lineations of mylonites in the RLMSZ do correspond to the maximum stretching direction for the following reasons. First, the principal axes for each site are relatively better defined than in the result of Ruf *et al.* (1988). Second, there exists a directional agreement in magnetic lineations between the mylonites in the different sites and of the different protoliths. Finally, the AMS of the mylonites clearly show enhancement of the AMS from a low-strain lens or from undeformed dolerites, indicating the overprinting of the original magnetic fabrics. Ishikawa and Yuse (2004) suggested west-side-up relative movement of the RLMSZ. The result of our study concludes that the expected maximum stretching direction in the RLMSZ dips about 50–60° to the north, both in the northern and southern part of the area.

6. Summary

(1) Ti-poor titanomagnetite and pyrrhotite are the two main magnetic minerals in sheared rocks in the RLMSZ. Pyrrhotite occurs characteristically in mylonites.

(2) AMS in mylonitic rocks showed enhancement of anisotropy degree (Pj) due to strain. Magnetic fabrics of mylonites in the RLMSZ showed magnetic foliations sub-parallel to mylonitic foliations and magnetic lineations with northward dip of about 50–60° and N-S strike, which imply the maximum stretching lineation in the RLMSZ.

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