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The relationship between the magnetic anisotropy and the *c*-axis fabric in a massive hematite ore

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Abstract. Preferred orientation of hematite ore from Minas Gerais, Brazil, was investigated by reflected-light microscopy, X-ray structural goniometry and magnetic anisotropy. A close relationship was found between *c*-axis fabrics determined by magnetic and non-magnetic methods; experiments confirmed the results of the theoretical treatment. For routine work it is advantageous to use both types of methods, profiting from rapidity of measurement of magnetic anisotropy and from detailed *c*-axis pole figures of pilot specimens provided by X-ray goniometry.

Key words: Hematite ore – *c*-axis fabric – Magnetic anisotropy

Introduction

The lattice-preferred orientation of crystals in a hematite ore is usually investigated by special reflected-light microscopy (e.g. Cameron and Green, 1950; Hennig-Michaeli, 1976) and X-ray pole figure goniometry (e.g. Siemes, 1977). In addition, it can also be studied by magnetic anisotropy (Hargraves, 1959; Uyeda et al., 1963; Porath and Chamalaun, 1966; Porath, 1968). As each of these methods has specific merits (cheap instrument for reflected-light microscopy, detailed lattice orientation pattern provided by X-ray goniometry, rapidity of measurement by magnetic anisotropy),it is advantageous to combine them. For this purpose it is desirable to know the interrelationship among the *c*-axis fabric determinations by these methods. To study this relationship we investigated hematite ore from Minas Gerais, Brazil, using all three methods.

Material used

The itabiritic hematite ore studied is a hand specimen from an unknown locality in Minas Gerais, Brazil (coming from the collection of the Department of Mineralogy and Economic Geology, RWTH Aachen). Macroscopically, a rather inhomogeneous distribution of hematite is indicated by high concentrations in massive ore layers and places of slightly lower content of hematite due to sheet silicate inclusions. Cross-sections of the specimen exhibit tight angular folds in a massive ore layer and elongated aggregations of sheet silicates as well as open elongated pores in the less rich ore (Fig. 1 a).

One of the fracture surfaces of the specimen is a cleavage plane (s_1) along a planar fold limb consisting of massive ore. The arrangement of the sheet silicate flakes indicates a foliation (s_2) inclined at about 20° to s_1 (Fig. 1 a and b). On s_1, several slightly scattered lineations are visible.

From the hand specimen, two slices approximately 2.5 cm thick were cut perpendicular to s_1 and to the mean direction of lineation (the shapes of these slices are clear from Fig. 1 a and c). One slice was investigated using reflected-light microscopy and X-ray pole figure goniometry and the other using magnetic anisotropy.

From the first slice, three mutually perpendicular sections were cut for microstructural studies and X-ray pole figure goniometry (for the location, see Fig. 1 c):

section $A(\perp s_1, \perp$ mean direction of lineations, plane of cross-section),
section $B(\perp s_1, \perp A)$,
section $C(\parallel s_1, \perp A, \perp B)$.

In addition, six C sections were prepared for investigating the variability in the *c*-axis distribution. Three of them came from the upper part of the hand specimen (*IT-O* in Fig. 1 c) and three from the lower part (*IT-U* in Fig. 1 c). The sections within each triad were cut 2 mm apart.

From the second slice, 13 test cube specimens for measuring the magnetic anisotropy were cut with their surfaces parallel to A, B and C, respectively, from the left part of the slice (see Fig. 1 d).

Reflected-light microscopy

Microstructurally, the ore is characterized by polygonal tabular hematite crystals (diameter 100–200 μm, thickness 20–50 μm) which lack intracrystalline deformation features (Fig. 2 a–c). The tabular hematites lie parallel to either s_1 or s_2. In the A section a strong preferred orientation of elongated grains along the trace of s_2 is observed locally.

The directional distribution of hematite *c*-axes can be determined qualitatively using the reflected-light microscopy. For individual hematite grains the orientation of the trace of the *c*-axis is measured by means of the polarization figure (Cameron and Green, 1950; Hennig-Michaeli, 1976). In section B (197 grains) there is a very sharp maximum of traces (Fig. 3 a), whereas in section A (430 grains) a larger scattering of the trace directions is observed (Fig. 3 b). The

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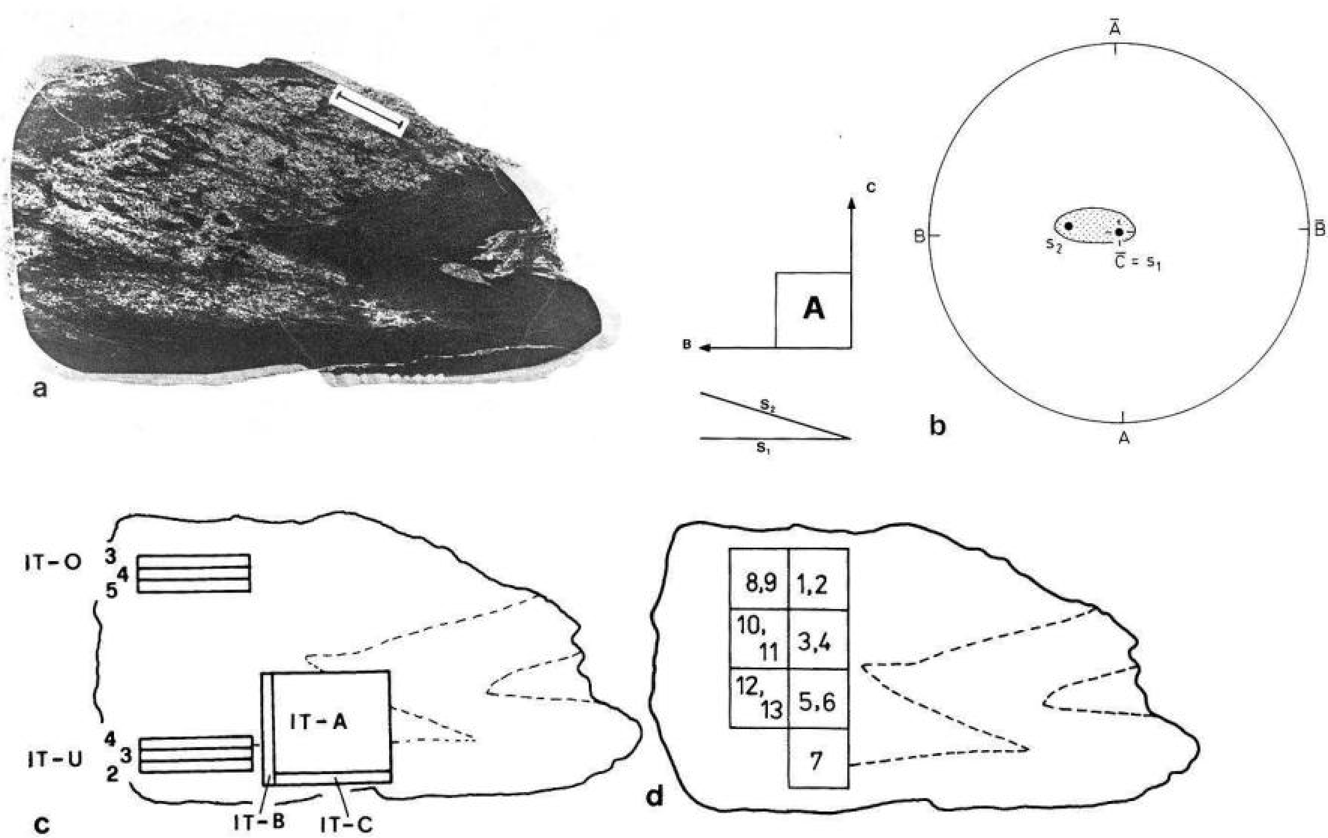


Fig. 1 a–d. Basic information concerning the structure and specimen locations of the sample of hematite ore from Minas Gerais, Brazil. **a** Cross-section of the hematite ore studied. Traces of s_1 (planar fold limb) and s_2 (foliation). Scale bar = 1 cm, **b** Poles of macroscopic structural faces (s_1, s_2); *closed circles* denote the mean directions, *stippled* is the area of occurrence. Equal area projection, lower hemisphere. **c** Locations of the specimens for X-ray pole figure goniometry, **d** Locations of the specimens for magnetic anisotropy.

The reference axes used in all figures are defined as shown in Fig. *1*a: A axis lies in the s_1 foliation and is parallel to the mean direction of lineations, *B* axis also lies in the s_1 foliation and is perpendicular to the *A* axis and *C* axis is perpendicular to the s_1 foliation. The notation of sections and planes in this paper is rather unusual from the point of view of physics, but in agreement with that used in X-ray pole figure goniometry – the sections and planes have the same names as the respective axes they are perpendicular to, not the names of the axes lying in them

trace distributions indicate that the *c*-axes of the hematite grains have a pronounced maximum in an orientation more or less parallel to the mean direction of the normals of s_1 and s_2 (Fig. 1b).

X-ray analysis of preferred orientation

Measurement of preferred orientation by means of an X-ray pole figure goniometer has been performed in the three mutually perpendicular sections *A*, *B* and *C*. The intensity data of the planes *A* and *B* were rotated into the plane *C* and combined with those of plane *C* to give complete pole figures. Details of the measurements of preferred orientation by means of X-rays and details of the presentation of the data are given by Siemes (1977). The complete pole figures of the (006)-, {104}-, {110}- and {300}-reflections are shown in Fig. 4a–d. If the {104}-reflection has a relative intensity of 100, the (006)-reflection has only a relative intensity of 2. Thus it is possible to measure the former reflection with great accuracy, but the latter with less precision.

Additional, but incomplete, pole figures were prepared from six *C* sections mentioned earlier to illustrate the variability in the *c*-axis preferred orientation (see Figs. 5 and 6). The calculated mean intensities of the complete pole figures, which are the intensities of pole figures of hematite without any preferred orientation, were used to establish reference levels for the relative intensities of the incomplete pole figures. Since all measurements were made under the same conditions, all the pole figures are comparable. From Figs. 5 and 6 it follows that in the lower part of the hand specimen (sections *U 2*, *U 3*, *U 4*, see Fig. 5), i.e. in the massive limb of the ore, the preferred orientation is stronger than in the upper part (sections 03, 04, 05, see Fig. 6), as is to be expected from the microscopic study. In the upper part of the hand specimen (Fig. 6), the maximum of the (006)-reflection is split into two areas of high intensity.

Though the hand specimen exhibits monoclinic structural symmetry, the distributions of the intensities in the pole figures show approximately orthorhombic symmetry with identical orientation of the mirror planes in the {104}- as well as in the (006)-pole figures. Only in Fig. 6a and b is there an unresolved discrepancy between the mirror planes in the {104}-pole figure and the (006)-pole figure.

The slightly different orientations of the symmetry planes in the pole figures obtained from different *C* sections prove that the preferred orientation is varying from place

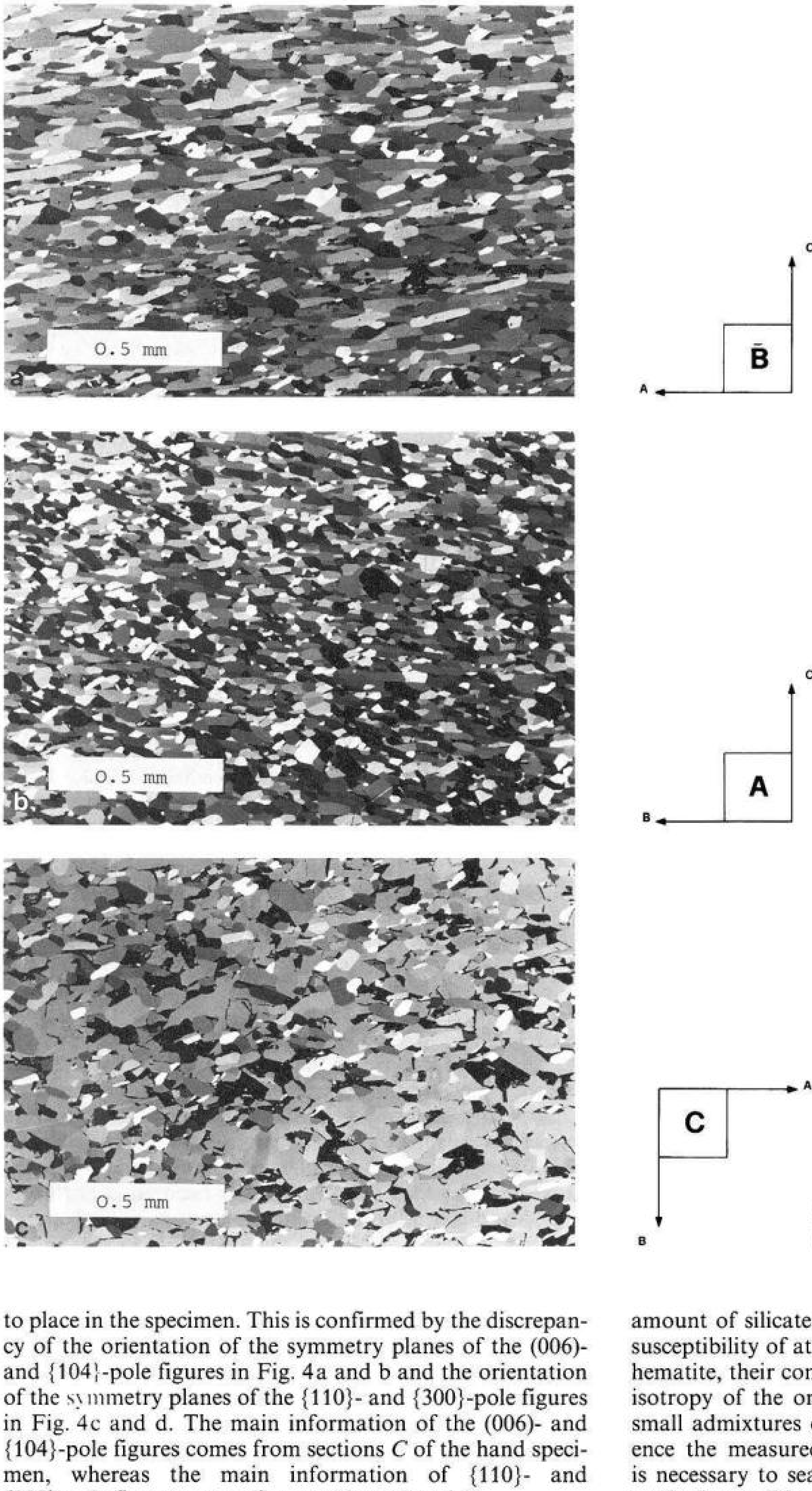


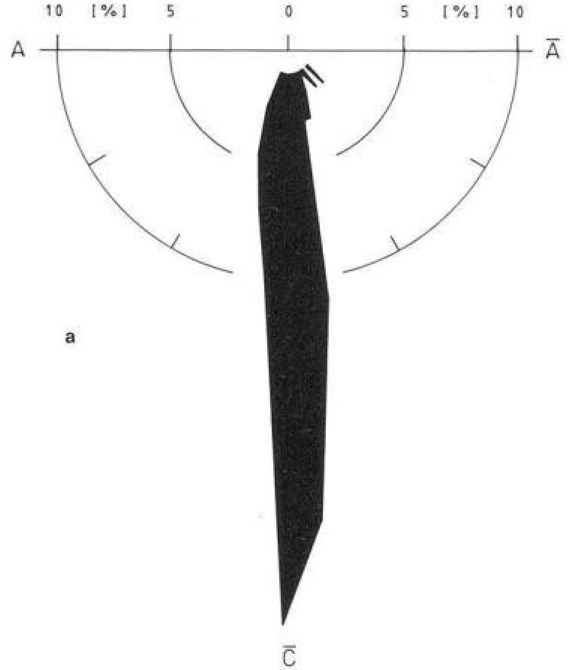
Fig. 2a–c. Microphotographs of the hematite ore. **a** Section *B*, **b** Section *A*, **c** Section *C*

to place in the specimen. This is confirmed by the discrepancy of the orientation of the symmetry planes of the (006)- and {104}-pole figures in Fig. 4a and b and the orientation of the symmetry planes of the {110}- and {300}-pole figures in Fig. 4c and d. The main information of the (006)- and {104}-pole figures comes from sections *C* of the hand specimen, whereas the main information of {110}- and {300}-pole figures comes from sections *A* and *B*.

Magnetic mineralogy of the ore

As shown in the preceding sections, the ore hand specimen investigated is composed virtually of hematite with a small amount of silicate inclusions. As silicates exhibit magnetic susceptibility of at least one order of magnitude lower than hematite, their contribution to the susceptibility and its anisotropy of the ore can be neglected. On the other hand, small admixtures of magnetite, as low as 0.1%, can influence the measured data considerably. For this reason it is necessary to search for magnetite by the most sensitive methods possible.

Under the ore microscope no magnetite has been identified. In order to confirm this by a magnetic method, we measured the magnetic anisotropy in different fields using the torque magnetometer. As the torque in fields higher than that for saturation of magnetite is independent of the



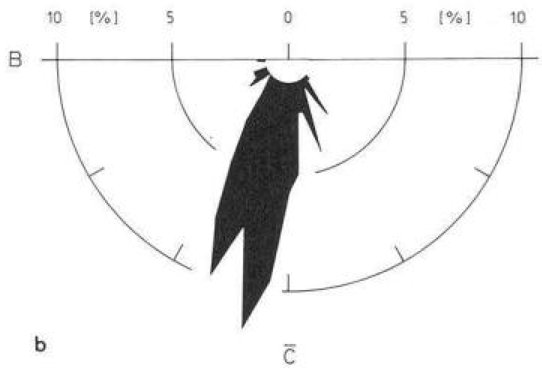


Fig. 3a, b. Directional distribution of traces of hematite c-axes, reflected-light measurements. **a** Section B, 197 traces of c-axes, **b** Section A, 430 traces of c-axes

field for magnetite (Stacey, 1960) and linearly variable for hematite (Porath and Chamalaun, 1966), we can estimate the contribution of both minerals to the anisotropy of the ore.

The magnetic anisotropy in a range of fields from 100–1000 mT was measured on the torque magnetometer developed by Parma (1980) and the measurements were processed by the TOR 1 program developed by Jelinek (unpublished). The results are shown in Fig. 8, where the dependence of the amplitudes of the second harmonic terms of the torque in the B plane of the specimen is presented. It is clear from the figure that the torque is, very closely, linearly dependent on the field. Consequently, the magnetic anisotropy of the ore is controlled exclusively by hematite.

Magnetic fabric and its correlation with optically and X-ray determined c-axis fabric

Let us assume, for the sake of mathematical simplicity, that hematite ore consists only of hematite crystals of the same size and magnetic properties not interacting magnetically and being so numerous that the distribution of their c-axes can be described by a continuous function. Then, the susceptibility tensor of the ore is (see Owens, 1974)

$$\mathbf{k} = \bar{K} \quad f(\theta,\phi)\,\mathbf{K}(\theta,\phi)\,\sin\theta\, d\phi\, d\theta, \tag{1}$$

where $\bar{K}$ is the mean susceptibility (defined as the arithmetical mean of the principal susceptibilities) of a crystal, $\mathbf{K}$ the normed susceptibility tensor of a crystal (the normalizing factor is the mean susceptibility) and $f(\theta,\phi)$ the frequency density function characterizing the distribution of the c-axes of hematite crystals on a surface of a unit hemisphere; θ, ϕ are conventional polar angles specifying the orientation of the c-axes. As the mean susceptibility of hematite is about 5×10^{-3} (Zapletal, 1983), the magnetic interactions in the field of hundreds μT (used in low-field anisotropy meters) can be regarded as negligible (according to the criteria of Owens and Rutter, 1978). (SI units are used throughout the present paper.)

Introducing the ratio $P_c = K_{ab}/K_c$, where K_{ab} is the susceptibility in the basal plane of hematite crystal and K_c that along the c-axis, the components of the tensor $\mathbf{K}$ are

$$\begin{aligned}
K_{11} &= 3[(1-P_c)\cos^2\phi\,\sin^2\theta + P_c]/(2P_c+1)\\
K_{22} &= 3[(1-P_c)\sin^2\phi\,\sin^2\theta + P_c]/(2P_c+1)\\
K_{33} &= 3[(1-P_c)\cos^2\theta + P_c]/(2P_c+1)\\
K_{12} &= K_{21} = 3(1-P_c)\sin^2\theta\cos\phi\,\sin\phi/(2P_c+1)\\
K_{23} &= K_{32} = 3(1-P_c)\sin\theta\cos\theta\,\sin\phi/(2P_c+1)\\
K_{13} &= K_{31} = 3(1-P_c)\sin\theta\cos\theta\,\cos\phi/(2P_c+1).
\end{aligned} \tag{2}$$

As the tensor representation of magnetic anisotropy is not too illustrative, specially constructed parameters and orientations of principal susceptibilities are used in magnetic anisotropy studies instead of tensors. Among many anisotropy parameters introduced up till now, one pair are of great importance, viz. the P' and T parameters introduced by Jelínek (1981). The P' parameter characterizes the anisotropy degree regardless of the shape of the susceptibility ellipsoid and is defined as follows:

$$P' = \exp\sqrt{\{2[(\eta_1-\eta)^2 + (\eta_2-\eta)^2 + (\eta_3-\eta)^2]\}}, \tag{3}$$

where $\eta_1 = \ln k_1$, $\eta_2 = \ln k_2$, $\eta_3 = \ln k_3$,

$\eta = (\eta_1+\eta_2+\eta_3)/3$ and $k_1 \geqq k_2 \geqq k_3$ are the principal susceptibilities. The T parameter characterizes the type of the preferred orientation regardless of the anisotropy degree and is defined as

$$T = 2(\eta_1-\eta_3)/(\eta_2-\eta_3) - 1. \tag{4}$$

It ranges $0 < T < +1$, if the c-axis pattern in hematite ore is more akin to the cluster pattern than to the girdle one and $-1 < T < 0$, if this pattern is more akin to the girdle than to the cluster.

If the magnetic fabric of an ore is represented by the P' and T parameters and the orientations of principal susceptibilities, the knowledge of $\bar{K}$, as it follows from Eqs.

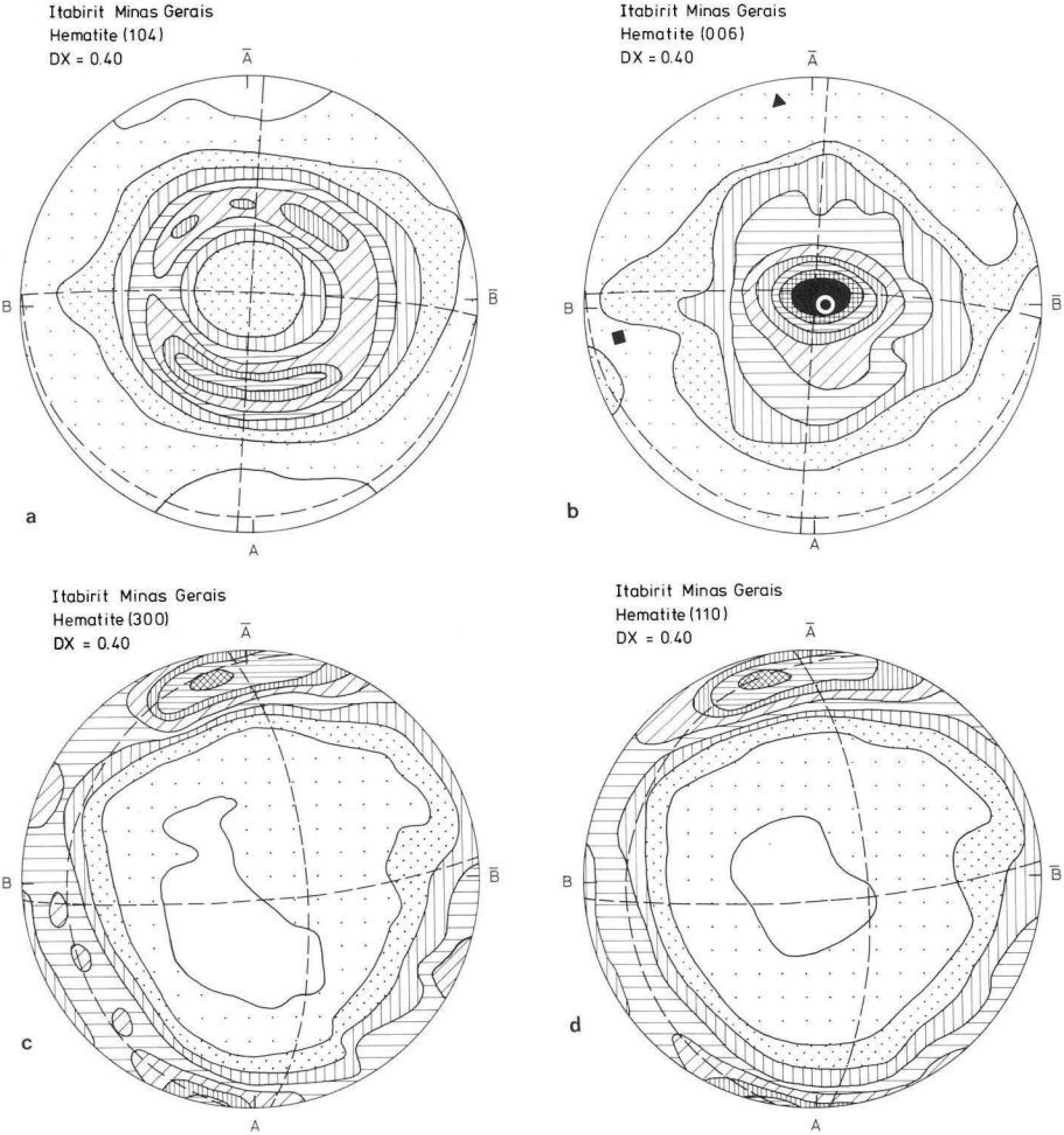
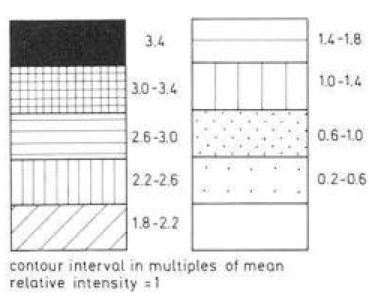


Fig. 4a–d. Complete pole figures of the hematite ore and directions of principal susceptibilities of the theoretical magnetic anisotropy (calculated using Eq. (1)–(4), see the main text). **a** {104}-reflection, **b** (006)-reflection, **c** {300}-reflection, **d** {110}-reflection

Legend for Figs. 4–7: ----- Planes of orthorhombic symmetry in X-ray pole figure diagrams

▲, ■, ● directions of the maximum, intermediate and minimum susceptibilities of the theoretical magnetic anisotropy; △, □, ○ directions of the maximum, intermediate and minimum susceptibilities of the theoretical magnetic anisotropy. Equal-area projection on lower hemisphere



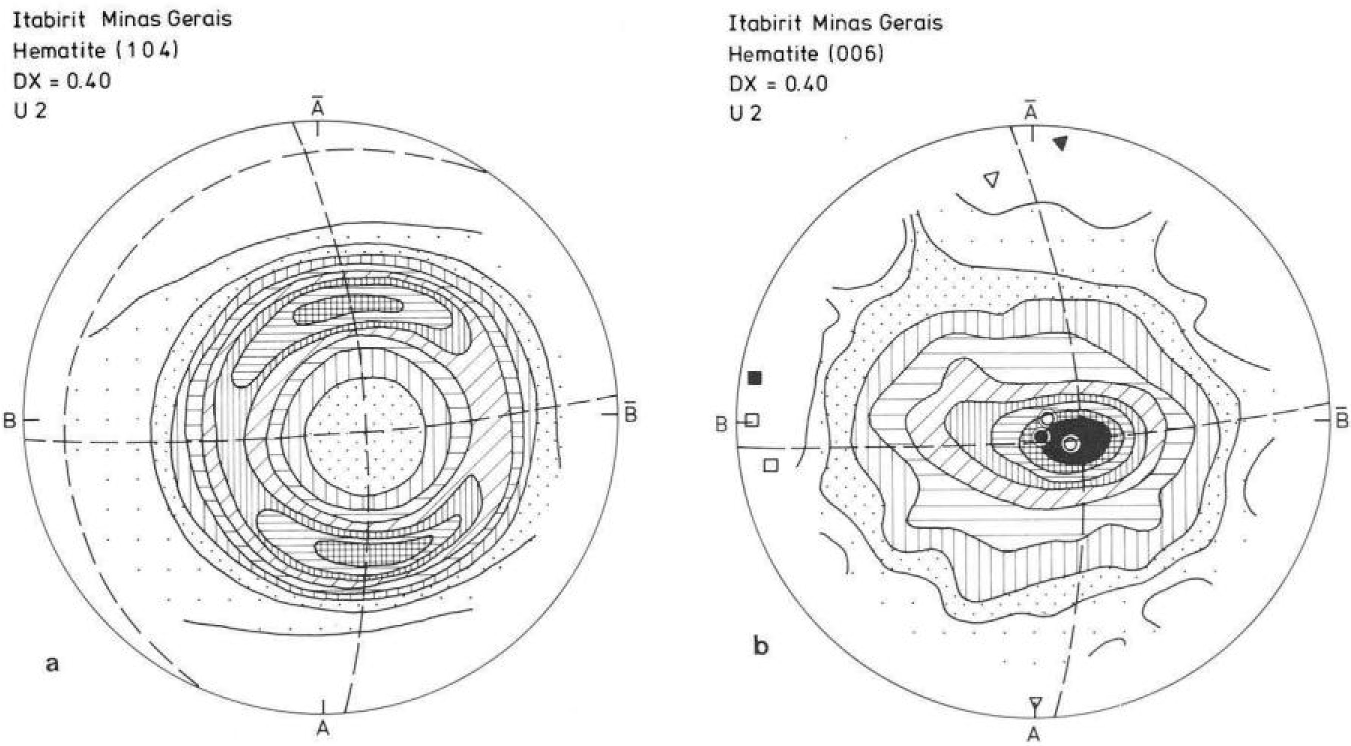


Fig. 5a, b. Incomplete pole figures from the lower part of the hematite ore. **a** {104}-reflection of section *U 2*, **b** (006)-reflection of section *U 2* and orientations of principal susceptibilities of theoretical magnetic anisotropy: section *U 2* (closed symbols), sections *U 3*, *U 4* (open symbols)

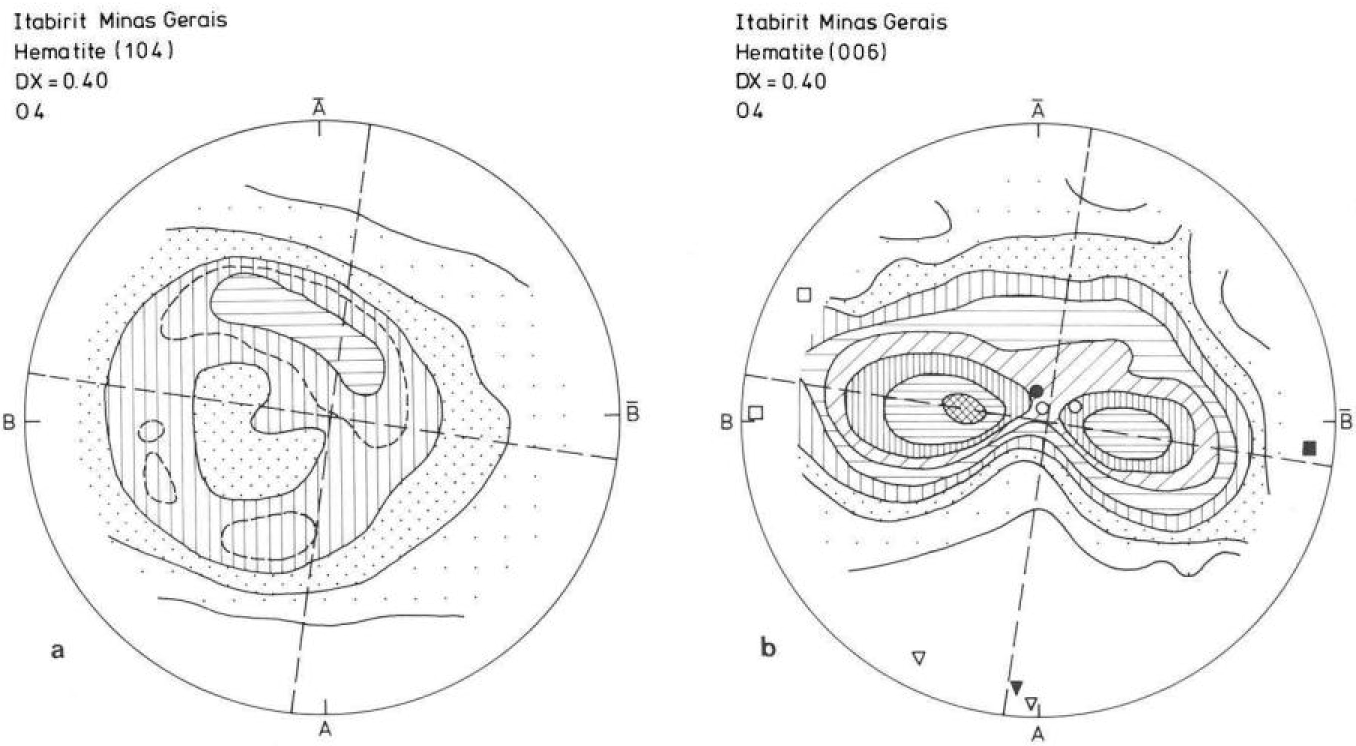


Fig. 6a, b. Incomplete pole figures from the upper part of the hematite ore. **a** {104}-reflection of section *O 4*, **b** (006)-reflection of section *O 4* and orientations of principal susceptibilities of theoretical magnetic anisotropy: section *O 4* (*closed symbols*), sections *O 3*, *O 5* (*open symbols*)

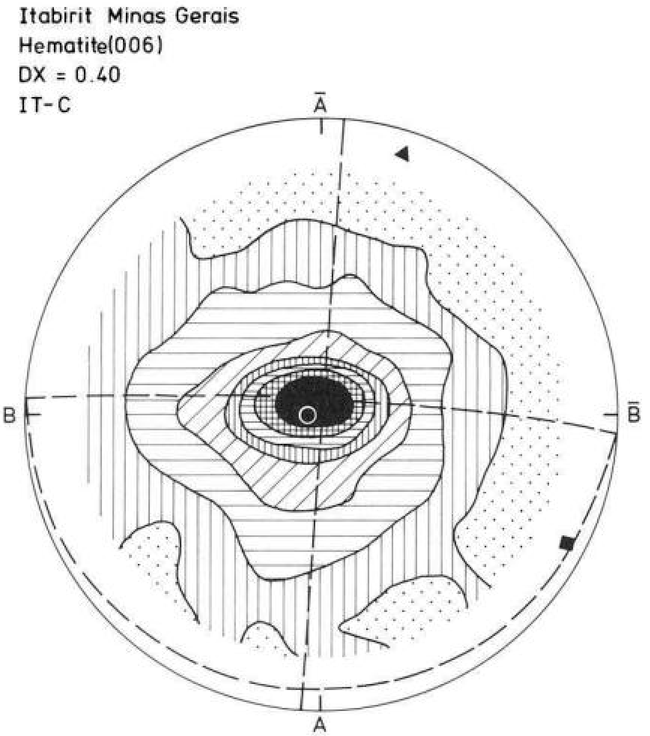


Fig. 7. Incomplete pole figure of the data of the *C* section of Fig. 4b. Equal area projection of the lower hemisphere of the (006)-reflection

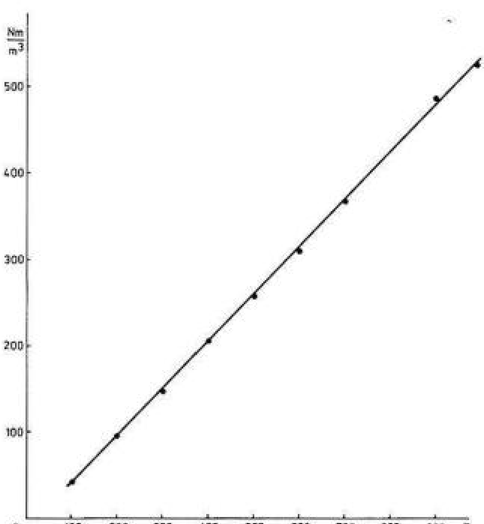


Fig. 8. Diagram to show the dependence of the amplitude of the second harmonic term of the torque on the magnetic field for the hematite ore from Minas Gerais, Brazil

(1)–(4), is not necessary for calculating these characteristics. In addition, Hrouda (1980) showed that in ores with $P_c >$ 100 the anisotropy is controlled only by the intensity of *c*-axis orientation of the highly anisotropic crystals, while the particular value of P_c is unimportant; for example, at constant *c*-axis concentration, $P_c = 100$, $P_c = 1000$, and $P_c =$ 10000 give rise to virtually the same values of ore anisotropy degree. As hematite single crystals exhibit high and virtually isotropic susceptibility in the basal plane and

Table 1.. Theoretical magnetic anisotropy parameters (for definition, see the text) calculated from the (006)-pole figures of hematite ore from Minas Gerais, Brazil, using Eqs. (1)–(4)

Specimen No.	P'	T
IT-CBA	2.30	0.81
IT-C	2.46	0.97
IT-U2	3.15	0.89
IT-U3	3.22	0.94
IT-U4	3.12	0.95
IT-03	2.93	0.87
IT-04	2.75	0.44
IT-05	2.88	0.83
Arithmetical mean	2.85	0.84
Standard deviation	0.33	0.17

very low susceptibility along the *c*-axis, with $P_c > 100$ (Uyeda et al. 1963; Porath and Chamalaun, 1966), any value of P_c higher than 100 may be used for calculation of the theoretical anisotropy.

Using these factors we calculated the theoretical anisotropy of our hematite ore according to Eqs. (1)–(4) and employing the (006)-pole figure for the function $f(\theta, \phi)$. The data for X-ray measurements were stored in digital form and subsequently used in calculation. The integration over the $f(\theta, \phi)$ function was made numerically by computer. The results are summarized in Figs. 4–7 showing the orientation of principal susceptibilities and in Table 1 giving the values of the P' and T parameters.

It can be seen in Figs. 4–7 that the minimum susceptibility directions mostly lie in the maxima of the *c*-axis concentrations. Only in the specimen *O 4*, whose *c*-axis cluster is doubled, does the minimum susceptibility direction lie between the two partial maxima (Fig. 6b). All the minimum susceptibility directions are near the *C* coordinate, i.e. roughly perpendicular to the s_1 foliation. The maximum susceptibility directions in all specimens are roughly perpendicular to the elongations of the *c*-axis maxima, lie near the *A* axis and the mean lineation. The orientations of all the principal susceptibilities are in agreement with the qualitative theoretical predictions following from the properties of hematite single crystals and the *c*-axis distribution patterns. The P' values in Table 1 are relatively high and correspond to strong *c*-axis orientation. T values $T > O$ are in qualitative agreement with the *c*-axis pattern (cluster type).

The magnetic anisotropy was measured by the KLY-2 Kappabridge (Jelínek, 1980) in a field of 380 µT (300 A/m) and calculated using the ANISO 11 program (Jelínek, 1977). The results are summarized in Fig. 9 and Table 2. In Fig. 9 the orientations of principal susceptibilities and of the main fabric elements with respect to the *A, B, C* coordinates are presented, while in Table 2 the values of the $\bar{k}$ ($\bar{k} = (k_1 + k_2 + k_3)/3$), P' and T parameters are given.

From Fig. 9 it is clear that the minimum susceptibility directions (poles to the magnetic foliation) are very well concentrated in space near the *C* coordinate and lie in a slightly elongated group in the area between the poles of the s_1 and s_2 planes. The directions of the maximum (magnetic lineation) and intermediate susceptibilities are scattered more than those of the minimum susceptibility and create partial girdles.

As obvious from Table 2, the anisotropy degree of our ore is very high, which indicates an intense preferred orien-

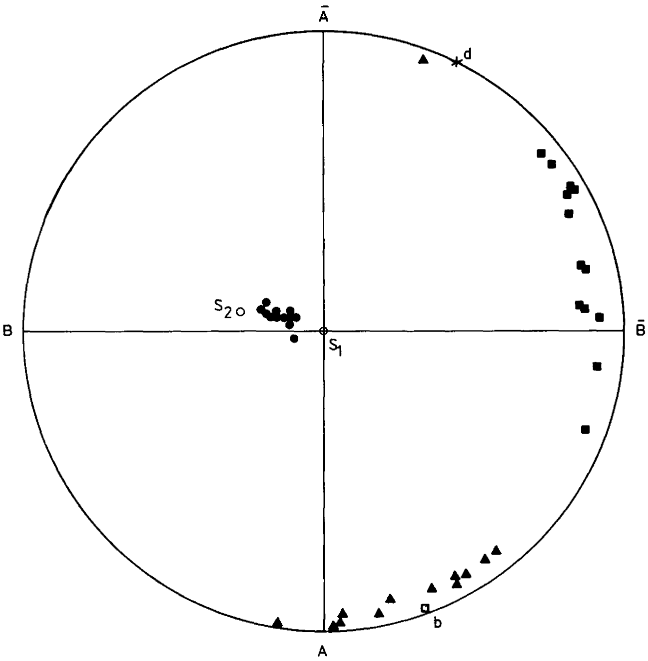


Fig. 9. Orientations of principal susceptibilities and main structural elements with reference to the *A, B, C* coordinate system for the hematite ore from Minas Gerais, Brazil. ▲ maximum susceptibility, ■ intermediate susceptibility, ● minimum susceptibility, o foliation pole, □ lineation (presumably parallel to the fold axis), * intersection line of s_1 and s_2 foliations. Equal area projection of the lower hemisphere

Table 2. Magnetic anisotropy parameters (for definition, see the text) for the hematite ore from Minas Gerais, Brazil

Specimen No.	$\bar{k}(10^{-6})$	P'	T
1	4823	2.222	0.49
2	4823	2.055	0.51
3	4929	1.990	0.38
4	5000	1.977	0.54
5	4730	1.914	0.45
6	5068	2.095	0.47
7	5253	2.901	0.74
8	4959	2.068	0.31
9	4753	1.951	0.36
10	4817	2.161	0.53
11	4950	2.129	0.68
12	5222	2.105	0.59
13	4811	2.132	0.55
Arithmetical mean	4934	2.131	0.51
Standard deviation	167	0.248	0.12

tation of the hematite by crystal lattice in the ore. The T values, ranging from 0.31 to 0.74, indicate that the hematite *c*-axes create a slightly elongated cluster pattern being in agreement with the X-ray *c*-axis fabric determination (see Figs. 4–7).

It can be seen in Figs. 4–7 and 9 that both the calculated minimum susceptibilities and the measured ones are oriented very near the *C* coordinate, i.e. the pole of the s_1 foliation. In this respect, the measured data is in very good agreement with that predicted. The maximum susceptibility directions, both the calculated and the measured, display relatively large scatters; nevertheless, their mean directions are near the *A* coordinate. Hence, despite these scatters the calculated and measured maximum susceptibility directions may be regarded as agreeing.

It can be seen in Tables 1 and 2 that the mean value of the anisotropy degree P' calculated is higher than that measured. The scatter of the calculated values is also higher than that of measured values (compare the standard deviations in Tables 1 and 2). The mean value of the shape factor T calculated is higher than that measured. The scatters do not differ too much.

It can be seen in Fig. 1c and d, too, that the anisotropy specimens Nos. 1, 2, 8, 9 are near the X-ray *IT-O* specimens and Nos. 5, 6, 7 are near the *IT-CBA* specimen. Specimen No. 7 is also near the *IT-U* specimens. It is clear from Tables 1 and 2 that the calculated values of the P' and T parameters are higher than those measured in all the three respective groups. The differences may have these explanations:

a) The measurement of the magnetic anisotropy is performed on the total volume of a specimen whereas the pole figures only represent thin mutually perpendicular specimen layers. The preferred orientation of the total specimen volume can be measured by means of neutron radiation texture goniometry (see e.g. Esling et al., 1978). Unfortunately, this method was not at our disposal.

b) Use of incomplete pole figures introduces additional errors into the calculation of the magnetic anisotropy. This can be demonstrated by an example. Figure 7 shows the incomplete (006)-pole figure which was taken from the *C* section of the hand specimen (*IT-C*). It represents the central part of the complete pole figure, Fig. 4b, but the plotted directions of the principal susceptibilities were calculated from the data of the incomplete pole figure. The maximum and intermediate susceptibilities of the incomplete pole figure deviate noticeably from those of the complete pole figure (*IT-CBA*, Fig. 4b). This discrepancy can be avoided if the complete pole figure is calculated from the incomplete data by means of the vector method (Ruer, 1976; Ruer and Baro, 1977). Complete pole figures may be obtained from only two incomplete measurements by means of the computer program developed by Vadon (1981).

c) All the assumptions for Eq. (1) need not be fulfilled. For example, the grains are obviously not of the same size (see Fig. 2).

Conclusions

The *c*-axis fabric of massive hematite ore from Minas Gerais, Brazil, was investigated by reflected-light microscopy, X-ray pole figure goniometry and magnetic anisotropy. From this work, the following results have emerged:

1. The orientations of principal susceptibilities measured are essentially the same as those predicted from the *c*-axis fabric determined by reflected-light microscopy and X-ray pole figure goniometry.

2. The measured values of the anisotropy degree and shape factor are slightly higher than those predicted from the *c*-axis fabric. These differences may result from the fact that the magnetic anisotropy and the X-ray measurements were not executed on exactly the same specimens, that the volumes of the ore measured by the respective methods were different (1 cm^3 cubes in magnetic anisotropy, thin

layers in X-ray pole figure goniometry), that for some predictions incomplete pole figures were used and that, for predictions, a very simple theory was used which may not have fully corresponded to reality. Nevertheless, the differences are small and the data obtained by both methods may be regarded as compatible.

3. For routine work it is advantageous to combine these different types of methods. Large collections of specimens should be investigated by magnetic anisotropy because of the rapidity of this method. Specially selected pilot specimens should subsequently be investigated by reflected-light microscopy and X-ray pole figure goniometry because these methods enable various fabric elements to be investigated and provide detailed pole figures with all partial maxima and minima.

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