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MAGNETIC AND METALLOGRAPHICAL STUDIES OF THE BOCAIUVA IRON METEORITE

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ABSTRACT

Bocaiuva iron meteorite (IAB) has been studied magnetically and metallographically in order to understand its stable natural remanent magnetization (NRM). This meteorite consists in major amounts of 6-7wt% Ni kamacite associated with taenite, plessite, schreibersite and magnetite for magnetic minerals. Tetrataenite, less than 0.2% in volume, is formed along the high Ni taenite lamellae and in the kamacite domain walls. The NRM direction is almost parallel to a dominant plane of the tetrataenite development. Bocaiuva may have acquired the stable NRM during the slow cooling process under 300°C inside the meteorite parent body or after shock heating by collision.

Key-words: Magnetic; Metallographical; Meteorite.

1 - INTRODUCTION

The Bocaiuva iron has been classified as a IAB meteorite and is unique in its structure which contains about 10 to 15% by volume of silicate inclusions, surrounded by kamacite (6.5wt% Ni), (Desnoyers et al., 1985). Taenite, plessite, chromite, schreibersite and pyrrhotite have been reported. A Widmanstatten pattern of 0.1 - 0.3 mm wide kamacite bands and Neumann bands are present. Magnetite, probably maghemite, and geothite are often found at the metal-silicate boundaries and are observed to fill the cracks in metal and silicates. Although Curvello et al. (1983) indicated troilite in this meteorite, pyrrhotite has been reported instead of troilite (Desnoyers et al., 1985). Forsterite, enstatite and diopside are observed in the silicate inclusions, as well as an unusual interstitial Ca rich plagioclase. The Mossbauer spectra of a thin slice sample and an extracted sample by HCl from Bocaiuva shows only the presence of kamacite and disordered taenite from 33 to 36% Ni contents respectively (Araujo et al., 1983). Scorzelli and Danon (1986) reported the taenite and schreibersite in the extracted materials by HCl. There is no evidence for the presence of ordered FeNi tetrataenite phase by Mossbauer spectroscopy, which suggests a rather fast cooling rate of the meteorite. In the present paper Bocaiuva was investigated magnetically and metallographically in order to understand the stability of its natural remanent magnetization (NRM).

In order to interpret the results obtained we performed a detailed investigation by a conventional metalographical method and electron microprobe analysis of the metal phases in Bocaiuva. Bitter pattern method for investigating the magnetic phases of the meteorite has been used with a magnetic fluid painting on the polished surface of the meteorite.

2 - MAGNETIC PROPERTIES

2.1 - Natural remanent magnetization (NRM), AF and thermal demagnetizations

The original NRM of a bulk sample of Bocaiuva has been found to be 1.519 x 10^{-2} Am^2/kg by using a spinner magnetometer. The bulk sample A (0.071g) was demagnetized up to 50 mT by 3 axes AF demagnetizer. The original NRM intensity, decreased steeply by 5 mT, then gradually to 50 mT. The variations of NRM components using a Zijderveld projection are shown in Fig. 1(a). The components decompose to 3 stages; the first stage is a relatively soft magnetic component up to 10 mT characterized by a large demagnetization of vertical component; the second stage is a stable one from 10 to 40 mT shifting toward zero for the horizontal components and shifting horizontally for the vertical component; the third stage is a relatively stable one from 40 to 50 mT shifting flat for the both components. The change of NRM directions, as shown in Fig. 1(b), represents the stable NRM between 10 to 40 mT. The median demagnetization field (MDF) value of this sample is about 5 mT. Bulk sample B (2.800g) was AF demagnetized to 14 mT, suggesting stable NRM from 10 to 30 mT with the MDF value of less than 5 mT. However, their NRM directions changed along a perpendicular plane of a great circle.

Sample C, D and E were thermally demagnetized from 50^{o} to 750^{o}C in steps 50^{o}C. The changes of NRM intensities and directions are shown in Fig. 2. The sample C (0.482g), having only stable NRM component due to carrying out of AF demagnetization to 15 mT, has relatively stable NRM between room temperature and 550-600^{o}C; the intensity (4.760×10^{-3} Am^{2}/kg) decreases smoothly up to 550^{o}C and the directions change within a small area up to 600^{o}C. However, unstable NRM is observed from 550-600 to 750^{o}C. A NRM blocking temperature is defined at 550^{o}C. Sample D (0.368g) is a sample having 3.045×10^{-2} Am^{2}/kg which is stronger about 10 times than samples C and E. The variations of NRM intensity are very small from room temperature to 300^{o}C but then decrease abruptly from 300 to 500^{o}C. Change of the directions is small up to 500^{o}C and becames large from 550 to 750^{o}C. The NRM blocking temperature is defined clearly at 550^{o}C. Sample E (0.694g) is also an one with 2.940×10^{-3} Am^{2}/kg. This sample has similar thermal demagnetization characteristics of that of sample C, except for the presence of some soft magnetic components from room temperature up to 150^{o}C.

2.2 - Distribution of NRM directions

A total of 22 samples with different orientations, ranged from 0.071 to 2.8g in weight, were prepared from a block sample of Bocaiuva. The original NRM of every sample was measured and then 18 samples were AF demagnetized by 15mT, which is the optimum AF demagnetization field intensity, by taking away the relatively soft NRM components (the first stage of AF demagnetization).

The variations of the NRM intensities are fairly large among the samples such as 1.1×10^{-1} to 4.6×10^{-3} Am^2/kg for the original samples and 1.4×10^{-2} to 4.4×10^{-3} Am^2/kg after the AF demagnetization. The respective average intensities are of the order of 10^{-2} and 10^{-3} Am^2/kg. The samples with weaker or stronger NRM intensities distribute at random in the block sample. The NRM directions before and after demagnetization are distributed as shown in Fig. 3. The distribution shows a tendency of approximate alignment along a great circle over an hemisphere. This tendency does not change by demagnetization, although the NRM directions of a few samples shift widely within the great circle by the demagnetization. This indicates that both of the hard and the relatively soft magnetic components of Bocaiuva have been magnetized in a same plane.

2.3 - Magnetic hysteresis properties and thermomagnetic curves

Magnetic hysteresis properties and thermomagnetic curves have been measured with the bulk of the 1 and 2 samples and with an extracted sample by HCl from the Bocaiuva meteorite. Magnetic hysteresis properties, saturation magnetization (I_S), saturation remanent magnetization (I_R), coercive force (H_C) and remanence coercive force (H_{RC}) were determined using the magnetization curve from - 1.4 to + 1.4 T in a steady magnetic field at room temperature. These values, before and after heating up to 850^{o}C, are listed in Table 1, whereas the values H_{RC} could not be obtained due to the weak magnetization as compared with the noise level (about 5 mT). The principal magnetic mineral in both bulk samples appears to be FeNi with low Ni content from their large I_S values (205.5 and 201 Am^2/kg for samples 1 and 2 respectively). Small values of I_R and H_C values may suggest multidomain structure of the principal magnetic minerals. These magnetic charcteristics do not change obviously by heating treatment to 850^{o}C. For the extracted samples, however, large values of H_C and H_{RC} (23.5 and 66.7 mT respectively) have been observed, which decrease markedly (H_C = 1.0 and H_{RC} 5 mT) after heating the sample to 650^{o}C. These marked changes of H_C and H_{RC} by heat treatment are explained by the presence of tetrataenite phase in the extracted sample.

Thermomagnetic curves (I_S-T curves) were obtained from room temperature up to 850^{o}C under 10^{-2} Pa atmospheric pressure, 200^{o}C/h of heating and cooling rates and 600 mT of steady magnetic field. The 1st and 2nd run curves are shown in Fig. 4 and the Curie points are listed in Table 1. The 1st run I_S-T curve of bulk 1 sample shows a phase transition temperature from bcc to fcc (α - τ) at 760^{o}C and from fcc to bcc (τ - α) at 610^{o}C suggesting 6% Ni FeNi alloy for the main magnetic mineral. Small change the of Curie point at around 450^{o}C was observed in the cooling curves. In the 2nd run I_S-T curves, the phase transition temperatures decrease to 725^{o}C ($\alpha - \tau$) and to 605^{o}C ($\tau - \alpha$), suggesting an increase of the Ni content to 8% in kamacite by the heat treatment. The Curie point observed at about 450^{o}C in the 1st run cooling curve disappears in that of 2nd run curve, suggesting that it is due to an unstable phase. In case of the bulk sample 2, the phase transitions were observed at temperatures of 745^{o}C ($\alpha - \tau$) and 605^{o}C ($\tau - \alpha$) for the 1st run cycle and 735^{o}C ($\alpha - \tau$) and 605^{o}C ($\tau - \alpha$) for the 2nd run cycle. This suggests that the bulk sample 2 consists of 7wt% Ni kamacite originally and 8wt% Ni kamacite after heating to 850^{o}C.

The I_S-T curves of the extracted samples are irreversible, with Curie points at about 310 and 550^{o}C in the heating curve and at about 255^{o}C in cooling curve. The main Curie points observed at about 310 and 255^{o}C can be attributed to the taenite with 34-36% Ni. It is also possible the Curie points results from schreibersite, since this mineral has a Curie point of about 300^{o}C. The I_S-T curve shows a very flat behaviour from 350 to 500^{o}C then decreases abruptly up to 550^{o}C, while there is no significant Curie point around 550^{o}C, in the cooling curve. Characteristics of the I_S-T curves between 350 to 550^{o}C are typical of the tetrataenite phase.

The weight of the extracted sample of 0.01305g (2.7%) was obtained from 0.482g of the bulk Bocaiuva sample.

If the I_S-T curves results from the tetrataenite phase, the magnetization intensity of the phase can be estimated to be about 3 Amm^2/kg. Since the saturation magnetization of a 50%Fe 50%Ni alloy is 85.5 Am^2/kg, the calculated amount of tetrataenite phase is found to be about 0.1% in weight, if this phase is supposed to be saturated at an external magnetic field of 0.6 T. Usually tetrataenite does not saturate at 0.6T, but the magnetization shows more than half of the saturation magnetization is attained. It may therefore be concluded that Bocaiuva contains the tetrataenite phase with less than 0.2wt% in the bulk sample.

3 - METALLOGRAPHY

3.1 - Microscopical observations

A sample of Bocaiuva, about 10 x 5 mm^2 in area, has been polished and light etched with Nital. Octahedrite structures on the surface were observed by metallographical microscope under bright (Fig. 5a) and dark fields (Fig. 5b). Clusters of many isolated or jointed silicate inclusions of less than 1mm in diameter are swathed by kamacite, schreiberrsite or iron-sulphide. It seems likely that the developments of Widmanstatten patterns with 0.1 - 0.3mm wide are disturbed by the silicate inclusions. Neumann bands are developed in kamacite phase, especially in that surrounded by the inclusions. Schreibersite and iron-sulphide are only observed at contact with the inclusions. Iron oxide is often found at the grain boundaries and filled in the cracks of silicate, schreibersite, iron-sulphide and rarely in kamacite. Lamellar taenite, 5-40 m in thick, appears along limbs of plessite andd kamacite lamellae. The spheroidaized taenite, 5-10 m in diameter is distributed commonly in wide area of plessite field. The acicular taenite clearly and less clearly defined, 20-10 m in length, appear also in the plessite field. These taenites do not show optical anisotropy under reflected light. The plessite, more than 1mm in size, is observed commonly in Bocaiuva. It disappears in the clusters of silicate inclusion.

3.2 - Identificationn of NRM carrier by the Bitter pattern method

In order to study the magnetic carriers in Bocaiuva we used the Bitter pattern method. The polished surface of the meteorite was painted with a magnetic fluid which is a coloidal suspension of magnetite (about 200 Å particle diameter). Figure 6 shows the Bitter pattern configuration of magnetic domains on the surface of kamacite, schreibersite and taenite lamellae. The domain structure of kamacite (5-20 m in wide and 5-20 m in length of each laths) shows parallel alignments or eddy patterns being composed o straight laths. After thermal demagnetization to 750°C, these systematic ordering configurations of domain structures collapse. The domain on schreibersite (under 10 m in wide annd 100 m in length) shows parallel alignment having internal zigzag deformations. No correlation is observed between these domain configurations of kamacite and schreibersite and the NRM directions of Bocaiuva. Small concentration of the magnetic fluid appear on the magnetite veins, although no magnetic fluid concentration aappears on the iron-sulphide grains.

The magnetic fluid concentrate heavily along the borders of some taenite lamellae suggesting strong NRM carrier. It consists of linking together of elliptical speckles which have no internal structures as mgnetic domains. From the speckles fine twings of the concentration branched out into the kamacite field along the kamacite domain walls. The dominant direcction of these lamellae is almost parallel to the NRM direction. These taenite taking strong NRM disappear after heat treatment at 650°C. The phenomenon is similar to the thermal disordering of tetrataenite lamellae in Toluca iron meteorite reported by Funaki et al. (1986).

4 - EPMA AND CMA ANALYSES

Desnoyers et al. (1985) reported chemical compositions of silicates, pyrrhotite and schreibersite in Bocaiuva, with some measurements for the FeNi phases. We measured the chemical compositions in detail of the metallic phases, and the results are summarized in Table 2. Kamacite of the selected 4 points (point 1-4) from the different grains consists of 92-93wt% Fe, 6-7wt% Ni, 0.5wt% Co, and small amount of P, Cu and Zn suggesting almost homogeneous composition of the grains. Measurement points for taenite (point 5, 6 and 7) were selected from lamellar taenite which did not show the heavy concentration of magnetic fluid (weak NRM lamellae). They have 778.0-81.5wt% Fe, 17.5-

21.2wt% Ni, 0.1-0.3wt% Co and small amount of P, S and others; the Ni content is very different among the lamellae. Point 8 is a taenite lamella showing heavy concentration of magnetic fluid (strong NRM lamella). At this point we observed the highest Ni content (37.6wt% Ni) in FeNi metals. Other elements in this lamella not differ, as compared with the weak NRM lamellae. Point 9 and 10, selected from spheroidaized taenite in plessite field, are about 86.5wt% Fe, 12wt% Ni and 0.4wt% Co for the main compositions. The compositions of a total of 77 points from schreibersite show variation of 78.0-81.5wt% Fe and 17.4-21.2wt% Ni and relatively homogenized 15.3-15,8wt% P.

Elemental distribution patterns of Fe, Ni, Co and P from 2 fields (1.0x0.67mm) were mapped using computer-aided microanalyzer (CMA). The number of dots of these pictures are 250 for length and 200 for side and the beem diameter is 5 m. One of the fıeld including kamacite, lamellar taenite, plessite, schreibersite and silicate inclusions is shown in Fig. 7. Concentrations of above elements and their occupied area of the two fields are listed in Table 3. In this picture, kamacite consists of 85-95wt% Fe, 5-8wt% Ni, 0.3-0.8wt% Co and less than 0.5wt% P. In general, uniform chemical composition of the kamacite phase is observed, although relatively low Ni dots (85-90wt% Fe) are distributed in the wide area of 90-95wt% Fe content over. The lamellar taenites consist of 50-85wt% Fe, 15-35wt% Ni, 0.2-0.4wt% Co and less than 0.5wt% P. There is a negative correlation between Fe and Ni; high Fe area includes low Ni. The plessites consist of 70-90wt% Fe, 5-30wt% Ni, 0.2-0.8wt%

Co and less than 0.5wt% Co. In plessite clearly distinguished zoning patterns of Fe, Ni and Co are observed from the center to limb; Ni contents increase to the limb, whereas Fe and Co contents decrease. Ni content in the limb of plessite markedly decreases around schreibersite. It seems likely that the Ni in plessite was absorbed by schreibersite. Schreibersite consists of les than 770wt% Fe, more than 15wt% Ni, less than 0.3wt% Co an 3-16wt% P. The average percentage of the elemental concentrations in this picture (including silicate area) are 79.0710% Fe, 7.5419% Ni, 0.4547% Co and 0.3137% P.

5 - DISCUSSION

Bulk samples of Bocaiuva exhibit very small coercivity (H_C = 1.5 - 4.0 and H_{RC} 5 mT). From the I_S-T curves the main magnetic mineral is found to be kamacite with 6-7wt% Ni. This value is supported by the EMPA and CMA analyses. The secondary magnetic minerals, such as taenite, plessite, magnetite and schreibersite, which exist in Bocaiuva, were investigated by EPMA and CMA analyses and by microscopic observations using the Bitter patern method. Pyrrhotite may be nonmagnetic at room temperature due to absence of characteristic of ferrimagnetic pyrrhotite in I_S-T curves and evidence of any concentration of magnetic fluid on this surface.

However, extracted samples of Bocaiuva exhibit extremely high coercivities (H_C = 23.5 and H_{RC} = 66.7 mT) which decrease to small (H_C = 1 and H_{RC} 5 mT) by heat treatment at 650°C. This coercivity change is characteristic of the tetrataenite (Nagata et al., 1986). The I_S-T curves of the extracted samples show a main Curie point at 310°C which is probably due to an overlap of the Curie points of taenite with 35-36wt% Ni and schreibersite. We used same method for obtaining the extracted samples as that of Scorzelli and Danon (1986) which observed an overlap pattern of the Mossbauer spectrum of taenite (33-36wt% Ni; Araujo et al., 1983) and that ofschreibesite (22.2-39.5wt% Ni).

The I_S-T curves of the extracted samples show a minor amount of tetrataenite phase, which is characterized by flat heating curves from 300 to 550°C with Curie point at 550°C in only heating curves. The microscopical observations with magnetic fluid and EPMA analyses showed high nickel taenite lamellae (37.6wt% Ni) which present very strong NRM. Funaki et al., (1986) reported the extremely strong NRM of tetrataenite extracted from lamellae of the Toluca iron meteorite. Its magnetic characteristics and those observed with Bocaiuva are essentially consistent.

Our results indicate that Bocaiuva includes a small amount of tetrataenite (less than 0.2wt%), as discussed in §2.3. No detection of tetrataenite in the bulk samples is due to the very small amount of tetrataenite, as compared with that of kamacite. Even in the extracted samples by HCl, tetrataenite has not been detected by previous Mossbauer measurements (Araujo et al., 1983; Scorzelli and Danon, 1986) because of overlapping with the much more intense lines of the Ni rich disordered taenite phase.

The NRM in Bocaiuva is very stable against AF demagnetization suggesting a relation with high coercitive magnetic minerals. The NRM decays completely by thermal demagnetization at 550^{o}C, supporting the assumption that it results mainly from tetrataenite. Brecher and Albright (1977) pointed out that all magnetization directions in octahedrites appear to be preferentially associated with the octahedral (111) crystallographic plains. The NRM directions of 22 block samples of Bocaiuva are almost parallel to a dominant plane oo lamellar tetrataenite development of the (111) plain. DuBois (1965) studied the magnetic domain configurations of kamacite and schreibersite in Odessa (coarse octahedrite) and reached the conclusion that the NRM and the domain configuration are roughly related. However no obvious correlations between the domain configurations and the NRM directions are observed with Bocaiuva. These experimental results of NRM tends to support the assumption that tetrataenite is the NRM carrier for Bocaiuva.

The amount of kamacite is much higher than that of other magnetic minerals in Bocaiuva as shown in Fig. 7. On the surface of the kamacite the magnetic multi-domain structures appear clearly by Bitter pattern method. One would expect that kamacite should contribute to the NRM of Bocaiuva. However, it does not appear that the NRM from kamacite of the multidomain structures affects Bocaiuva strongly due to its good NRM stability.

Among the octahedrite meteorites having kamacite as main magnetic mineral, relatively stable NRM against AF demagnetization have been observed with Y-75031, Y-75105 and ALH-762 (Nagata, 1979), whereas their coercities are very small. As the former two meteorites have a small size, they probably acquired the stable TRM through the earth's atmosphere in presence of the geomagnetic field. ALH-7762 is however a relatively large meteorite and the measurements were effectued with samples obtained sufficiently away from its fusion crust, suggesting that they were not affected by heating through the passage in the earth's atmosphere. The samples of Bocaiuva weere extracted from inside of the meteorite and the NRM characteristics are very similar to that of ALH-762 meteorite. On the other hand, Toluca (medium octahedrite) has extremely unstable NRM, although it contains relatively large amount of tetrataenite as compared to Bocaiuva. These experimental evidences suggest that the contribution of kamacite to NRM differs among the octahedrite meteorites.

In case of Bocaiuva, the reason of the weak contribution of kamacite to NRM seems to be due to the fact that the NRM directions of kamacite magnetic domains are completely random, and consequently the integrated NRM is negligible as compared to that arising from tetrataenite.

Desnoyers et **al.** (1985) indicatd that Bocaiuva cooled rapidly from 1100^{o}C to the temperature where thee diffuson in the silicates is stopped, then it must cool down slowly up to 600^{o}C as indicated by the presence of

Widmanstatten patterns. From our magnetic and metallographical results, the existence of small amounts of tetrataenite phase in Bocaiuva suggest that this meteorite further cooled slowly under 300°C. Bocaiuva exhibit many Neumann bands in the kamacite field due to shocks produced by collisions of the meteorite. Original tetrataenite could be disordered by temperature increase due to these shock effects and subsequently reformed again by further cooling of the meteorite. Poor development of the tetrataenite phase may result by these type of events.

6 - CONCLUSIONS

Bocaiuva exhibit a very stable NRM against AF demagnetization, contrasting with low H_C and H_{RC} values. The NRM directions align to a plane related to the octahedrite structure. The NRM is broken down by thermal demagnetization at 550°C. Extremely strong NRM lamellae are observed by the Bitter pattern method but they disappear after heat treatment at 600°C. Extracted lamellae have large H_C and H_{RC} values and present a Curie point at 550°C; the coercivity decreases to small values and the Curie point disappears after heating at 600°C. This magnetic behavior is consistent with that of typical tetrataenite. Both EPMA and CMA analyses and the magnetic results indicate the presence of tetrataenite phase in high Ni (38wt%) lamellae. Probably fine tetrataenite exists in small amounts dispersed in kamacite domain walls besides some tetrataenite in lamellae. Tetrataenite could not be detected in previous Mossbauer results because of the overlapping with the much more intense lines of the spectrum of the Ni rich disordered taenite phase. One concludes from these results that Bocaiuva cooled down slowly around 300°C, producing the tetrataenite phase in the high Ni regions.

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FIGURE CAPTIONS

FIGURE 1

AF demagnetization curves of a bulk sample of Bocaiuva. (a) Zijderveld projection of NRM components. (b) the directional changes of NRM.

FIGURE 2

Thermal demagnetization curves of directions and intensities for 3 bulk samples. Sample (C): already demagnetized to 15mR before the thermal demagnetization. (D) and (E): original NRM.

FIGURE 3

Distribution of NRM directions for bulk samples before and after AF demagnetization to 15mT.

FIGURE 4

Thermomagnetic (I_S-T) curves of a bulk sample and an extracted sample by HCl obtained by 0.6T external magnetic field. Solid curves: 1st run I_S-T curves; Dotted curves: 2nd run I_S-T curves.

FIGURE 5

Silicate inclusions and Widmanstatten patterns of Bocaiuva taken by bright field (up) and dark field (down) microscope.

FIGURE 6

Features of strong NRM regions of Bocaiuva by Bitter pattern method. Scale:: m, K: kamacite, T: taenite, TT:

tetrataenite, M: magnetite. (a) and (b): configurations of mgnetic domains of kamacite ((a) bright and (b) dark fields). (c) and (d): configurations of magnetic domains taken under bright field (c) and dark field (d) of schreibersite. (e): extremely strong NRM lamellae (tetrataenite) and the NRM direction (arrow) of the sample. (f): branched out of extremely strong NRM twings (tetrataenite) into the kamacite field tthrough domain walls from tetrataenite lamella.

FIGURE 7

Elemental distribution patterns of Fe, Ni, P and on Bocaiuva by computer-aided microanalyzer (CMA).

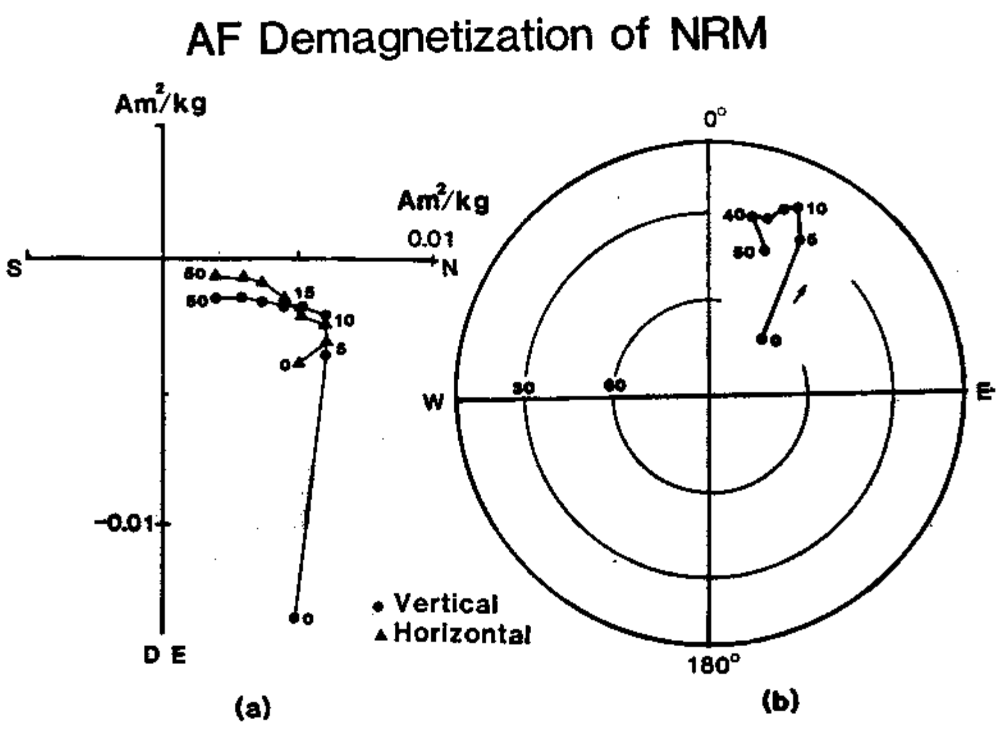
AF Demagnetization of NRM
Am²/kg
Am²/kg
0.01
S
N
-0.01
D E
50
50
15
10
5
0
0
• Vertical
▲ Horizontal
(a)
0°
40
10
50
5
0
W
30
60
E
180°
(b)

Fig. 1

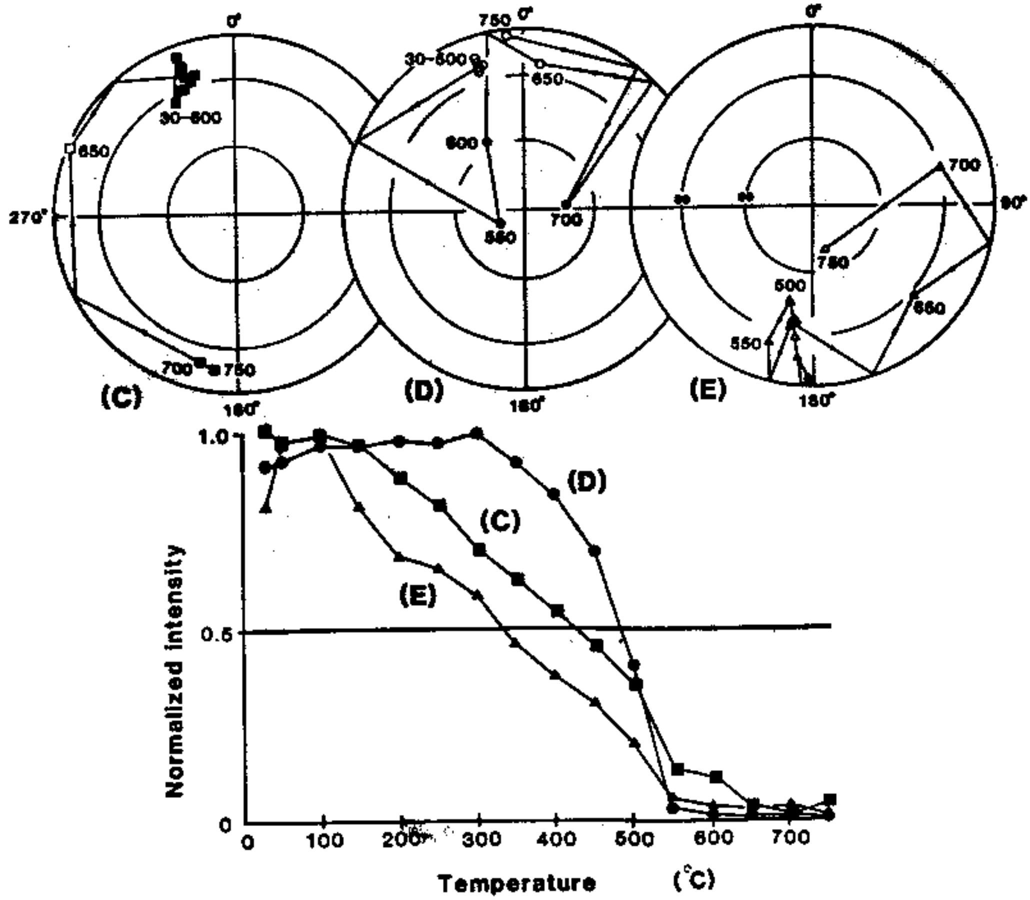
0°
270°
180°
30-600
650
700
750
(C)
750
0°
30-500
650
600
550
700
180°
(D)
0°
90°
700
750
500
550
650
180°
(E)
1.0
0.5
0
Normalized intensity
(D)
(C)
(E)
0
100
200
300
400
500
600
700
Temperature
(°C)

Fig. 2

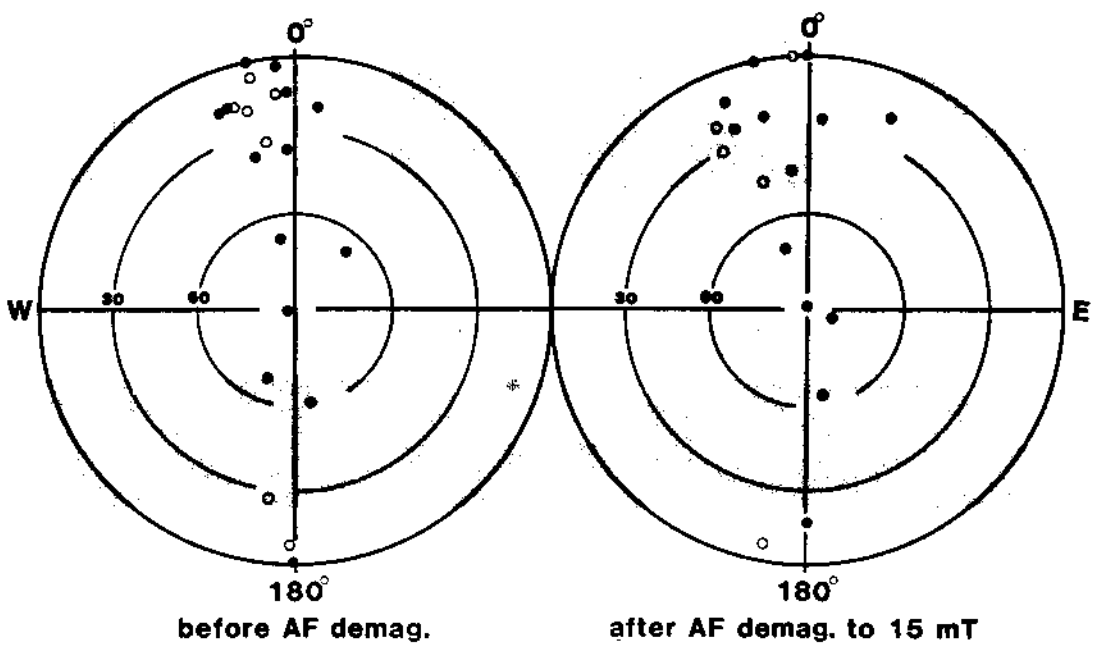

Fig. 3

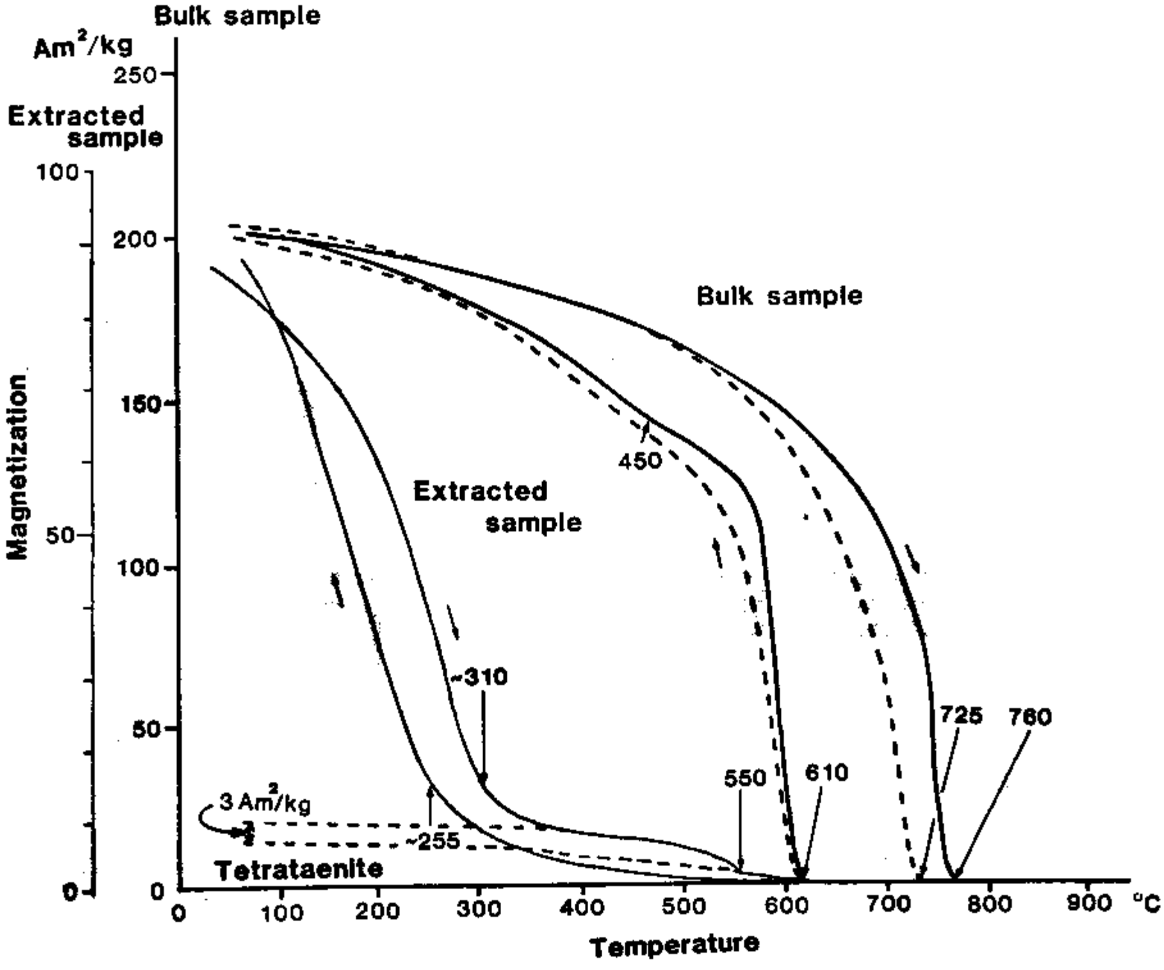
Bulk sample
Am²/kg
250
Extracted sample
100
200
150
50
100
50
0
0
Magnetization
Bulk sample
Extracted sample
450
~310
725
760
550
610
3 Am²/kg
~255
Tetrataenite
0
100
200
300
400
500
600
700
800
900
°C
Temperature

Fig. 4

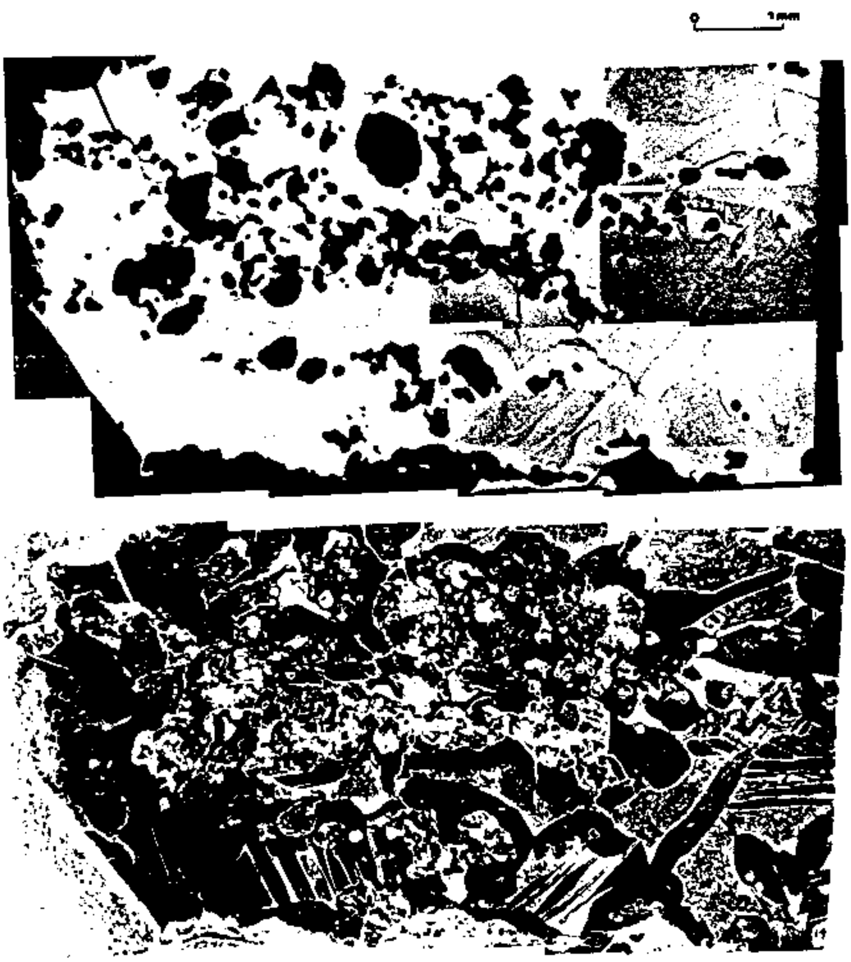

Fig. 5

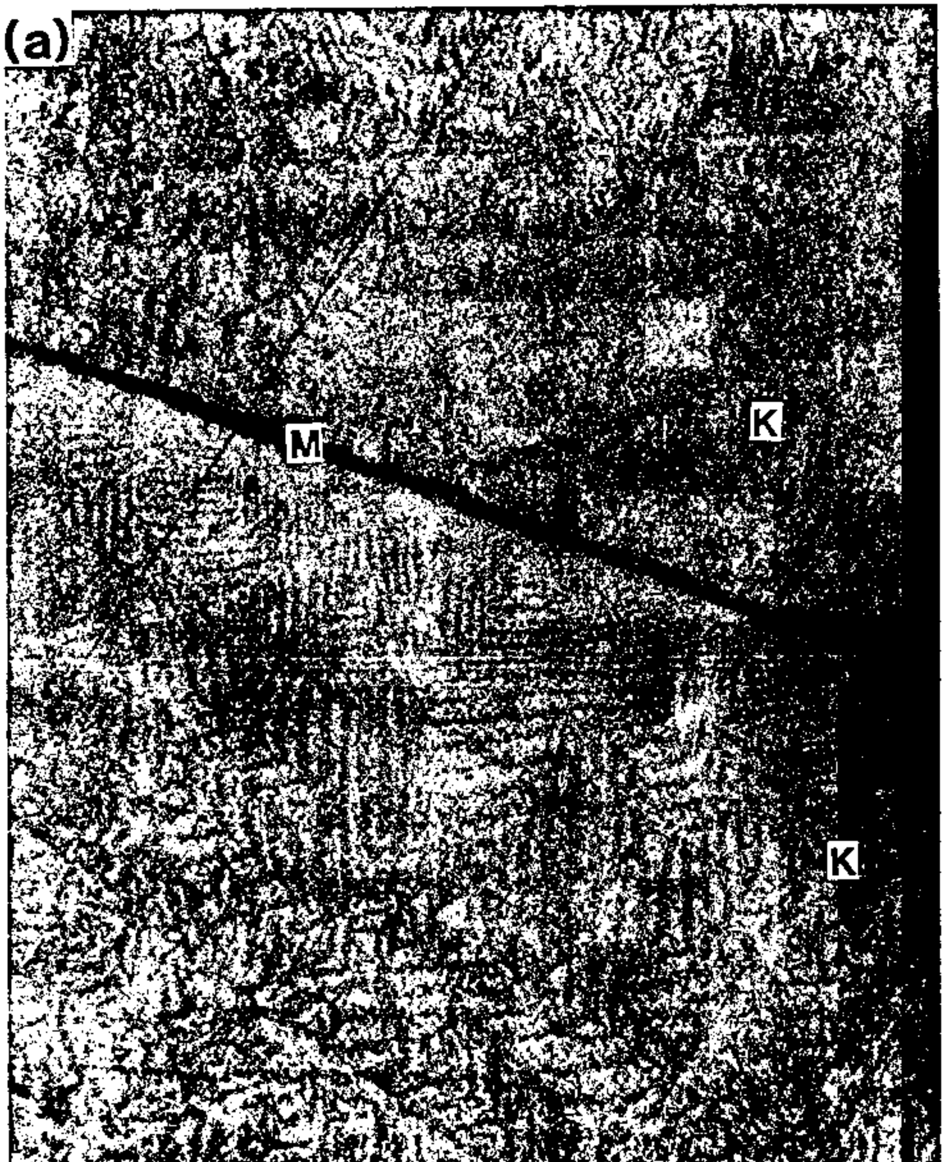

Fig. 6 (a)

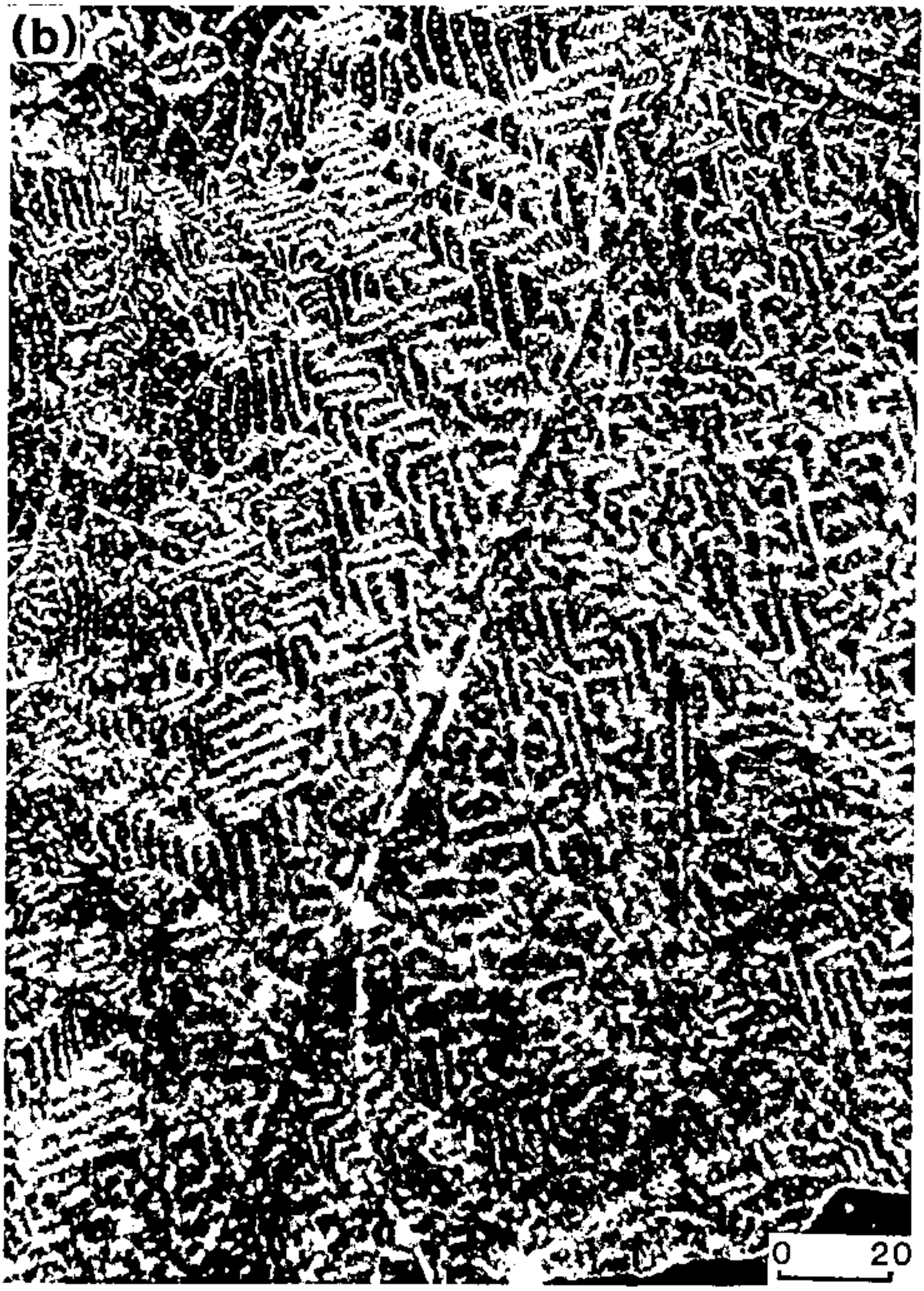

Fig. 6 (b)

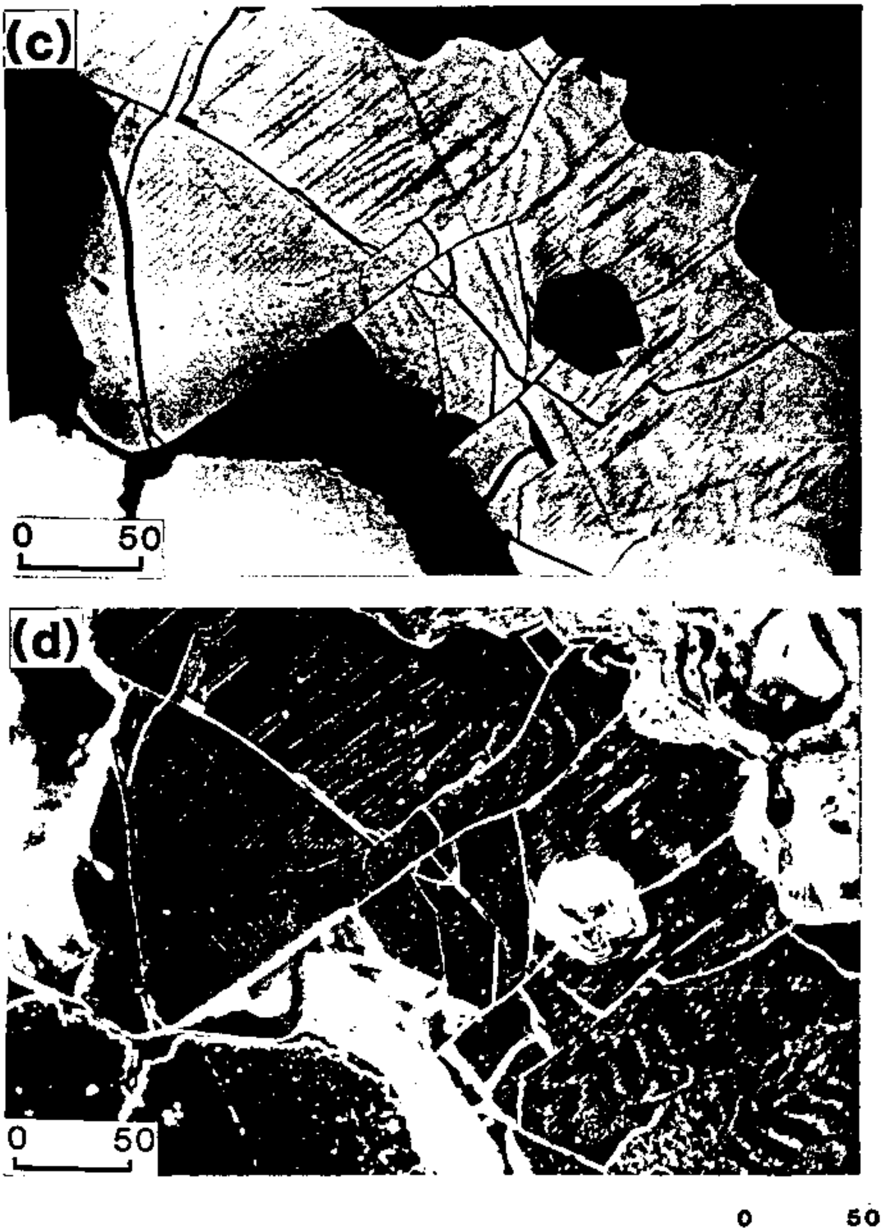

Fig. 6 (c)(up) and (d)(bottom)

Fig. 6 (e)

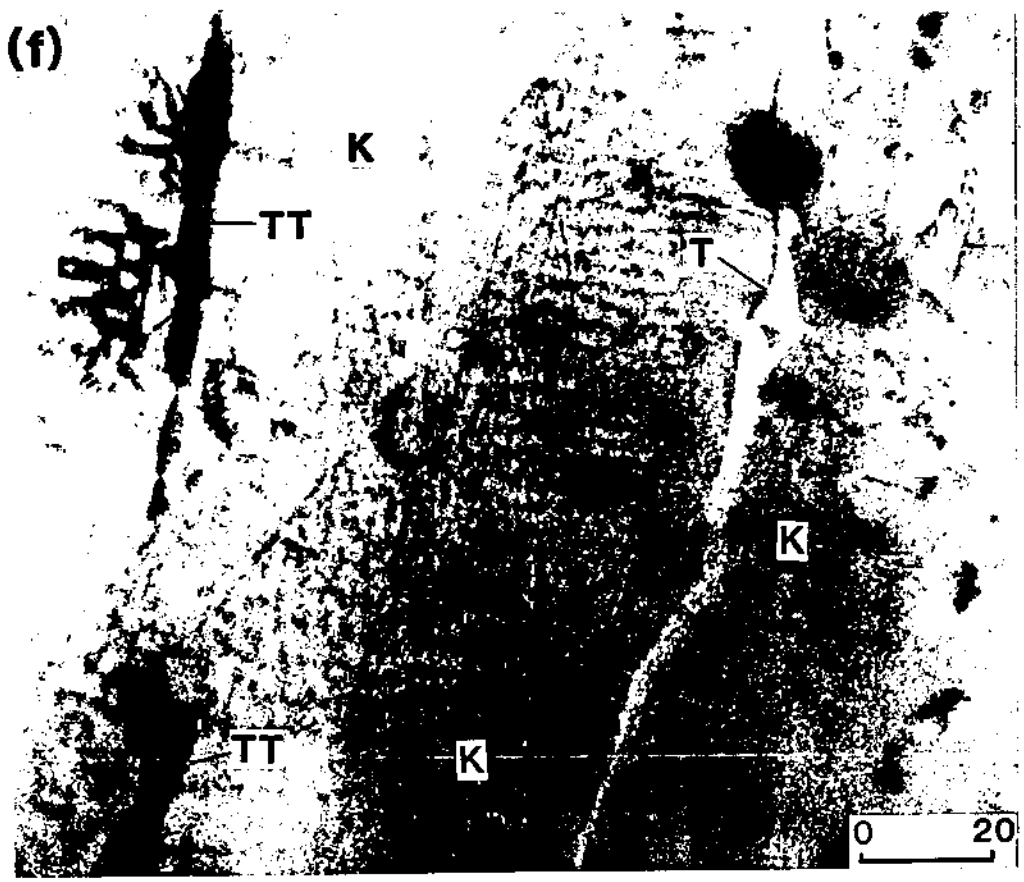

Fig. 6 (f)

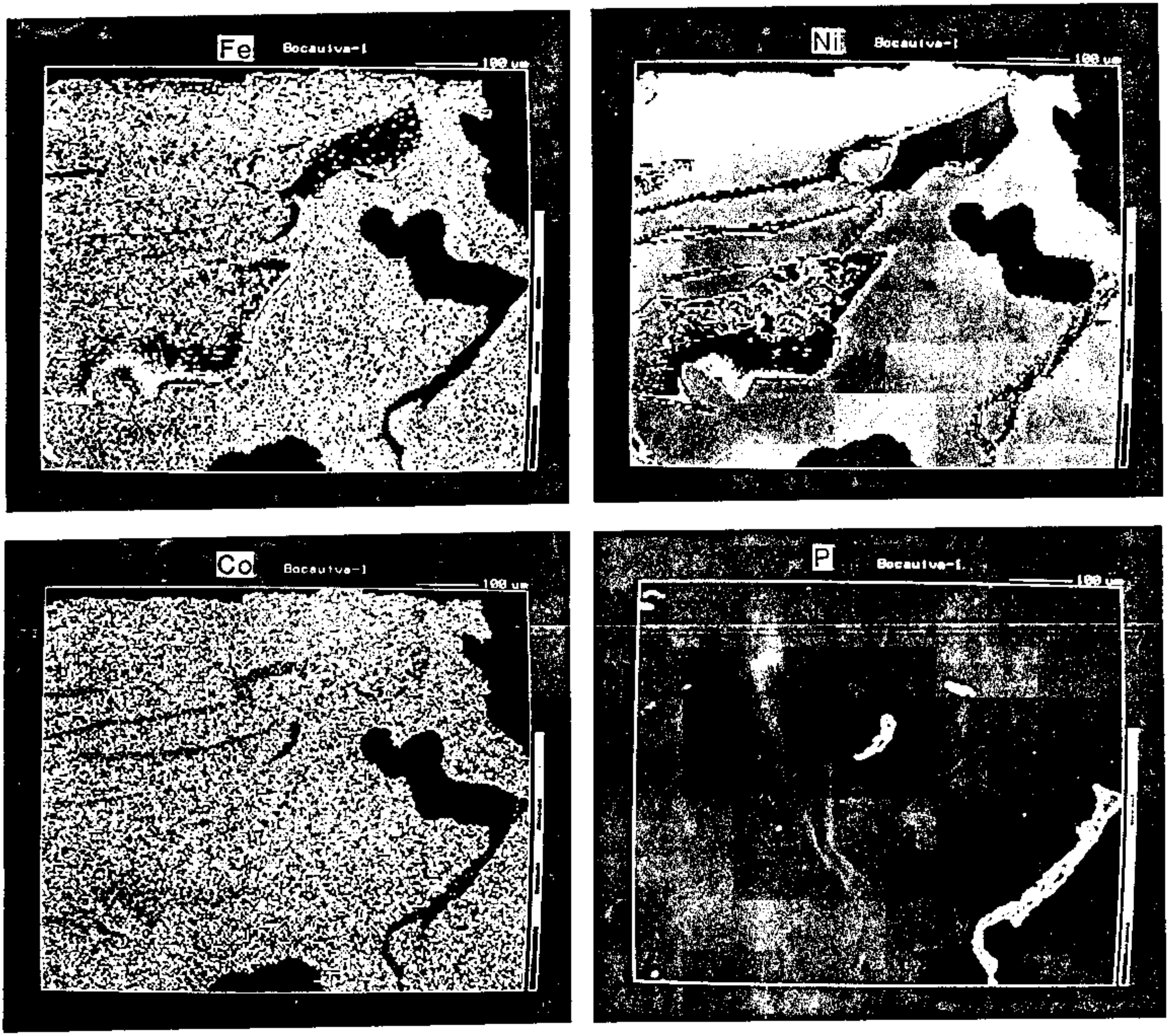
Fe
Bocaiuva-1
100 um
Ni
Bocaiuva-1
100 um
Co
Bocaiuva-1
100 um
P
Bocaiuva-1
100 um

Fig. 7

Table 1. Magnetic hysteresis properties and Curie Points of Bocaiuva.

Sample	Heating	I_S	I_R	H_C	H_{RC}	Tc heating	Tc cooling
		Am^2/kg	Am^2/kg	mT	mT	°C	°C
Bulk 1	before	205.5	0.5	4	<5	760	610 ~450
	after	209	0.02	1.5	<5	725	605
Bulk 2	before	201	0.035	2.5	<5	745	605
	after	212	0.04	1.0	<5	735	605
Lamella	before	87.5	1.5	23.5	66.7	310 550	255
	after	82.5	0.005	1.0	<5	290	260

Table 2. Chemical compositions of iron-nickel and schreibersite grains analyzed by EPMA. 1-12: this study. a-h: Desnoyers et al. (1985). (unit wt%)

No	Fe	Ni	Co	P	S	Cu	Zn	total
kamacite								
1	92.428	6.839	0.533	0.100	0.005			99.905
2	92.417	6.950	0.499	0.043	0.021			99.930
3	92.094	6.896	0.510	0.093	0.000			99.593
4	93.541	6.150	0.562	0.136	0.007			100.396
a	91.9	6.65	0.35	0.18		0.06	0.03	99.17
b	92.7	6.51	0.34	0.05		0.05	0.03	99.68
taenite lamellae								
5	81.454	17.482	0.334	0.042	0.001			99.314
6	81.163	17.935	0.332	0.009	0.018			99.456
7	78.023	21.158	0.349	0.016	0.030			99.576
c	81.2	17.6	0.14	0.02		0.28	0.03	99.27
8	61.043	37.613	0.142	0.021	0.010			98.828
plessite								
9	86.566	11.874	0.419	0.048	0.013			98.920
10	86.526	12.175	0.404	0.024	0.005			99.133
schreibersite								
11	59.816	24.968	0.192	15.808	0.070			100.854
12	55.232	28.437	0.190	15.584	0.084			99.528
d	61.0	22.2	0.07	15.3	0.08	0.14	0.74	99.53
e	56.6	26.9	0.05	15.5	0.06	0.12	0.74	99.97
f	54.3	29.0	0.04	15.5	0.07	0.15	0.72	99.78
g	52.0	31.5	0.04	15.5	0.06	0.13	0.73	99.96
h	43.8	39.5	0.03	15.4	0.06	0.15	0.72	99.66

Table 3. Element concentrations and their occupied areas.

		Fe		Ni		Co		P	
	color	conc.	area	conc.	area	conc.	area	conc.	area
		wt%	%	wt%	%	wt%	%	wt%	%
Field 1	white	95.0	0.00	35.0	0.11	1.0	0.01	18.0	0.00
	pink	95.0	48.57	35.0	0.63	1.0	0.89	18.0	0.01
	red	90.0	27.33	30.0	3.53	0.8	24.11	16.0	0.50
	yellow	85.0	5.45	22.0	4.64	0.6	32.25	14.0	0.63
	green	80.0	3.02	15.0	11.21	0.5	19.44	12.0	0.63
	sky-blue	75.0	1.84	8.0	67.66	0.4	7.73	8.0	0.60
	blue	70.0	2.74	5.0	1.97	0.3	3.08	3.0	0.59
	black	50.0	11.06	2.0	10.25	0.2	12.49	0.5	97.06
	total	79.0710		7.5419		0.4548		0.3137	
Field 2	white	95.0	0.01	35.0	0.00	1.0	0.00	18.0	0.02
	pink	95.0	34.18	35.0	0.29	1.0	1.31	18.0	1.22
	red	90.0	7.46	30.0	7.17	0.8	19.21	16.0	10.64
	yellow	85.0	0.60	22.0	11.15	0.6	14.39	14.0	3.86
	green	80.0	0.53	15.0	1.83	0.5	7.54	12.0	2.75
	sky-blue	75.0	0.46	8.0	35.29	0.4	2.85	8.0	1.94
	blue	70.0	19.28	5.0	8.73	0.3	6.95	3.0	2.61
	black	50.0	37.48	2.0	35.54	0.2	47.75	0.5	76.97
	total	53.1934		6.6292		0.2404		2.7573	

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