MAGNETIC ANISOTROPY AND POROSITY OF ANTARCTIC CHONDRITES

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Abstract: Magnetic susceptibility anisotropy and porosity were measured in eleven Antarctic meteorites. These meteorites are ordinary chondrites (H and L type) in various metamorphic stages. Large magnetic anisotropy has been observed in most of the chondrites. The foliation type of the anisotropy, inferred from the shape of the susceptibility ellipsoid indicates that a uniaxial compressional type deformation is responsible for the anisotropy. The degree of the anisotropy and the porosity do not correlate with the petrologic type of the chondrites. Based on the present observation, dynamical compression during the initial accumulation stage of chondritic parent bodies was concluded as a main cause of the anisotropy. Porosity-anisotropy relation in these chondrites suggests that this accumulation stage also determined the observed porosity values.

1. Introduction

Anisotropic properties have been reported in many chondrites. STACEY *et al.* (1961) measured the magnetic anisotropy of eight chondrites by means of a torque meter, and found a good correlation between the magnetic grain elongation estimated from the anisotropy and the degree of compaction reflected in their porosities. WEAVING (1962) observed that the maximum, minimum and intermediate susceptibility directions were constant throughout each meteorite. BRECHER and ARRHENIUS (1974) found a large magnetic anisotropy in carbonaceous chondrites. Besides this magnetic anisotropy, preferred orientation of chondrules has been observed (DODD, 1965; MARTIN *et al.*, 1975; MARTIN and MILLS, 1980). The origin of such anisotropies is still uncertain. STACEY *et al.* (1961) proposed a metamorphic origin of the anisotropy based on their observation. This interpretation assumes that the anisotropy increases with the increase of thermal metamorphism. However, the preferred orientation of chondrules in unequilibrated chondrites (DODD, 1965; MARTIN *et al.*, 1975) and the high magnetic anisotropy in carbonaceous chondrites (BRECHER and ARRHENIUS, 1974) contradict with their interpretation. Magnetic anisotropy in terrestrial rocks has been extensively studied (for a recent review, see HROUDA, 1982). The observations revealed the processes of deposition and compaction in sedimentary rocks and the deformation histories in metamorphic and igneous rocks. Anisotropies shown in these terrestrial rocks are usually less than 10%, that is, $K_{max}/K_{min}<1.1$. On the other hand, chondrites are characterized by larger anisotropies ($K_{max}/K_{min}>1.3$). As noted by WEAVING (1962) and DODD (1965), establishing of the origin of the anisotropy in chondrites must be important for discussing the early evolution of the solar system.

From this point of view, questions to be solved are: (1) How common is magnetic anisotropy and preferred orientation of chondrules in chondrites? (2) Is there any correlation between the anisotropic properties and the chemical or petrologic type of chondrites? (3) What is the mechanism which caused such a large anisotropy? and finally (4) What can be said about the formation process of chondrites from the anisotropy measurements. In the present paper, magnetic susceptibility anisotropy and porosity in ordinary chondrites were measured to answer these questions.

2. Samples and Experiments

For our measurements we used eleven Antarctic meteorites which have been collected and distributed by the National Institute of Polar Research. All the samples are ordinary chondrites in various degree of metamorphism. Each sample was cut into a rectangular shape with a volume of more than 1 cm^3. The large size of the sample reduces the effect of inhomogeneity, and the rectangular shape is convenient for calculating the demagnetizing factors.

A Schonstedt SSM-1A spinner magnetometer was used for the anisotropy measurement. Theory and operation of the anisotropy measurement with a spinner magnetometer has been described by NÖLTIMIER (1971). We employed a 6-spin measurement to minimize the effect of sample inhomogeneity. In an anisotropic material, magnetic susceptibility is expressed by a symmetric tensor with six independent component, K_{11}, K_{22}, K_{33}, K_{12}, K_{23} and K_{31}. Spinner measurement gives six values, $K_{22}-K_{11}$, $K_{33}-K_{22}$, $K_{11}-K_{22}$, $2K_{12}$, $2K_{23}$ and $2K_{31}$. However, since the first three values are not independent of each other, we need to measure an absolute value of one of the three diagonal components to determine the full susceptibility matrix. A Bison susceptibility bridge was used for this purpose. Calibration of the sensitivity of the two instruments was made for combining these two measurements.

Once the six components of the susceptibility are determined, three principal values and their directions can be easily calculated by a standard method. However, one more correction is required to obtain the intrinsic susceptibility. In general, the internal magnetic field of the sample is different from the external field because of the existence of the demagnetizing field inside the sample. If we choose the coordinate system so that the three coordinate axes are parallel to each edge of the sample, the demagnetizing tensor is diagonalized. Therefore, the induced magnetization, $\vec{J}$, can be expressed as

$$\vec{J}=K(\vec{H}_{ext}-N\vec{J}), \tag{1}$$

where K and N are the matrix representation of the susceptibility and the demagnetizing factor, respectively. They are explicitly given by

$$K=\begin{bmatrix} K_{11} & K_{12} & K_{31} \\ K_{12} & K_{22} & K_{23} \\ K_{31} & K_{23} & K_{33} \end{bmatrix}$$

and

$$N=\begin{bmatrix} N_1 & 0 & 0 \\ 0 & N_2 & 0 \\ 0 & 0 & N_3 \end{bmatrix},$$

whereas the observed susceptibility, K^*, is given by

$$\vec{J}=K^*\vec{H}_{ext}. \tag{2}$$

The relation between K and K^* is derived from eqs. (1) and (2) as

$$K(I-NK^*)=K^*, \tag{3}$$

where I is the unit matrix. First order expansion of eq. (3) for each component of the susceptibility matrix is given by

$$\begin{aligned}
K_{11}&=K_{11}^*+N_1(K_{11}^{*2}+K_{12}^{*2}+K_{31}^{*2})\\
K_{22}&=K_{22}^*+N_2(K_{12}^{*2}+K_{22}^{*2}+K_{23}^{*2})\\
K_{33}&=K_{33}^*+N_3(K_{31}^{*2}+K_{23}^{*2}+K_{33}^{*2})\\
K_{12}&=K_{12}^*+\frac{N_1+N_2}{2}(K_{11}^*K_{12}^*+K_{12}^*K_{22}^*+K_{31}^*K_{23}^*)\\
K_{23}^*&=K_{23}^*+\frac{N_2+N_3}{2}(K_{12}^*K_{31}^*+K_{22}^*K_{23}^*+K_{23}^*K_{33}^*)\\
K_{31}^*&=K_{31}^*+\frac{N_1+N_3}{2}(K_{31}^*K_{11}^*+K_{23}^*K_{12}^*+K_{33}^*K_{31}^*).
\end{aligned} \tag{4}$$

In the present experiment, eq. (4) was used to estimate the intrinsic susceptibility from the observed values. Analytical expression of the demagnetizing factor, which is necessary for the above calculation, was given by RHODES and ROWLANDS (1954).

In Table 1, the obtained three principal values of the susceptibility and their mean values are listed, where K_{max}, K_{int} and K_{min} are the maximum, intermediate, and minimum susceptibilities, respectively. And the mean suceptibility, $\bar{K}$, is defined by

$$\bar{K}^{-1}=\frac{1}{3}(K_{max}^{-1}+K_{int}^{-1}+K_{min}^{-1}). \tag{5}$$

Table 1. Maximum, intermediate and minimum principal susceptibilities and their mean values.

Sample	Type	$\bar{K}$	K_{max}	K_{int} (10^{-3} G/Oe)	K_{min}
Y-74156	H4	46.09	55.44	53.72	35 17
Y-74647	H4–5	69.23	81.04	76.39	55 86
ALH-77294	H5	44.18	53.22	50.72	34.02
ALH-77288	H6	46.02	46.71	46.19	45.19
Y-74191	L3	14.12	16.56	15.95	11.19
Y-75097	L4	19.22	21.96	21.22	15.77
MET-78003	L6	18.95	22.41	21.49	14.89
ALH-78251	L6	14.12	15.64	15.35	11 99
ALH-78103	L6	14.30	16.15	15.43	12.03
ALH-769	L6	12.78	14.20	14.04	10.75
ALH-77231	L6	17.34	19.62	18.53	14.70

Table 2. Summary of physical properties of Antarctic ordinary chondrites.

Sample	Type	Intrinsic density (g/cc)	Bulk density (g/cc)	Porosity (%)
Y-74156	H4	3.80	3.45	9.2
Y-74647	H4–5	3.83	3.48	9.1
ALH-77294	H5	3.84	3.34	12.9
ALH-77288	H6	3.77	3.69	2.0
Y-74191	L3	3.60	3.23	10.3
Y-75097	L4	3.65	3.27	10.3
MET-78003	L6	3.59	2.89	19.4
ALH-78251	L6	3.73	3.23	13.4
ALH-78103	L6	3.70	3.21	13.2
ALH-769	L6	3.61	3.33	7.8
ALH-77231	L6	3.58	3.07	14.3

Besides the magnetic susceptibility, physical properties of the same samples were measured. The measured properties are bulk density, intrinsic density and porosity. The intrinsic density was measured by a helium pycrometer, and the bulk volume of each sample was determined with a standard immersion technique. The bulk density and the porosity were calculated from the above values. Table 2 summarizes the observed physical properties for the present samples. Detailed description of the measurements is given by YOMOGIDA (1982).

3. Magnetic Susceptibility Anisotropy

In order to characterize the anisotropic properties, various parameters have been used. These properties are obtained by combining three principal susceptibilities listed in Table 1. As a measure of the degree of the anisotropy, K_{max}/K_{min} has been commonly used. In describing the anisotropy type, GRAHAM (1967) introduced the parameter, V, which is defined by

$$\tan^2 V=(K_{int}-K_{min})/(K_{max}-K_{int}). \tag{6}$$

Since V varies from 0° to 45° for prolate ellipsoids and from 45° to 90° for oblate ellipsoids, it is a quantitative parameter for describing the relative shape of the susceptibility ellipsoid.

The two parameters, K_{max}/K_{min} and V, are shown in Fig. 1 for the present samples. The magnetic susceptibility data are summarized as follows:

(1) As shown in Table 1, the mean susceptibility in H chondrites is larger than that in L chondrites by about a factor of three. This is consistent with the fact that the metal content in H chondrites is higher than that in L chondrites.

(2) No systematic vatiation of the mean susceptibility with the petrologic type is observed within each chemical group of chondrites. This suggests that the amount of metal does not change systematically during the metamorphism.

(3) The variation of the susceptibility ratio (K_{max}/K_{min}) has no correlation either with the chemical group (H and L) or with the petrologic type. Note that the unequilibrated chondrites (L3, H4) have large anisotropies.

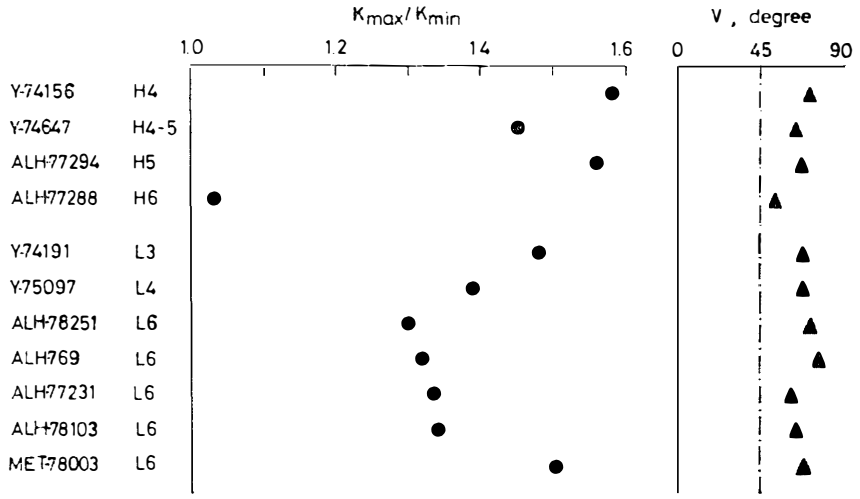

Fig. 1. Magnetic susceptibility ratio, K_{max}/K_{min}, and anisotropy parameter, V. Definition of V is given in text.

(4) The index V for all the chondrites has values greater than 45°, which suggests that the corresponding susceptibility ellipsoids are oblate types.

4. Porosity and Other Physical Properties

Results of the physical property measurements on Antarctic meteorites have been reported (MATSUI *et al.*, 1980; YOMOGIDA and MATSUI, 1981), and the results of the intrinsic and bulk density, and the porosity are listed in Table 2. Narrow range of the intrinsic density in each group of the chondrites guarantees the accuracy of the porosity measurement. High intrinsic density in H chondrites is consistent with the high iron-nickel metal content of H chondrites. The results of the porosity measurement are summarized as follows:

(1) The range of the variation of the porosity is very large (2% to 20%).

(2) No systematic difference in porosities between H and L chondrite is observed.

(3) The variation of the porosity is apparently independent of the petrologic type.

(4) Correlations of the porosity with the ultrasonic-wave velocities and the thermal conductivity (YOMOGIDA, 1982) indicate that thin cracks exist within the chondrites.

5. Origin of the Magnetic Anisotropy in Chondrites

Various causes of the magnetic anisotropy in terrestrial rocks have been suggested. Grain or crystalline alignment of ferromagnetic minerals is considered to be the most important factor controlling the magnetic anisotropy. The ferromagnetic minerals in terrestrial rocks are mainly magnetite, hematite and pyrrhotite. On the other hand, Fe-Ni metals are the most dominant ferromagnetic minerals in ordinary chondrites. In Fe-Ni metal grains, the grain shape effect dominates the magneto-crystalline effect. Therefore, the observed magnetic anisotropy in the chondrites can be attributed to the directional distribution of the non-spherical metal grains.

The alignment of the metal grains reflects force systems exerted on the chondrites during their evolutional histories. We divide the evolution of ordinary chondrites into three stages, *i.e.*, accumulation, metamorphism and destruction stages. In the first stage, chondrite parent bodies grow by the capture of colliding planetesimals. Temperature within the parent bodies was estimated not to increase efficiently for any reasonable models of accretion if the size of the parent bodies is less than 100 km. Hence, at this stage, mechanical forces dominate the deformation. On the other hand the temperature effect is dominant in the second metamorphic stage, where the deformation is mainly controlled by diffusion process. The last stage involves the destruction of the parent bodies and the fall of the fragments on the earth. At this stage, collisional shock is the main cause of the deformation.

The main question is which evolutional stage is responsible for the observed magnetic anisotropy. The last stage can be examined based on the rock fracture experiments of terrestrial rocks which have been extensively made in rock mechanics. The following two results are important for the present argument. (1) Under a low confining pressure and a low temperature, deformation before fracture is very small (less than 1% in strain) in most of the rocks (HANDIN, 1966), and only a part of this strain remains as a permanent strain after the release of the stress. (2) Deformation before fracture decreases as the strain rate increases. Collisional shocks at the last stage are characterized by high strain rate. Based on the above results, this process may cause destruction of the colliding bodies but the deformation of each fragment must be small. On the other hand, large deformation is required to explain the observed anisotropy. Therefore, the presently available data indicate that the collisional shock in the last stage cannot be a main cause of the anisotropy. The second metamorphic stage is also improbable as the cause of the anisotropy, because the low-metamorphosed chondrites have large anisotropy.

The above arguments have excluded the last two stages. Now we will discuss the possibility of the first stage. At this stage meteorite parent bodies are regarded as loose aggregates of dust grains. This material can be deformed easily by a small force where the deformation is controlled by rearrangement, plastic deformation, and fracture of particles. Large deformation inferred from the anisotropy data is possible at this stage. No correlation of the degree of the anisotropy with the petrologic type is also explained since the deformation had occurred before metamorphism. Forces required for the deformation can be supplied either by collisional shocks of the accumulating small bodies or by a static pressure due to overlying material. The shape of the susceptibility ellipsoids in the present chondrites indicates that the deformation was due to a uniaxial compression. This type of the stress system is realized by the dynamical compression, but not by the static compression within a self-gravitating spherical body. Hence, the collisional shock during the accumulation stage of the parent bodies is the most probable cause of the anisotropy.

The magnetic anisotropy reflects a non-volumetric part of the deformation. On the other hand, volumetric deformation accompanies the change of the porosity. Therefore, the porosity is a clue to the past volume change of the chondrites. Using the same argument as the magnetic anisotropy, we can conclude that the observed porosity was mainly determined at the initial accumulating stage. Large porosity variation can

not be attributed to the collisional shock at the destruction stage, because volume change (dilatancy) before fracture is generally much smaller than the observed porosities of up to 20%. Also, highly variable porosities in five L6 chondrites indicate that reduction of porosity during the metamorphic stage was inefficient.

6. Porosity *vs.* Anisotropy Relation

If we assume that the magnetic anisotropy and the porosity were determined at the same stage of the evolution of the chondrites, correlation between the two properties is expected. We examine the relation based on a simple compaction model. Figure 2 schematically shows the present model. During the compactive deformation, the distance along the vertical direction (z-axis) decreases by a factor of f, and the horizontal scale remains constant. This type of deformation (compaction) can be caused by a vertical compression on a porous substance. After the deformation, the initial volume, V_0, and the initial porosity, ϕ_0, change to

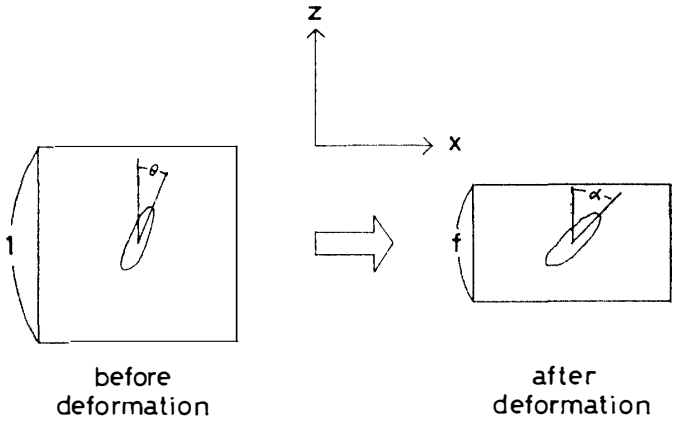

Fig. 2. Schematic diagram of the deformation model.

$$V = fV_0, \tag{7}$$

$$\phi = \phi_0 - (1-f). \tag{8}$$

We assume that magnetic grains in the substance were isotropically distributed at the initial state. Then, this substance is magnetically isotropic. The isotropic distribution of the magnetic grains can be expressed by a directional distribution function, $F(\theta)$, defined by

$$F(\theta)\mathrm{d}\theta = \frac{1}{2}\cos\theta\,\mathrm{d}\theta, \tag{9}$$

where θ is the angle between the elongated axis of each grain and z-axis, and varies from 0 to $\pi/2$. After the deformation, the angle changes to α, where α relates to θ by

$$\tan\theta = f\tan\alpha. \tag{10}$$

Combining eqs. (9) and (10), the distribution function $G(\alpha)$ at the deformed state can be expressed as

$$G(\alpha)\mathrm{d}\alpha = \frac{f^2 \cos\alpha \, \mathrm{d}\alpha}{\{1-(1-f^2)\cos^2\alpha\}^{3/2}} \,. \tag{11}$$

Next we assume that each magnetic grain has an elongated shape and has an uniaxial magnetic anisotropy. Then the susceptibility of each grain is expressed as

$$K(\gamma) = K_0 \cos^2\gamma, \tag{12}$$

where γ is the angle between the elongated axis of the grain and the external magnetic field. Susceptibilities of the deformed state in the vertical (z) and horizontal (x) directions can be calculated from eqs. (11) and (12) as

$$K_x = \frac{NK_0 f^2}{2} \int_0^{\pi/2} \frac{\cos^3\alpha \mathrm{d}\alpha}{\{1-(1-f^2)\cos^2\alpha\}^{3/2}} \,, \tag{13}$$

$$K_z = NK_0 f^2 \int_0^{\pi/2} \frac{\sin^2\alpha \cos\alpha \, \mathrm{d}\alpha}{\{1-(1-f^2)\cos^2\alpha\}^{3/2}} \,, \tag{14}$$

where N is the number density of the magnetic grains. These equations can be easily integrated and the susceptibility ratio, K_x/K_z, are expressed with elementary functions as

$$\frac{K_x}{K_z} = \frac{1}{2}\left(\frac{\sqrt{1-f^2}}{f} - \log\left|\frac{1+\sqrt{1-f^2}}{f}\right| \Big/ -\sqrt{1-f^2} + \log\left|\frac{1+\sqrt{1-f^2}}{f}\right|\right). \tag{15}$$

Equations (8) and (15) give the relation between the porosity and the susceptibility ratio when the compactive deformation controlled both properties.

In order to check the validity of the present model, we compare the model calculation with the observed data. The susceptibility ratio, K_{max}/K_{min}, and the porosity in the present eleven chondrites are plotted in Fig. 3. The two dashed curves in the figure

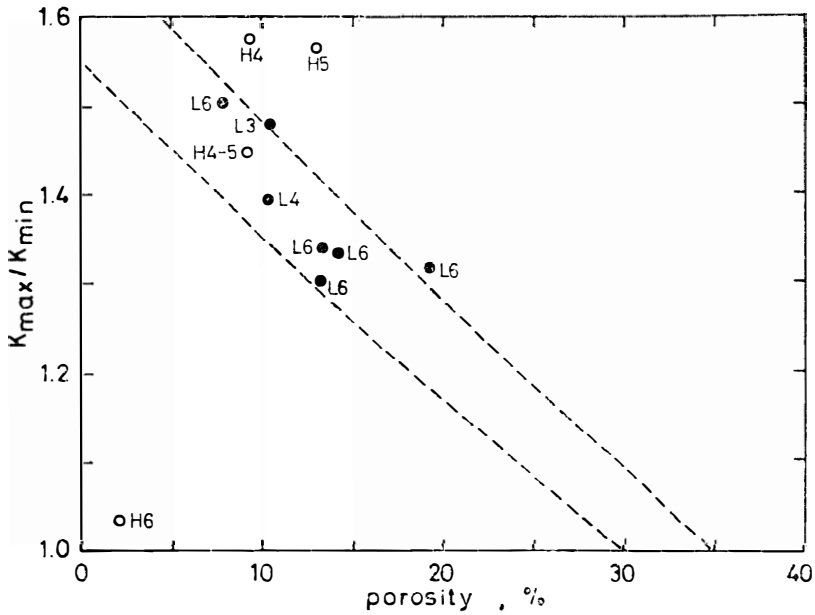

Fig. 3. Relation between the susceptibility ratio, K_{max}/K_{min} and the porosity of Antarctic chondrites. Two dashed curves are results of the model calculations, where initial porosities of 30% and 35% were assumed.

were calculated from eqs. (8) and (15) for the initial porosities of 30% and 35% respectively. Although the number of samples is too small to derive a definite conclusion, the comparison indicates that most of the samples can be explained by the compaction model with the initial porosity of around 30%. In more detail, seven L chondrites are compatible with this model, but H chondrites may indicate a different trend.

7. Conclusions

We have examined the magnetic anisotropy and the porosity in eleven Antarctic chondrites. We conclude that these properties reflect conditions during the accumulation stage of their parent bodies. Thus, these properties can be used to infer the accumulating process of the chondrite parent bodies. Pressure exerted by collisions and its duration time are main parameters to be determined. Aside from this application, the magnetic anisotropy can be used to reconstruct the paleo-orientation of the chondrites within their parent bodies. Since the compression axis is in a radial direction, and the minimum susceptibility direction corresponds to the compression axis, the high susceptibility plane ($K_{max}-K_{int}$ plane) can be considered to be parallel to the surface of the parent body. This interpretation enable us to handle the directional data of chondritic samples in their parent bodies. For example, structure of the magnetic field in the early solar system may be discussed from the study of the remanent magnetization of chondrites.

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