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# ANISOTROPY OF MAGNETIC HYSTERESIS PROPERTIES OF AUDIO-TAPE SAMPLES: ITS APPLICATION FOR THE MAGNETIC ANISOTROPY OF GNEISSIC ROCKS

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***Abstract:*** The magnetic anisotropy of hysteresis properties of audio-tape samples which were made from single domain (SD) of $\gamma$-hematite were measured using a vibration sample magnetometer (VSM). Subsequently after alternating field demagnetization (AF demagnetization) of natural remanent magnetization (NRM) up to 60 mT, the anhysteretic remanent magnetization (ARM) was produced by applying an external alternating field up to 120 mT under the geomagnetic field in the laboratory. After these ARM acquisitions, these ARMs were demagnetized by AF field up to 70 mT. On the hysteresis properties of audio-tape, $H_C$ (coercivity) and $I_R$ (saturation isothermal remanent magnetization) were found to be more anisotropic than $\chi_{diff}$ (differential susceptibility at low field); these anisotropic maximum axes were parallel to the length of the tape. The anisotropic maximum axis of $\chi_{diff}$ was perpendicular to that of $I_R$ and $H_C$ in the tape plane. The most stable remanent magnetization after AF demagnetization remained parallel to the maximum axis of $H_C$ and of $I_R$. On the basis of the similarity of the magnetic properties between the tape sample and the gneissic rocks from the Skarvsnes area, East Antarctica, it is clear that SD alignment in rocks shows the perpendicular anisotropic maximum axis of $\chi_{diff}$ to that of $I_R$ and $H_C$. Therefore, this anti-phase of the anisotropy may be an important index to determine SD alignment in metamorphic rocks. The present study suggests that the NRM from old rocks not always shows the ancient geomagnetic field.

## 1. Introduction

The measurement of anisotropy of magnetic hysteresis properties is a useful method for the identification of the alignment of magnetic minerals in rocks. Some gneissic rocks have magnetic mineral alignment, and show magnetic anisotropy. NAKAI *et al.* (1993) have measured the anisotropy of the magnetic hysteresis properties (*i.e.*, $H_C$ (coercivity), $I_R$ (saturation isothermal remanent magnetization) and $\chi_{diff}$ (differential susceptibility at low field)) of gneissic rocks from Skarvsnes (Latitude=69.5°S, Longitude=36.6°E), East Antarctica, with a Vibration Sample Magnetometer (VSM). The values of $H_C$ and $I_R$ of these rocks from Skarvsnes were more anisotropic than $\chi_{diff}$. Therefore, NAKAI *et al.* (1993) concluded that $H_C$ and $I_R$ were a more effective measure of the magnetic anisotropy of paleomagnetic rock samples than $\chi_{diff}$. The maximum anisotropy axis of $H_C$ and $I_R$

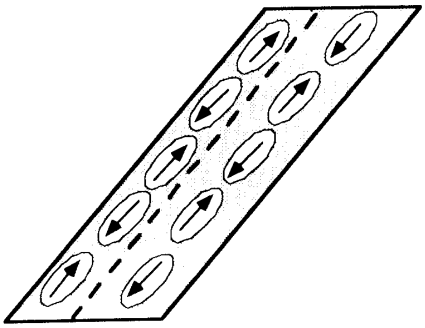

*Fig. 1. The SD alignment of an audio-tape sample.*

coincided with the direction of lineation in the sample, and the natural remanent magnetization (NRM) direction after thermal demagnetization turned toward the maximum anisotropy axis (NAKAI *et al.*, 1993). However, it is still not clear what grain alignment contributes to the anisotropies of $I_R$, $H_C$ and $\chi_{diff}$.

In general, both multi domain (MD) and single domain (SD) size grain magnetic minerals are contained in natural rocks ; sometimes they are aligned. In order to understand the characteristics of magnetic minerals which show alignment, the author prepared an audio-tape in which ellipsoidal grains of SD of $\gamma$-hematite are well known to align, as shown in Fig. 1, and measured the anisotropy of the hysteresis properties using a VSM. If the gneissic rocks have SD alignment, the anisotropy of hysteresis properties of the gneissic rocks should to be similar to those of an audio-tape. In this paper, the author compared the magnetic anisotropy of audio-tape samples with that of gneissic rocks from Skarvsnes, and reports what size grains contribute to the magnetic anisotropy.

## 2. Measurements of the Audio-tape Samples

A piece of an audio-tape was cut to 1 cm length and was set as shown in Fig. 2. The hysteresis loops of the audio-tape sample were measured every 5° with a VSM in the X-Y, Y-Z and Z-X planes (Fig. 3). The anisotropy of three magnetic properties ($I_R$, $H_C$ and $\chi_{diff}$) was obtained from these hysteresis loops (NAKAI *et al.*, 1993). From these measurements, I realized that the maximum value of $H_C$ of my audio-tape sample is very

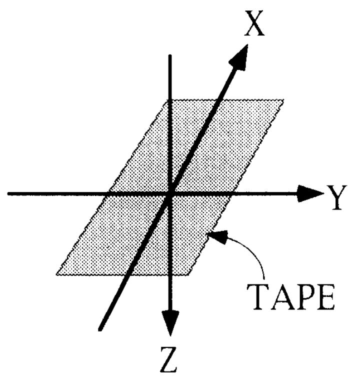


*Fig. 2. The setting of the X-Y-Z axes for the autio-tape samples.*

large (about 300 mT).

The 60 mT alternating field demagnetizations (AF demagnetization) of NRM were carried out for the audio-tape samples which were set as shown in Fig. 2. The result is shown in Fig. 4. This is in agreement with the above result that the samples have high

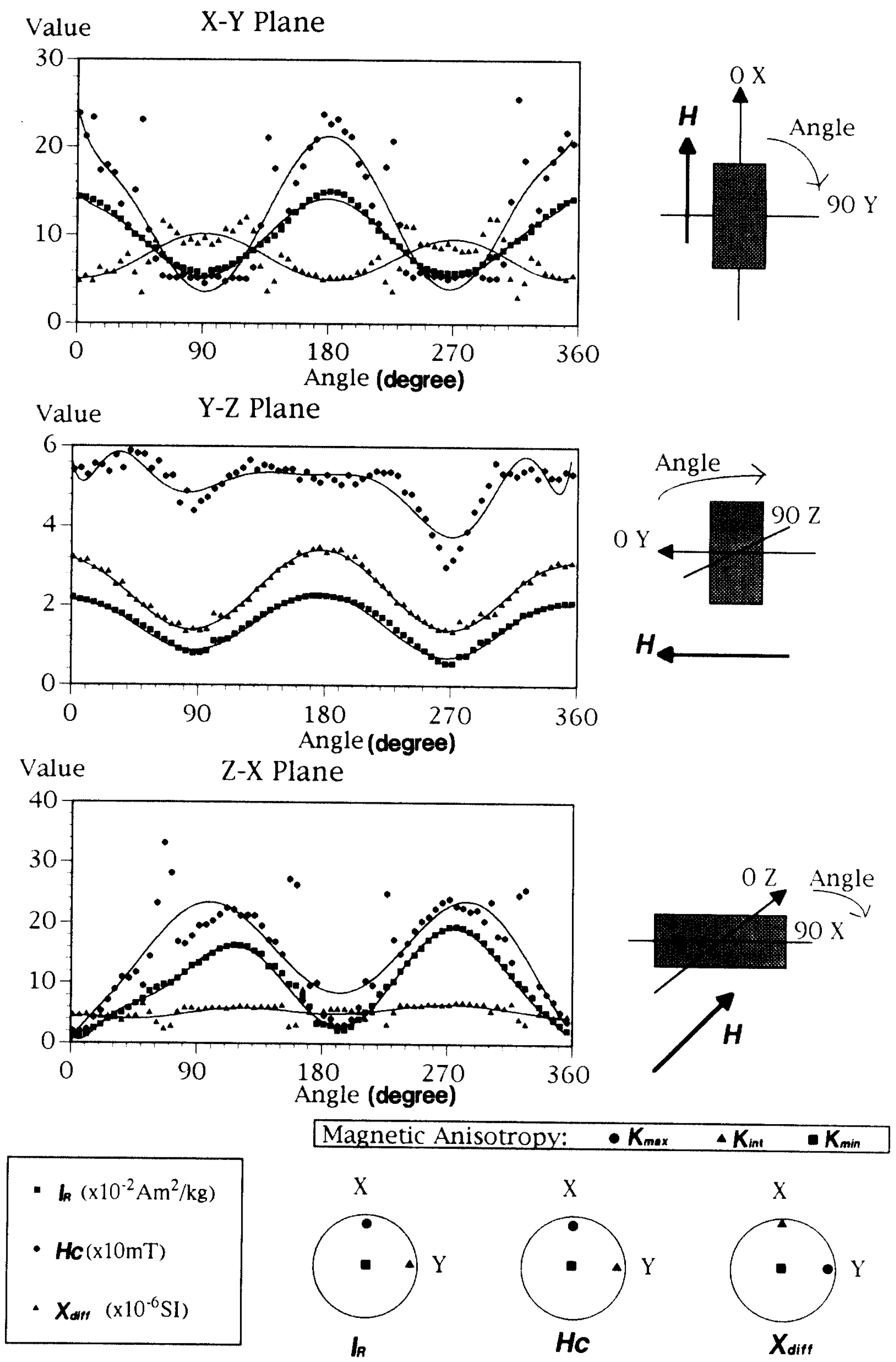


*Fig. 3.* *The magnetic anisotropy of the audio-tape samples. H : The direction of the external field of a VSM, $I_R$ : saturation isothermal remanent magnetization, $H_C$ : coercivity, $\chi_{diff}$ : differential susceptibility at low field, $K_{max}$, $K_{int}$, $K_{min}$ : The eigenvector axes of the ellipsoid of a magnetic anisotropy tensor.*

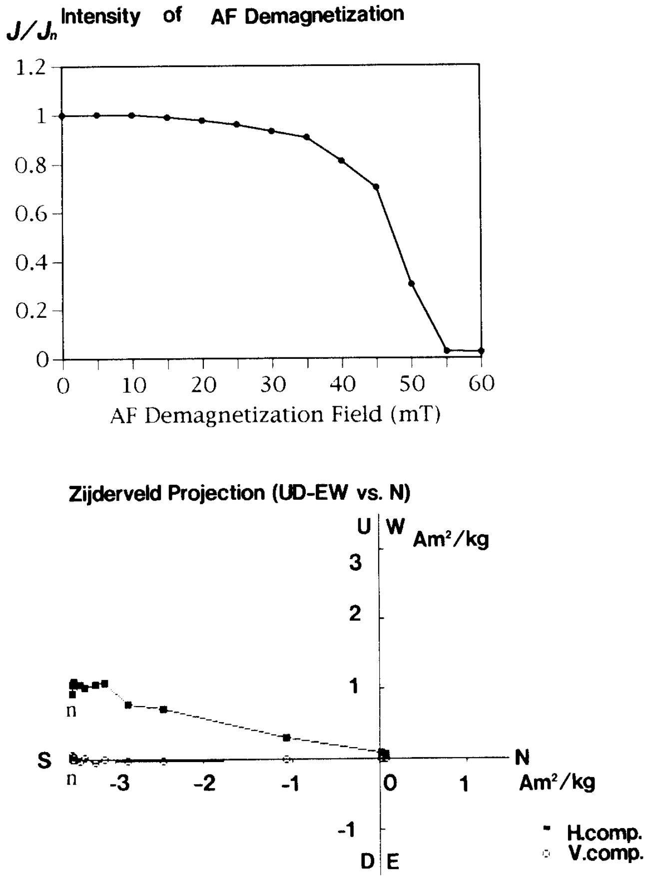


*Fig. 4.* *Change of intensity and the Zijderveld projection with the stepwise AF demagnetization of the audio-tape sample. J : intensity of remanent magnetization, $J_n$ : intensity of an NRM, E : East (Y), W : West (– Y), N : North (X), S : South (– X), U : up (– Z), D : Down (Z). H. comp. : horizontal component, V. comp. : vertical component, n : a position of an NRM.*

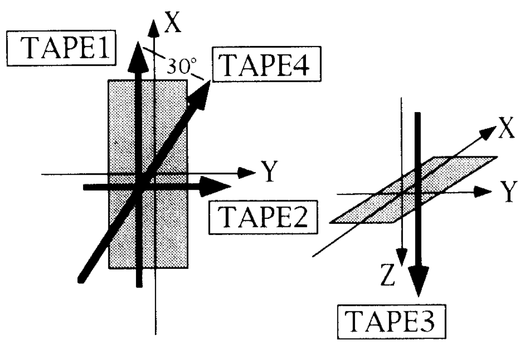


*Fig. 5.* *The ARM directions for the audio-tape samples. An alternating external field was applied to four audio-tape samples (TAPE1–4) under the geomagnetic field in laboratory. The big arrows show the direction of the geomagnetic field ($H_E$).*

$H_C$ ; these results imply that a magnetic carrier of the audio-tape samples is an SD grain (DAY *et al.*, 1977).

An audio-tape cannot be heated ; therefore, we cannot magnetize it by heating (thermo-remanent magnetization ; TRM). Instead, anhysteretic remanent magnetization (ARM) was created stepwise at 10 mT on four samples into four directions (TAPE1-4, in Fig. 5) under the geomagnetic field $H_E$ (about $3.566 \times 10^4$ nT), and alternating fields up to 120 mT (Fig. 6). Subsequently, the AF demagnetizations were carried out stepwise at every 5 mT up to 70 mT (Fig. 7). These results on ARM show that these ARMs are very stable, suggesting that TRM of this sample is also stable and supporting the above implication that a magnetic carrier of the audio-tape sample is made of an SD grain.

## 3. The Anisotropy of Hysteresis Properties

Figure 3 shows the anisotropy of hysteresis properties ($I_R$, $H_C$ and $\chi_{diff}$) of the audio-tape sample using a VSM. The anisotropy of $I_R$ and $H_C$ is larger than $\chi_{diff}$ in the X-Y and Z-X planes, but the anisotropy of these three properties is almost the same in the Y-Z plane. In the Y-Z plane and in the Z-X plane, three properties are in phase, showing peak anisotropy at the same angle (Y-Z plane : Angle$=0°$, $180°$ and $360°$, Z-X plane : Angle$=120°$ and $270°$), while in the X-Y plane, the anisotropy of $\chi_{diff}$ shows the anti-phase to that of $I_R$ and $H_C$, the peak anisotropy angles being $90°$ and $270°$.

Anisotropy of magnetic susceptibility (AMS) is a frequently used anisotropic property. Here, susceptibility means initial susceptibility. $\chi_{diff}$ in experiments is regarded as an initial susceptibility. An AMS is an ellipsoid of magnetic susceptibility defined by the length and orientation of its three principal axes, $K_{max} > K_{int} > K_{min}$. These are the three eigenvectors of the anisotropy tensor. Using these quantities, the parameters ; *L, F, P* and *E* are defined as follows (ROCHETTE *et al.*, 1992).

$$L \text{ (lineation)} = K_{max}/K_{int}, \quad (1)$$
$$F \text{ (foliation)} = K_{int}/K_{min}, \quad (2)$$
$$P \text{ (anisotropy factor)} = K_{max}/K_{min}, \quad (3)$$
$$E \text{ (ellipsoid)} = F/L = K_{int}^2/K_{max}K_{min}. \quad (4)$$

It is considered that $L$ is a measure of the extent of linear parallel orientation of particles, and $F$ of their planar distribution. The ratio $E$ is termed the eccentricity $E$ of the ellipsoid (COLLINSON, 1983). If $E > 1$ the ellipsoid is oblate ; if $E < 1$ the ellipsoid is prolate. These parameters are usually used for AMS, but these are useful for other magnetic anisotropies (*i.e.*, $I_R$ and $H_C$). Therefore I calculated these parameters (*L, F, P*

*Table 1. The magnetic anisotropy parameters of an audio-tape samples.*

| | $L$ | $F$ | $P$ | $E$ | Shape of $E$ |
|---|---|---|---|---|---|
| $I_R$ | 4.06 | 4.13 | 16.81 | 1.02 | oblate |
| $H_C$ | 4.63 | 1.59 | 7.37 | 0.34 | prolate |
| $\chi_{diff}$ | 1.19 | 1.86 | 2.21 | 1.56 | oblate |

$L$ : lineation of magnetic anisotropy, $F$: foliation of magnetic anisotropy,
$P$ : anisotropy factor, $E$ : ellipsoid of magnetic anisotripy ($F/L$).

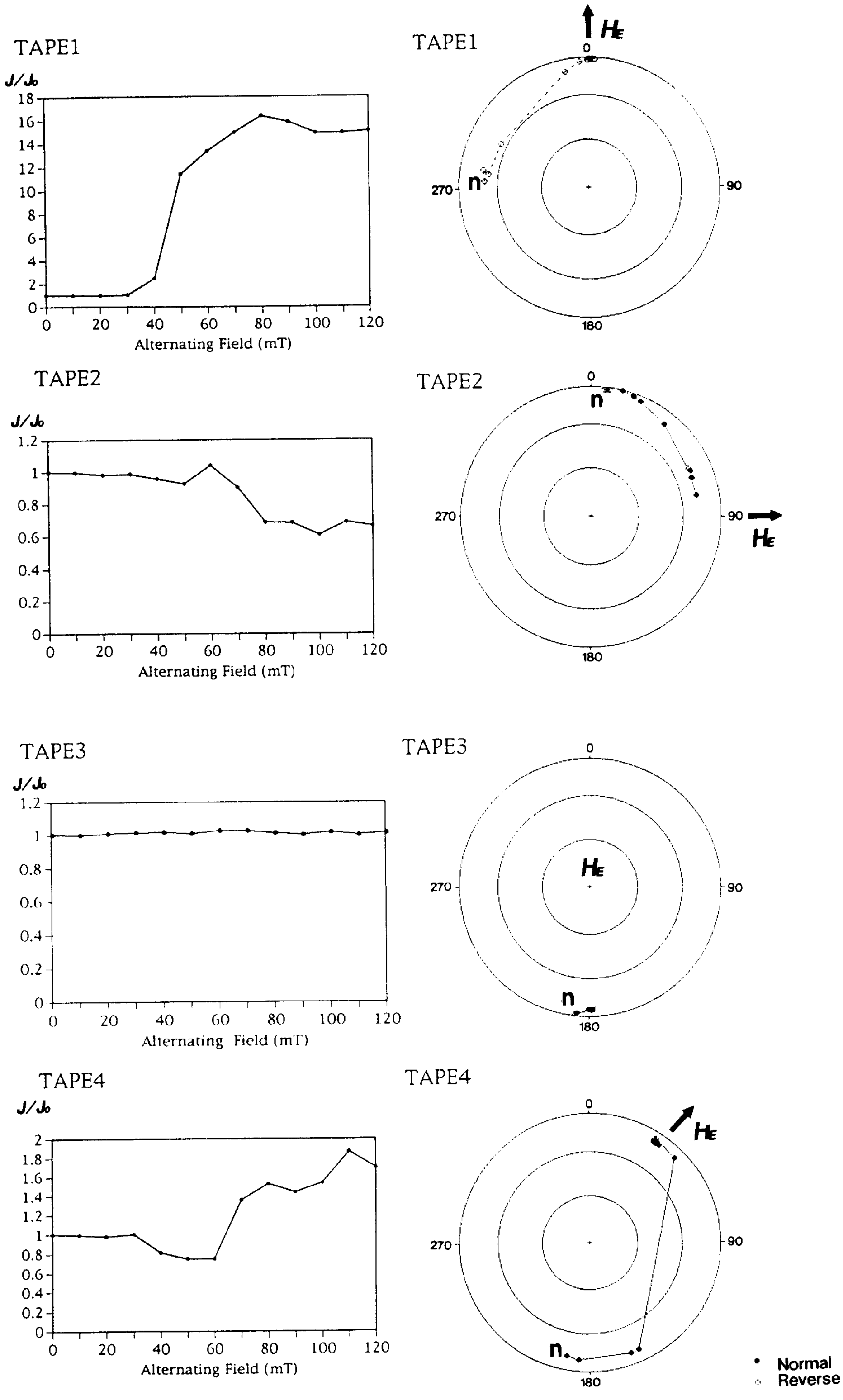


*Fig. 6. Experiments on the ARM of audio-tape samples. $H_E$ : the direction of the geomagnetic field, n : a position before ARM experiments. "0" on the polar chart is the direction of the X axis. J : intensity of remanent magnetization. $J_0$ : intensity of a remanent magnetization before ARM experiments.*

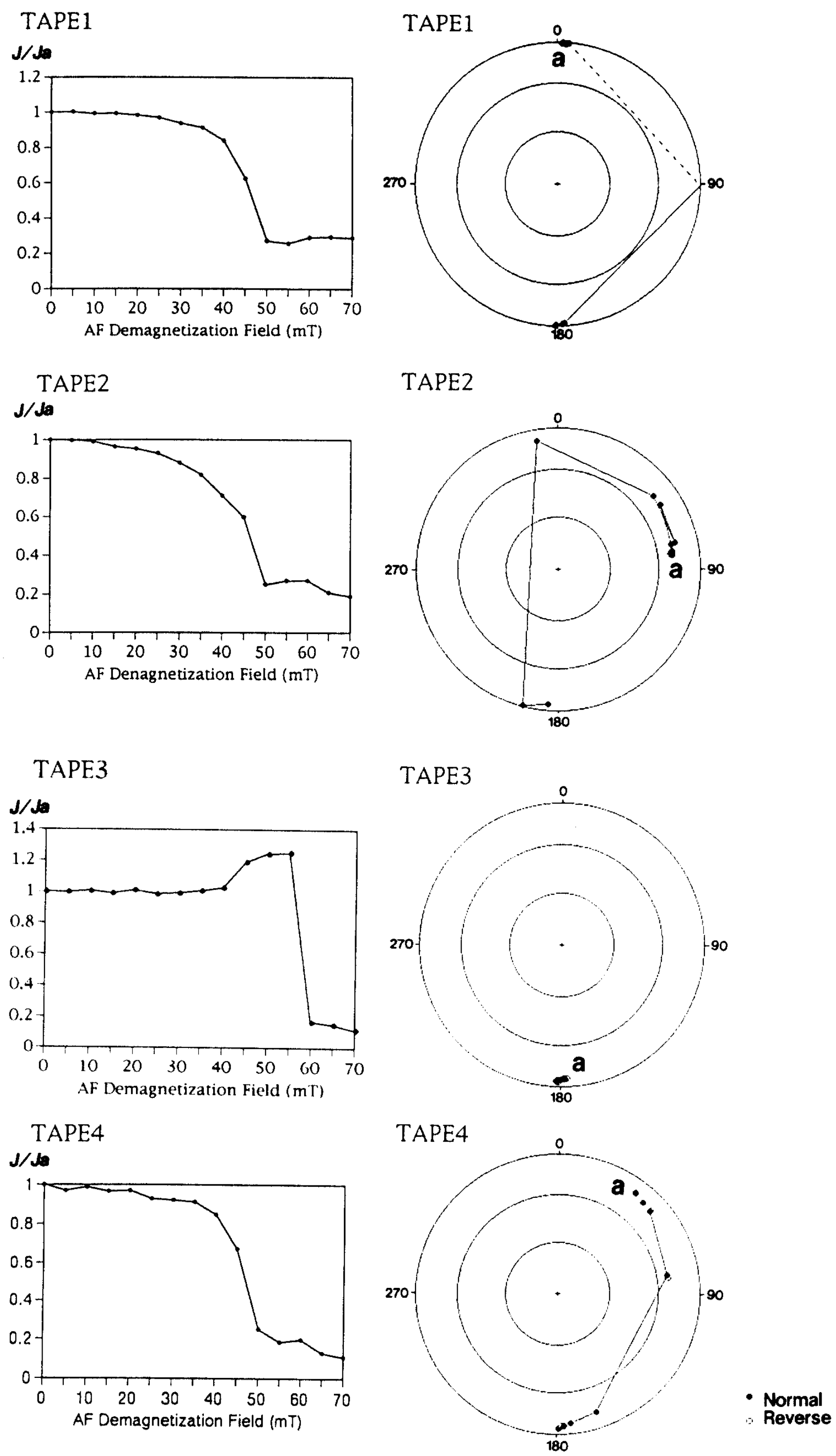


*Fig. 7.* *The AF demagnetizations after ARM experiments. a : a position before AF demagnetizations. "0" on the polar chart is the direction of the X axis. J : intensity of remanent magnetization. $J_a$ : intensity of remanent magnetization before AF demagnetizations.*

and $E$) of the audio-tape samples ; averages of these parameters are listed in Table 1.

The averages of $L$, $F$ and $P$ of $I_R$ and $H_C$ are larger than those of $\chi_{diff}$, and the each average of $E$ shows different value (Table 1). On the basis of these results, I conclude that these magnetic anisotropies ($\chi_{diff}$, $I_R$ and $H_C$) are controlled by different magnetic grains or characteristics. As shown in Fig. 3, the direction of $K_{max}$ of $I_R$ and $H_C$ is parallel to that of X, $K_{int}$ to Y and $K_{min}$ to Z. Taking the configuration of the magnetic grain in the audio-tape (Fig. 1) into account, these results are reasonable. On the other hand, the $K_{max}$, $K_{int}$ and $K_{min}$ of $\chi_{diff}$ are parallel to that of Y, X and Z, respectively, this result does not agree with two other anisotropies ($I_R$ and $H_C$).

## 4. ARM Experiments and AF Demagnetizations

Figure 6 shows the change of ARM intensities and directions during the acquisition process. The arrow of $H_E$ is the direction of the external direct field. When the sample has no magnetic anisotropy, the ARM is thought to be obtained in the direction of the external field. In TAPE1, the direction of $H_E$ is in the X axis, which coincides with the direction of $K_{max}$ of $H_C$ and $I_R$. The ARM intensity of TAPE1 increased considerably with an alternating field increase and saturated at about 80 mT, and the direction of the ARM turned to that of the external field $H_E$.

In TAPE2, the direction of $H_E$ is the Y axis as shown in Fig. 5. The ARM intensity of TAPE2 decreased at 80 mT of the alternating field, and the direction of the ARM changed to that of $H_E$ from that of the NRM direction at 80 mT. This means that the sample ARMs were parallel to $H_E$. Consequently, the intensity of TAPE2 decreased at 80 mT, due to the acquisition of an ARM which is perpendicular to the original NRM.

In the case of TAPE3, $H_E$ was applied in the direction of the Z axis which coincided with the direction of $K_{min}$ *of* $H_C$ and $I_R$ anisotropy. The ARM intensity and the ARM direction of TAPE3 neither changed nor acquired ARM parallel to the Z axis under the alternating field from 10 mT to 120 mT. Considering the configuration of grains (Fig. 1), this result is natural.

In the case of TAPE4, at 80 mT of the alternating field, the ARM intensity increased to about that of the original NRM, and the direction of the ARM changed to that of $H_E$ (about 30° from the X axis). The increase in the ARM of TAPE4 may be due to the X component of the ARM.

The above-mentioned results can be summarized into two important points. The first point is that the saturation point of an ARM for an audio-tape is an alternating field of 80 mT. The next point is that the X axis of an audio-tape is the easiest direction to obtain an ARM.

After the ARM experiments, stepped AF demagnetizations (5–70 mT, stepwise 5 mT) were carried out. The intensity of ARM of TAPE1, 2 and 4 decreased to 50 mT, and that of TAPE3 decreased to 60 mT, showing that these samples have lost an original ARM at each AF field. After the decay of the ARM, the direction of the remanent magnetization of TAPE1～4 turned toward parallel to the X axis (Fig. 7). As shown in Fig. 1, the X axis is the direction of a $\gamma$-hematite SD alignment, and as shown in Fig. 3, the directions of $H_C$ and $I_R$ are the X axis. These results indicate that the most stable remanent magnetization after high AF demagnetization lies in the direction of the SD alignment which coincides with the $K_{max}$ axis of anisotropy of $H_C$ and $I_R$.

## 5. The Magnetic Anisotropy of the Gneissic Rocks from Skarvsnes

NAKAI *et al.* (1993) reported on the paleomagnetism and the magnetic anisotropy of gneissic rocks from the Skarvsnes area, East Antarctica. Skarvsnes which is situated in the granulite facies area of the Lützow Holm Complex (LHC) is well studied by many authors (HIROI *et al.*, 1987, 1991 ; SHIRAISHI *et al.*, 1987 ; MOTOYOSHI *et al.*, 1989 ; ISHIKAWA *et al.*, 1977), and the age of the regional metamorphism was reported to be about 500 Ma (SHIRAISHI *et al.*, 1992, 1994). Therefore, the author considers that the gneissic rocks from Skarvsnes obtained TRMs about 500 Ma.

NAKAI *et al.* (1993) classified paleomagnetic samples of gneissic rocks from Skarvsnes

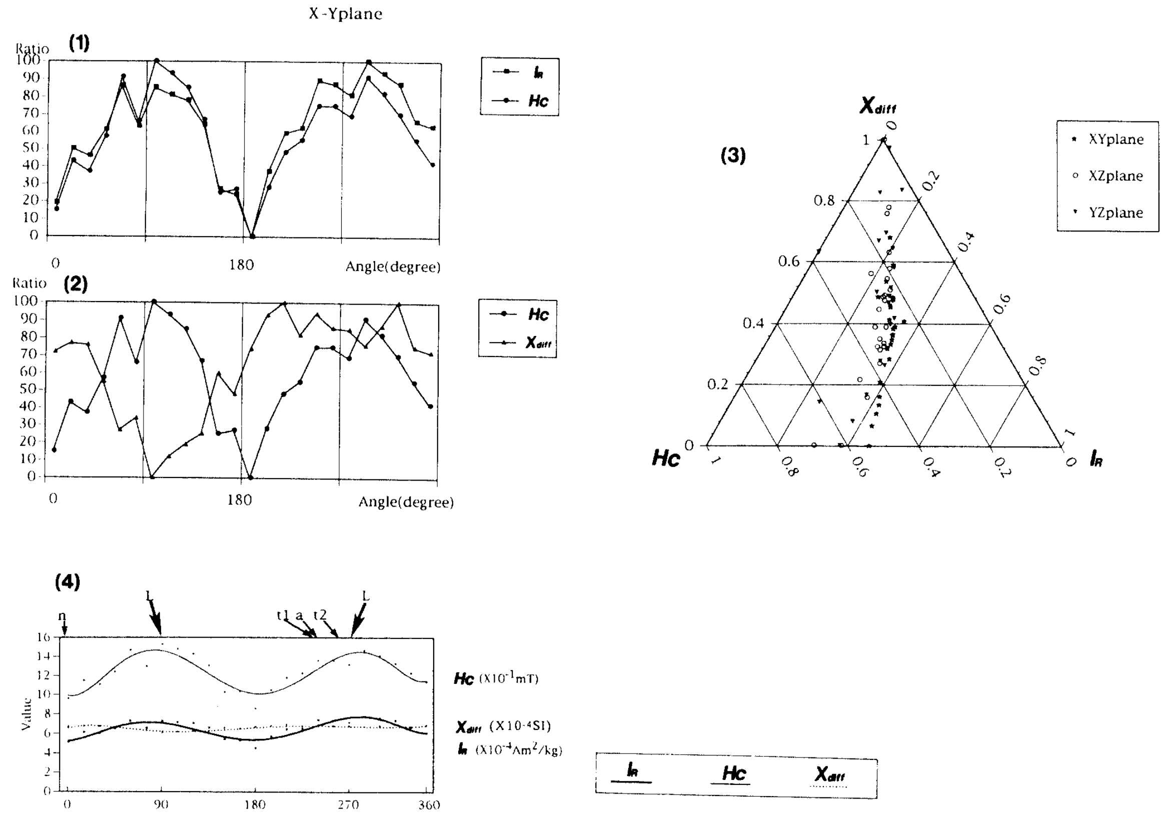


*Fig. 8. The magnetic anisotropy of a c type pilot sample of a gneissic rock from Skarvsnes. $I_R$ : saturation isothermal remanent magnetization, $H_C$ : coercivity, $\chi_{diff}$ : differential susceptibility at low field.*

*(1) Change of the anisotropy ratio with $H_C$ and $I_R$ (X-Y plane).*

*(2) Change of the anisotropy ratio with $H_C$ and $\chi_{diff}$ (X-Y plane).*

*(3) A triangle diagram (a ternary chart) of the anisotropy ratio of $H_C$, $I_R$ and $\chi_{diff}$.*

*(4) Change of anisotropic value with $H_C$, $I_R$ and $\chi_{diff}$.*

*↓ L : direction of lineation in the sample.*

*↓ : direction of NRM (n : original NRM, a : after AF demagnetization at 25 mT, t1, t2 : after thermal demagnetization at 180°C, 280°C).*

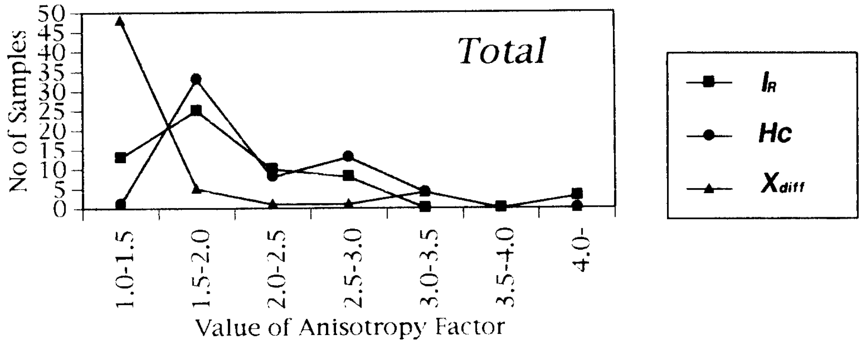


*Fig. 9. Value of anisotropy factor of gneissic rocks from Skarvsnes. $I_R$ : saturation isothermal remanent magnetization, $H_C$ : coercivity, $\chi_{diff}$ : differential susceptibility at low field.*

into three groups (*a, b, c*) on the basis of paleomagnetic and rock magnetic characteristics. The *a* type is less anisotropic and showed reliable paleomagnetic results. The *b* type has measurable magnetic anisotropy and shows the inconsistent pole position both with that of the apparent polar wander path (APWP) by THOMPSON and CLARK (1982) of Gondwana at 500 Ma, and with that of 500 Ma from other areas in East Antarctica (FUNAKI and WASILEWSKI, 1986; FUNAKI and SAITO, 1992). The *c* type has large magnetic anisotropy (Fig. 8-(3)), and NRM directions of *c* type were scattered. Clear gneissosity was observed in *c* type gneissic rocks, and after AF and thermal demagnetizations, the NRM direction of the *c* type pilot sample turned toward the direction of the mineral lineation consistent with that of $K_{max}$ of $H_C$ and $I_R$ (NAKAI *et al*., 1993).

In this paper, the author calculated the anisotropy factors ($P$) of the c type samples as shown in Fig. 9, and checked the characteristics of the anisotropies of the pilot sample of c type (Fig. 8). Consequently, the $K_{max}$ direction of $\chi_{diff}$ is observed to be perpendicular to that of the lineation of rocks (Fig. 8-(4)). These results are very similar to those of the audio-tape experiments in X-Y plane as shown in Fig. 3.

Figure 9 shows the distribution of the $P$ values ($P = K_{max}/K_{min}$) of 59 samples from Skarvsnes. The $P$ values of $H_C$ and $I_R$ are larger than those of $\chi_{diff}$, and the measurements of $H_C$ and $I_R$ are a more effective method of studying magnetic mineral alignment than measurement of $\chi_{diff}$ (Fig. 9). These results are similar to those of the audio-tape experiments (Table 1).

## 6. Discussion

Three anisotropic results of the audio-tape experiments coincide with that of the gneissic rocks from Skarvsnes. The first result is that the $H_C$ and $I_R$ values are more anisotropic than the $\chi_{diff}$ value (Figs. 3, 9 and Table 1). STEPHENSON *et al*. (1986) reported that the anisotropy of an isothermal remanent magnetization (IRM : the same property of $I_R$ in this paper) was larger than that of $\chi_i$ (the same property as $\chi_{diff}$ in this paper). The results of this study agree with STEPHENSON's conclusion.

The second consistency is that the $K_{max}$ direction of $\chi_{diff}$ is clearly perpendicular to that of $I_R$ and $H_C$ (Figs. 3 and 8). POTTER and STEPHENSON (1988, 1990) observed similar phenomena in samples with uniaxial anisotropy. JACKSON (1991) and ROCHETTE *et al.* (1992) indicated that the AMS was perpendicular to the long axis of an ellipsoid grain of SD. Therefore, if the magnetic grains are SD, the $K_{max}$ of AMS may be perpendicular to that of the anisotropy of magnetic remanence (AMR). However, if the magnetic grains are MD, the $K_{max}$ of AMS may be parallel to that of the AMR. In addition, the AMR shows the direction of the long axis of magnetic grains, and the maximum axes of $H_C$ and $I_R$ are thought to coincide with the long axis of grains. Figure 8-(1), (2) shows the variation ratio ($K_{min}/(K_{max}$-$K_{min}) \times 100$) of anisotropy of the hysteresis properties obtained from the pilot sample from Skarvsnes, and Fig. 8-(3) is a triangle diagram of the variation ratio of three hysteresis properties of this pilot sample. This triangle diagram indicates that the variation of $\chi_{diff}$ shows an anti-phase *vs.* $H_C$ and $I_R$. Thus the previous theoretical results are consistent with the experimental results of the audio-tape and Skarvsnes samples.

The third consistency is the relationship between the direction of a remanent magnetization and that of $K_{max}$ of $H_C$ and $I_R$. After AF and thermal demagnetizations, the NRM direction of the *c* type pilot sample from Skarvsnes turned toward mineral lineation which was consistent with the direction of $K_{max}$ of $H_C$ and $I_R$ (Fig. 8-(4)). After the high AF demagnetizations, the audio-tape experiments showed that the most stable remanent magnetization was the magnetic component in the direction of $K_{max}$ of $H_C$ and $I_R$. This effect proves that the $K_{max}$ axes of the anisotropy with $H_C$ and $I_R$ have the most stable NRM, because the $K_{max}$ axes of $H_C$ and $I_R$ agree with the lineation of SD grains. This effect suggests that the most stable NRM component remains in the direction of the $K_{max}$ axis of $H_C$ and $I_R$ rather than that of the ancient geomagnetic field. Therefore it is a very important effect to study NRMs from the old rocks.

The NRMs of some metamorphic rocks have been reported to be under the influence of the magnetic mineral alignment (IRVING and PARK, 1973; KHAN, 1962; FULLER, 1963). Thus, the magnetic anisotropy using a VSM is a very useful method to determine the alignment of SD grains, and to judge if the reliable NRMs were obtained in metamorphic rocks.

## 7. Concluding Remarks

(1) Magnetic anisotropy experiments on audio-tape show similar results to experiments on gneissic rocks from Skarvsnes.

(2) The $H_C$ and $I_R$ values of the hysteresis properties of the audio-tape and of the gneissic rocks from Skarvsnes are more anisotropic than the $\chi_{diff}$ value.

(3) When the magnetic minerals are SD, the anisotropic $K_{max}$ axis of $\chi_{diff}$ is clearly perpendicular to that of $I_R$ and $H_C$. Therefore, the anti-phase of the anisotropy in $\chi_{diff}$ *vs.* $H_C$ *and* $I_R$ may be an important index to determine SD alignment.

(4) The most stable remanent magnetization remains in the direction of $K_{max}$ of $H_C$ or $I_R$. This is a very important effect to study NRMs from old rocks and metamorphic rocks.


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