PREFERRED ORIENTATION OF PHYLLOSILICATES IN YAMATO-74642 AND -74662, IN RELATION TO DEFORMATION OF C2 CHONDRITES

Akio FUJIMURA, Manabu KATO and Mineo KUMAZAWA

Department of Earth Sciences, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464

Abstract: The preferred orientation of phyllosilicates in two Yamato chondrites (C2) has been examined by means of X-ray pole figure goniometry. Both C2 chondrites show almost the same textural features under the optical microscope as those of Murchison (C2) studied previously. In Yamato-74642, however, X-ray diffraction intensity of phyllosilicates is extremely weak and no information on the oriented texture could be obtained. Hydrous minerals in Yamato-74642 have probably been altered by some thermal event. Yamato-74662 possesses a weak but clear preferred orientation of phyllosilicates, indicating evidence of anisotropic deformation. The magnitude of plastic deformation is estimated to be in the order of 10%.

1. Introduction

The study of anisotropic textures of meteoritic material is expected to provide some information on the mechanical environment which these supposedly primitive materials have experienced at the early stage of planetary evolution. The ordinary chondrites usually show a considerable degree of foliation as revealed by the preferential orientation of aspherical constituents such as oblate chondrules, lithic fragments and mineral grains (*e.g.*, DODD, 1965). In the case of more primitive materials such as carbonaceous chondrites, however, very careful examination is necessary to clarify the anisotropic structure, because the fabric elements to be examined usually are nearly equant and few in number within a limited volume of the sample (KING *et al.*, 1978; MARTIN *et al.*, 1975). We draw attention to the fact that the major constituent of carbonaceous chondrites (C1 and C2) is very fine-grained and dust-like material. Therefore, the study of the texture produced by the alignment of such small grains enables us to provide sufficient statistical information on the anisotropic texture in carbonaceous chondrites. The dominant constituent mineral in the type 2 carbonaceous chondrite is phyllosilicate which possesses a very anisotropic character in its internal structure and external habit. The phyllosilicate behaves sensitively to the anisotropic physical conditions, and easily develops a preferential distribution of orientation. Basically, phyllosilicate [001] or c^*-axis (reciprocal axis), which corresponds to the plane normal, is preferentially oriented parallel to the axis of maximum shortening or maximum compressive stress. Further, the degree of preferred orientation is directly related to the degree of deformation. Therefore the preferred orientation of phyllosilicate [001] would reflect efficiently the degree and type of mechanical deformations during the accretion process and/or the later evolution of the carbonaceous chondrites.

In the previous textural study of the Murchison (C2) chondrite (FUJIMURA *et al.*, 1982), orientation density distribution of phyllosilicate [001] (possibly serpentine) in the matrix, was determined by X-ray pole figure goniometry. The result indicated a weak but clear preferred orientation of an axial concentration type. The present work is an extension of the previous work on Murchison to Yamato-74642 and -74662 (both C2), in order to see whether or not such preferred orientation of phyllosilicate in type and in degree is a common characteristics of carbonaceous chondrites.

2. Samples and Their Textural Observation

The chondrite samples provided by the National Institute of Polar Research are a small chip of 123 mg for Yamato-74642 and 89 mg for Yamato-74662. They were found on the surface of bare ice near Yamato Mountains in Antarctica in 1974, and are supposed to have been buried and carried there in flowing glacier ice (YANAI, 1978). Both meteorites are classified as carbonaceous chondrite of type 2 on the basis of their appearance and bulk chemical composition (YANAI, 1979; YANAI and HARAMURA, 1978).

A careful and extensive observation of the chondritic chips was made under binocular microscope. However, none of the anisotropic textures were recognized. Further search for the anisotropic textures was made in vain on the petrographic thin sections.

In both Yamato chondrites, the texture as a whole is quite similar to that of Murchison in that inclusions with various features are distributed heterogeneously in a fine-grained matrix. However, the size of inclusions is significantly smaller than in Murchison, maximum diameter being 250 μm for Yamato-74642 and 200 μm for Yamato-74662. The matrix consists of two different parts; "light" and "dark", which are clearly distinguished under non-polarized light, but not at all under polarized light. The light part, brownish yellow in color, usually occurs around the inclusions as if they are mantled. The dark part contains very small opaque grains and irregular aggregates of opaque materials. The opaque aggregates sometimes include a few opaque spherules (<50 μm), which appears metallic under a reflection microscope.

The relative quantity of matrix material to inclusions was determined by a point-counting method. The matrix content is 69% for Yamato-74642 and 80% for Yamato-74662. These values compare well with that of Murchison (79% by FUCHS *et al.*, 1973 and 64% by MCSWEEN, 1979). More than 50% of the matrix is non-opaque and is presumed to be hydrous minerals or phyllosilicates, the preferred orientation of which being the subject of this study. A small amount of yellowish phase resembling spinach phase (FUCHS *et al.*, 1973), is also present between the high-temperature minerals in inclusions. This yellowish material in inclusions is supposed to be also phyllosilicates.

The microscopic observations indicate that there is no significant difference in texture between these two Yamato chondrites and Murchison.

3. Identification of Phyllosilicate by X-ray Diffraction

3.1. Yamato-74662

An X-ray diffraction pattern of the powdered bulk sample shows only one diffraction peak at 7.3 Å in the range of d-spacing larger than 4.4 Å, where an unidentified broad peak occurs. The diffraction peak at 7.3 Å in Murchison is identified with (001) of serpentine-group minerals (NORO *et al.*, 1980). AKAI (1981) reported that the most abundant phyllosilicate in the matrix of Yamato-74662 is the same in structure and habit to that observed in Murchison matrix (MACKINNON and BUSECK, 1979; AKAI, 1980; BARBER, 1981) on the basis of HRTEM (high resolution transmission electron microscope) images. He also noted a presence of roll-shaped phyllosilicate, though in small quantity. Thus the platy serpentine is a dominant phyllosilicate in the matrix as in the case of Murchison.

3.2. Yamato-74642

An ordinary 2θ scanning of X-ray diffraction does not show any peak corresponding to the known phyllosilicates, both for the powdered bulk sample and sliced piece of Yamato-74642. This feature is a significant contrast to those for Yamato-74662 and Murchison, for which a clear and dominant diffraction peak appears at $d \simeq 7.3$ Å. Numbers of trials have been made to increase the diffraction intensity and the signal to noise ratio (step scanning of fixed time mode, angular oscillation, raise of X-ray power, choice of slit conditions and of wave length of X-ray, etc.). By adopting a very appropriate measuring condition, the presence of a very small diffraction peak at $d \simeq$ 7.3 Å was recognized, which may be identified with (001) of serpentine group minerals as in the case of Murchison. The very weak X-ray diffraction at $d \simeq 7.3$ Å on Yamato-74642 is possibly due to some alteration. The original meteorite weighed 10.6 g, and was described as "abraded individual without fusion crust, black interior" (YANAI, 1979). We suppose that the sample chip examined in this work might have experienced some heating, or been located close to fusion crust.

4. Pole Figure Goniometry by X-ray Diffraction

A thin section of *ca.* 100 μm in uniform thickness was set on a sample holder (designed specially for the present small samples) of an automated pole figure goniometer (Rigaku-denki) and the preferred orientation of phyllosilicate [001] ($d \simeq 7.3$ Å) was determined by the angular variation of its diffraction intensity. The methods of sample preparation, data acquisition, background reduction, and absorption correction are essentially the same to those employed in the previous work on Murchison (FUJIMURA *et al.*, 1982).

The areas subjected to actual measurement are 3.5 and 2.7 mm in diameter for Yamato-74642 and -74662, respectively. This means that the sample volume of matrix for the measurement is 0.8 to 0.5 mm^3. Such a small sample volume usually lowers the reliability of the resulting preferred orientation as a representative and average property of the heterogeneous chondrites. We cannot avoid this because of limited sample availability. However, the sample size is sufficiently large when compared with the spatial scale of chondritic inclusions and of the related textures. The small sample volume usually introduces a counting statistical error originating from the insufficient number of phyllosilicate grains. However, the phyllosilicates are very small in grain size and more than 10^{12} grains are supposed to be included in the measured volume. In order to reduce the statistical counting errors of diffracted X-ray photons, we have employed angular oscillation ($\pm 2.5°$) and step scanning (5° interval) of fixed time mode (100 to 400 s) together. Despite the careful measurement, the quality of the results is not high for Yamato-74642. An additional problem arising from the small sample size is the limited coverage in the range of solid angle for the measurement. Reflection method cannot be used in the present small sample because of low diffraction angle (large d-spacing of phyllosilicate), and the data obtained are limited to the angular range covered by transmission method alone, as shown in Figs. 1 and 2a.

5. Results and Discussion

5.1. Yamato-74642

As pointed out in the previous section, the diffraction intensity of X-ray from phyllosilicates is very weak in Yamato-74642. Both the background intensity and the observed diffraction intensity at 7.3 Å are ~60000 counts/200 s, and the effective diffraction intensity, which is the observed intensity less background intensity, ranges from

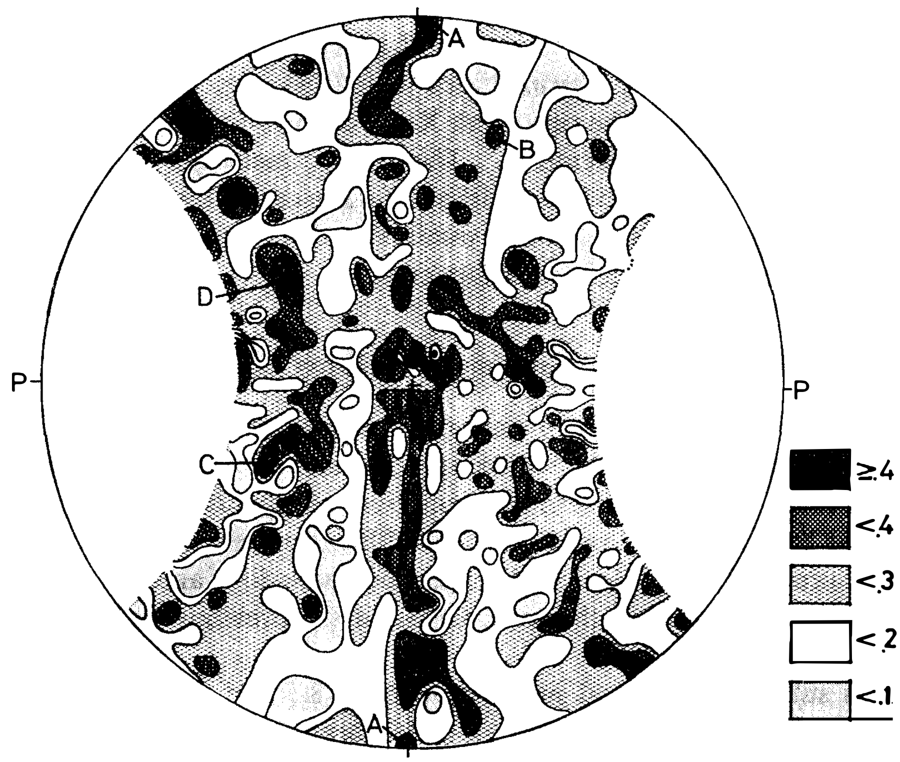

Fig. 1. The orientation distribution of the c-axis of phyllosilicate in Yamato-74642 (equal angle projection). The values of X-ray diffraction intensity are normalized by 5000 counts/200 s. Positions A, B, C and D show the four strongest maxima (A corresponds to the normalized value of about 10, B and C to 2, and D to 1). P shows the plane normal of the thin section sample. The left and right domains are the unmeasured areas.*

a negative value to a maximum of 50000 counts/200 s, with a mode of 1000 counts/200 s. Therefore the statistical error of the effective diffraction intensity is ± 500 counts/200 s ($=2\sqrt{60000}$). The orientation density of the 7.3 Å plane normal is then represented in Fig. 1 by the effective diffraction intensity by a multiple of 5000 counts/200 s. The values of the density level in Fig. 1 have a statistical error ± 0.1 and the level of mode is 0.2. Further they have an additional error originating from uncertain absorption, ranging from 0 to ± 0.1 toward the margin of the measured domain by the transmission method. Despite many trials in improving the S/N in Yamato-74642, the reliability of the final result in Fig. 1 is regarded as extremely low. At one glance at Fig. 1, we recognize the absence of any particular symmetry. Further, the greatest fraction of variation in orientation density appears to be the statistical fluctuation, though a trace of multiple concentration of phyllosilicate orientation may not be denied.

The most important question in Yamato-74642 is why the diffraction peaks of phyllosilicates are too weak to read out the textural data. The present result shows that the information on the oriented texture has been largely lost, rather than that the texture is concluded to be isotropic from the data. The microscopic observation of texture of Yamato-74642 does not show any significant difference from that of Murchison and Yamato-74662. Thus the crystal structure of phyllosilicates should have been disordered or changed apparently by some mechanisms. The X-ray powder diffraction of Murchison matrix separated from the part close to a fusion crust did not show any significant peak at low angles ($d \gtrsim 4.3$ Å). From this analogy we suppose that the present piece of Yamato-74642 had suffered some heating probably at the time of fall onto the earth, and that the greatest fraction of hydrous minerals of our concern has been thermally changed.

5.2. *Yamato-74662*

The observed orientation distribution of phyllosilicate c^*-axis normalized by the maximum value is shown in Fig. 2. The statistical error of contour level is ± 0.1 and there is an additional uncertainty up to ± 0.1 at the very margin of the measured domain. The reliability of the present pole figure is far better than that of Yamato-74642, due to higher S/N and even background. Figure 2a apparently shows a pattern indicative of oriented texture. However, the problem in the present pole figure is a presence of uncovered range of measurement (left and right sides of Fig. 2a) because of the geometric limitation of X-ray optics. There are several interpretations of orientation distribution in the blank region of Fig. 2a and we consider two extreme cases; (A) the blank region has the same level of orientation distribution (0.5–0.6) as in the most measured region, and (B) there is an area of very high orientation density around X in the blank region and the observed area of high orientation density is its tail. Then the two different interpretations above are explained below in detail.

5.2.1. Interpolation A (Orientation density is intuitively assumed to be low in the blank region)

The preferred orientation shows a smooth, partial girdle with a pole at b in Fig. 2a. The pattern has orthorhombic symmetry with axes at a, b and c, when the minor deviation is ignored. Such a type of pole figure for a plate normal is never produced by sedimentation and is well related to the anisotropic deformation of a triaxial type, the

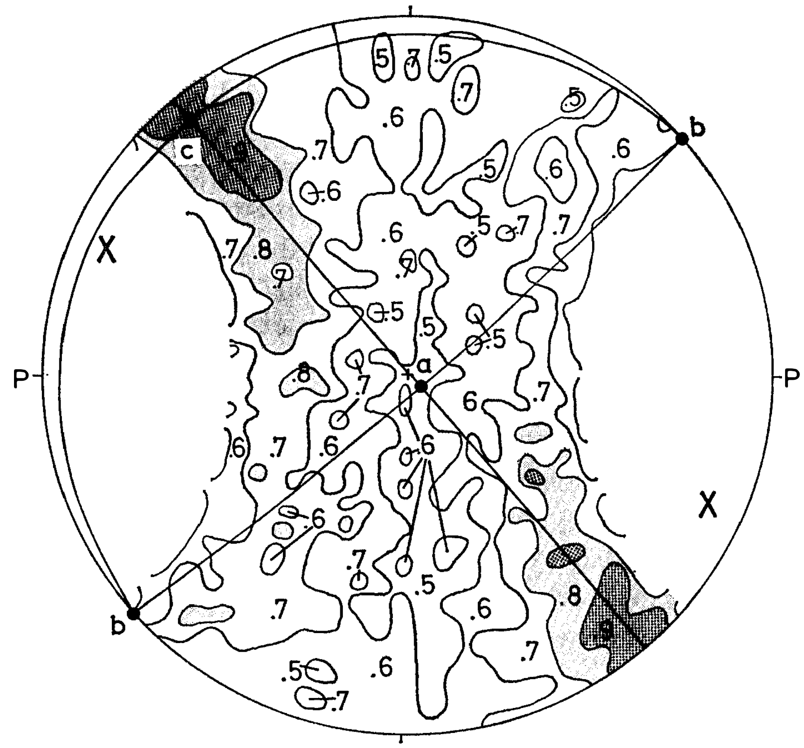

Fig. 2a. Preferred orientation of the c-axis of phyllosilicate in Yamato-74662 (equal angle projection). The values of effective diffraction intensity of X-ray are normalized by the maximum one (9380 counts/100 s). The plane normal of the thin section sample is shown by P. When the orientation density in the blank region without data is assumed to be 0.5, c and b axes of an orthogonal coordinate are set referring to the maximum and minimum concentration, respectively. Then the orientation distribution of phyllosilicate c*-axis shows a partial girdle type or lineation dominant texture.*

maximum elongation being along b and the maximum compression along c. Apparently, the axial tension along b is a dominant component, as suggested from the girdle pattern. The tensional strain along b is estimated to be $\sim 7\%$ by the simple analysis of strain (MARCH, 1932). The type of texture generated by a uniaxial extension is usually referred to L (lineation) type in contrast to F (foliation) type generated by a uniaxial compression. Thus Yamato-74662 is interpreted to possess an L-dominant textural type in this case.

5.2.2. Interpolation B (The maximum orientation density lies around X in the blank region)

The X-ray diffraction intensity data were expanded into spherical surface harmonics up to the 2nd order, and an interpolated smooth pole figure is synthesized. This procedure is adequate to obtain the orientation distribution with an orthorhombic symmetry, as shown in Fig. 2b. The value of contour level are given by multiples of an average density. The type of preferred orientation is regarded as the most simple and idealized F type, which is the same as that of Murchison. The F type texture may be generated either by sedimentation or by uniaxial compression. The sedimentation would not be sufficient to produce the preferred orientation of very small phyllosilicate grains (FUJIMURA *et al.*, 1982), and deformation is the most likely process to produce

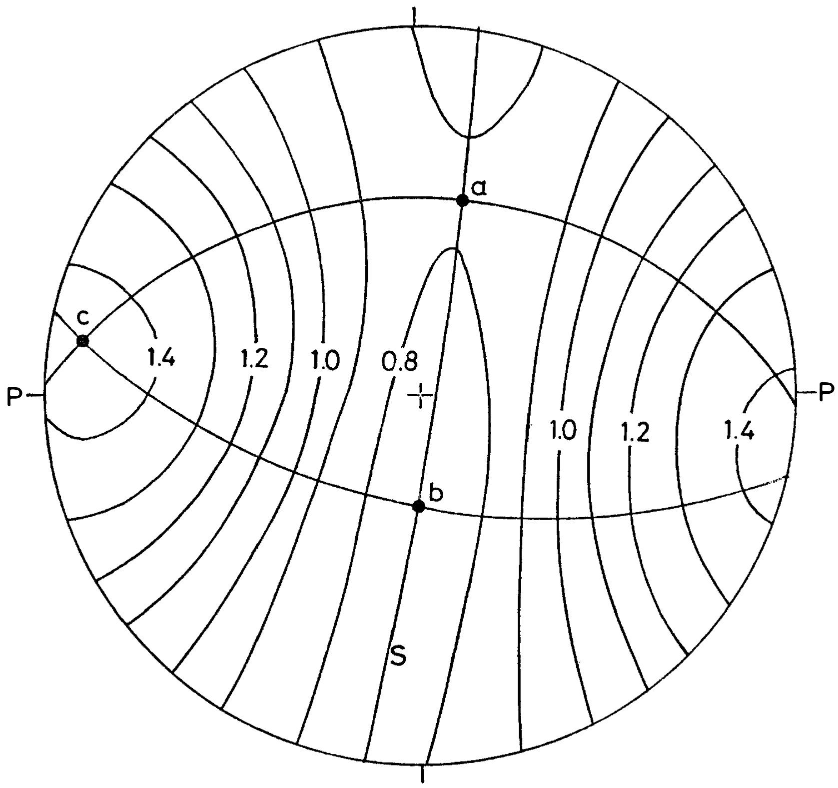

Fig. 2b. The orientation density distribution of the c-axis of phyllosilicate in Yamato-74662. The measured data were expanded by the spherical surface harmonics up to the 2nd order, and the pole figure was synthesized by the harmonics. Contours are given in multiples of an average level, which corresponds to 7255 counts/100 s. This pole figure shows a point maximum at c as symmetry axis, and is a foliation type.*

this texture. The estimated deformation is uniaxial compression of 12% strain along an axis c. The orientation of relative extension lies along a great circle S in Fig. 2b.

The two contradictory interpretations based on two different interpolations in the blank region hold as well, and they result in opposite textural types; L and F, which cannot be distinguished at present without further measurement on the larger specimen by reflection technique or on the other piece of specimen with different orientation. However, common to the two contradictory discussions is that there is a positive indication of anisotropic strain amounting to the order of 10%.

6. Summary and Conclusion

By examining two Yamato C2 chondrites by means of X-ray pole figure goniometry, positive evidence suggesting deformation of $\sim$10% is detected in Yamato-74662, while no useful information is extracted out of Yamato-74642, which might have suffered from some alteration. Unfortunately, however, the type of deformation in Yamato-74662 could not be determined without ambiguity, because of the limited sample size provided by the National Institute of Polar Research. The interpolation technique by spherical harmonic expansion of the pole figure of Yamato-74662 predicts the type of texture as a foliation type, which is the same as that of Murchison. The unambiguous determination of the textural type should be made by further study of this chondrite.

Among most chondrites studied (six C3 chondrites (KING *et al.,* 1978) and nineteen ordinary chondrites (DODD, 1965)) structural-petrologically, show the preferred orientation of non-equant constituent grains, indicating the possibility of deformation. Both of the two fresh C2 chondrites (Yamato-74662 and Murchison) studied, possess an anisotropic fabric, indicating a deformation under stress. This suggests that the history of deformation may be a common characteristic of carbonaceous chondrites of type 2, as in the case of C3 and ordinary chondrites.

The lack of success in the determination of the textural type of Yamato-74662, even with an extensive measurement of orientation density in more than 70% of whole solid angles, raises a problem in textural study with a limited size and limited orientation of sample. In studies on the texture of chondrites, DODD (1965) employed one, two or three petrographic thin sections for most of his chondritic samples, and MARTIN and MILLS (1980) employed as many as six thin sections with unspecified orientation in the case of Parnallee (LL3). However, the unambiguous determination of textural type has been difficult in many cases. Studies of most meteoritic samples are still at the exploratory stage, and the full description of texture, is to be made by employing more than two sections with well specified orientations. With a pole figure goniometry, however, only one thin section of $0.1 \times 10 \times 10$ mm^3 enables us to determine quantitatively the lattice orientation of phyllosilicate in whole solid angles by using both reflection and transmission techniques, as in the case of previous study on Murchison (FUJIMURA *et al.*, 1982).

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