THERMOMAGNETIC ANALYSIS OF METEORITES, 2: C2 CHONDRITES

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ABSTRACT

Samples of all eighteen of the known C2 chondrites have been analyzed thermomagnetically. For eleven of these, initial Fe_3O_4 content is low (generally <1%) and the J_s-T curves are irreversible. The heating curves show variable and erratic behavior, whereas the cooling curves appear to be that of Fe_3O_4. The saturation moment after cooling is greater (up to 10 times larger) than it is initially. This behavior is interpreted to be the result of the production of magnetite from a thermally unstable phase--apparently FeS. Four of the remaining 7 C2 chondrites contain Fe_3O_4 as the only significant magnetic phase: initial magnetite contents range from 4 to 13 percent. The remaining three C2 chondrites contain iron or nickel-iron in addition to Fe_3O_4. These seven C2 chondrites show little evidence of the breakdown of a thermally unstable phase.

1. INTRODUCTION

In part I of this series [1], saturation magnetization vs temperature (J_s-T) analyses were reported for samples of the five known C1 chondrites.* Magnetite was found to be the only magnetic phase in four of the meteorites, and was the dominant phase in the other . This paper presents the results of similar analysis on all eighteen (18) of the C2 chondrites.

The apparatus used to measure saturation moment vs temperature is the same as that described in detail by Larson, et al. [3]. The system consists prinicpally of a Cahn electrobalance, a furnace capable of attaining 900°C, and a movable 2,500-oersted permanent magnet. To minimize oxidation-reduction reactions that might occur during the experiment, H_2 and CO_2 gases are flowed past the sample: the oxygen fugacity at any moment can be monitored by measurement of the electrical potential developed across a solid-state ceramic electrolyte (yttria-doped zirconia) that is positioned adjacent to the sample. Typically, heatings to and coolings from 600°C and 800°C take about 20 and 30 minutes, respectively.

2. RESULTS AND DISCUSSION

On the basis of their thermomagnetic behavior the C2 chondrites can be divided into three groups: (A) those containing little, if any, magnetite initially, (B) those containing magnetite as the only major magnetic component (similar to the C1 chondrites), and (C) those whose thermomagnetic behavior cannot be classified within the first two groups. The number of C2 chondrites in each group is 11, 4, and 3, respectively.

Group A - In Figs. 1 and 2 are presented the saturation magnetization versus temperature (J_s-T) curves for the C2 chondrites in the first group. The most striking aspect of the J_s-T curves of all samples in this group is their

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*As in Part I, we employ the classification scheme for chondrites of Van Schmus and Wood [2].

irreversibility. The saturation moment after the experiment is generally three to four times as large as it was initially; in the case of Murchison it is about 10 times larger at the end of the experiment. The distinctive Curie temperature of about 550 to 580°C and the generally blocky shape of the cooling curves is indicative of essentially pure Fe_3O_4. It appears that magnetite was produced by the breakdown of some non-magnetic phase during the course of the experiment. Alteration of the phase begins generally when a temperature of 300 to 350°C has been reached but in the case of Murchison it starts at about 250°C. It appears that the initial product is not pure magnetite but rather an intermediate phase with a variable Curie temperature which is less than 580°C. If heating is slow, it is possible by the time the temperature has reached 400 to 500°C for the saturation moment to have increased above the initial value. Continued heating, however, causes J_s to fall as the intermediate Curie temperatures are exceeded. If heating is slowed at any temperature above that at which alteration of the phase begins, the J_s will begin to rise. The heating curves of Group A samples, therefore, are quite variable, such that no two heating curves, even from the same sample, are the same. The particular shape of any one curve is primarily a function of the heating rate, and amount and grain size of the unstable phase.

The Cold Bokkeveld sample (Fig.1) and one Pollen sample (Fig. 1) were subjected to reheatings to help evaluate the extent of alteration. Although some additional magnetite was produced during the second heating, it can be seen from the J_s-T curves for these two samples that most of the alteration occurred during the first heating.

The J_s-T curves of the Crescent sample (Fig. 2) and a second sample of the Pollen meteorite (Fig. 2) show the presence of an additional magnetic component which becomes non-ferromagnetic at about 770°C. There is no lag in

magnetization reacquisition upon cooling from 800°C down to the 580°C Curie temperature of magnetite. The loss of magnetization at 770°C and the lack of a lag during reacquisition are indicative of essentially nickel-free iron. Data we have obtained from measurement of synthetic alloys of known Ni-Fe composition indicate that this behavior is restricted to iron containing less than 2 percent nickel.

The increase in J_s from magnetite production was most prominent in Murchison (Fig. 1). In an extensive study of the chemistry and mineralogy of the Murchison C2 chondrite, Fuchs, et al. [4] report the presence of three components, any one of which could be the "unstable" phase that alters to magnetite: (1) a layer-lattice silicate, (2) a weakly magnetic, "poorly characterized" Fe-S-O phase or, (3) troilite disseminated in a finely divided state throughout the matrix. For investigation of these alternatives, Dr. Edward Olsen kindly provided us with sample material from a large xenolithic "C3 inclusion" from Murchison. Fuchs, et al. [4] report that this material is rich in nickel-iron sulfides, but contains neither layer-lattice silicate nor "poorly characterized" Fe-S-O phase. The J_s-T curve obtained for the "C3 inclusion" (see Fig. 3) is very similar to the Murchison curve (Fig. 1) and quite similar to the "typical " curve of Group A. This strongly suggests (but does not prove) that the unstable phase is troilite.

To further verify that the observed magnetite production is characteristic of troilite, we ran J_s-T curves on samples of that mineral removed from the Staunton iron meteorite. One sample was run in a mixed-gas atmosphere and another was run in a vacuum of about 4×10^{-4} torr. The troilite did break down to produce Fe_3O_4 in both cases and the J_2-T curves, as shown in Fig. 3, are very similar. We pulverized the troilite to see if the breakdown was grain-size dependent. As the grain size was progressively reduced, the breakdown

began at progressively lower temperatures and the rate of alteration increased accordingly. The finest-ground material (μ) began to decompose at about 150°C.

The J_s-T curves for pure troilite are virtually identical to those obtained from the eleven C2 chondrites (see Figs. 1 and 2). The fact that magnetite was produced even when troilite was heated under partial vacuum indicates that the reaction involved is probably oxidation   and not a gas-phase reaction peculiar to the gases in our system.

Banerjee and Hargraves [5] also observed the production of magnetite in a Murchison sample during heating under vacuum; and earlier, Stacey, et al. [6] noted that FeS broke down to magnetite during heating of chondrites. However, the latter's samples were dominated by the presence of iron so that the formation of magnetite created little effect.

Troilite is essentially ubiquitous in chondritic meteorites (except in the C1 chondrites): its presence most likely accounts for the irreversible behavior of the J_s-T curves during heating which we have found so common in C2 chondrites. We have also observed this phenomenon in the C3 and in unequilibrated and ordinary chondrites as well (data on the C3 and C4 chondrites will be presented in Part III of this series). In their discussion of the alternative possibilities which could account for the magnetite production, Fuchs, et al. [4] point out that their samples of the layer-lattice silicate phase from Murchison were black in color; they suggested that this might be due to the presence of finely divided troilite. They further noted that during heating, magnetite was produced (as determined by x-ray studies) at temperatures below the break-down temperature of the layer-lattice silicate phase. It seems likely then, that formation of magnetite, as indicated by their thermal studies, actually resulted from the alteration of troilite. Perhaps the "poorly characterized" Fe-S-O phase observed by Fuchs, et al. [4] represents an intermediate stage of the progressive oxidation

of troilite, similar   in nature to the intermediate alteration
phases that we observed forming during the heating of many C2 chondrites.

Because the shapes of the initial heating curves for those meteorites shown
in Figs. 1 and 2 are not like those expected for samples containing magnetite
(see, for example [1] and Fig. 4) we qualitatively estimate that the magnetite
content of these meteorites is initially quite low. If we assume that the
initial saturation magnetization is due entirely to magnetite, however, we can
determine an upper limit of magnetite content. The upper-limit weight-percent
Fe_3O_4 values thusly determined are shown in Table 1. With the exception of
Boriskino and Mighei (Fig. 1) which were measured as whole pieces, the meteorite
samples were gently crushed to <100 mesh and measured as aliquots of 50-200 mg.
Care was taken in this homogenization procedure not to subject the material to
undue mechanical stress so as to minimize the possibility of maghemite produc-
tion or physical alteration of the sulfide phases. Error estimates represent
analytical uncertainty based on deviations observed in measuring a high purity
standard of known content. The actual magnetite content of the C2 chondrites
shown in Table 1 is probably much lower than our upper limit determination.
Fuchs, et al. [4] report that magnetite is present in the Murchison meteorite
in trace amounts only. Our data indicate that certainly it can be no greater
than 0.75 percent, on the average.

In the above discussion we have assumed (from the Curie temperature of
-580°C) that essentially pure magnetite was produced in the Group A C2 chondrites
during the heating experiments. During analysis of the Allende C3 chondrite
Butler [7] performed thermomagnetic experiments and obtained results not unlike
those we have just described. However, he suggested that the increase in
saturation magnetization observed during heating and the resultant Curie tempera-
ture near 580°C were due to a rather complicated "high temperature homogeniza-
tion" of Ni-Fe alloys. To evaluate Butler's suggestion we have performed

reduction experiments in our thermomagnetic balance system on selected chondrites. For instance, the "C3 inclusion" from Murchison which was run initially in an oxygen fugacity in the magnetite stability range was, after cooling, reheated to 700°C and held in a reducing atmosphere (in the iron stability field) for about 15 minutes. The dashed curve above 600°C on Fig. 3d shows the high-temperature portion of the J_s-T analysis following reduction. After reduction a component exists which previously was not present in the sample. From the high Curie point and lack of $\gamma \rightarrow \alpha$ transition, it is estimated to be Fe with less than 2 percent Ni. It appears almost conclusively that the change of a material with a Curie temperature of 580°C to one with a reversible Curie temperature of 770°C is indicative of pure Fe_3O_4 being reduced to pure Fe. Reduction experiments performed on other Group A C2 chondrites are similar to this result.

Group B - The J_s-T curves for the four Group B C2 chondrites are shown in Fig. 4. They are similar to those obtained from C1 chondrites [1] in that for each sample, magnetite is the major magnetic component--as indicated by the Curie temperature (~580°C) and the blocky character of the J_s-T curves. The slight increase observed in saturation magnetization during cooling for the Essebi and Mokoia samples is similar to that which we observed for the Revelstoke C1 chondrite [1] and is suggestive of the behavior noted for the eleven Group A C2 chondrites shown in Figs. 1 and 2. It appears to be related to the breakdown of a small amount of troilite to magnetite during the experiment.

We have made estimates of the magnetite content of these meteorites from room-temperature saturation-magnetization measurements. As with the other C2 chondrites, determinations were made on aliquots taken from gently crushed 50 to 200 mg samples; the results obtained from these measurements are shown in Table 2. The reported error is analytical only and does not reflect sample inhomogeneity or the possible contribution from magnetic pyrrhotite, if present.

In its most magnetic stoichiometry, pyrrohtite is only about one-fifth as magnetic as magnetite. If pyrrhotite was present in large quantities, we would expect to see it expressed (Curie temperature ~350°C) in the J_s-T curves: it is not in evidence.

The Bells, Essebi, Kaba, and Mokoia meteorites have magnetite contents comparable to the values obtained by us for C1 chondrites [1]. The magnetite content of the Group B C2 meteorites ranges from about 4 to 13 weight percent and averages about 9.6 weight percent. Although the bulk chemical composition of Group A and Group B C2 chondrites is quite similar [8-10], the magnetite content varies appreciably. This suggests similarly diverse minerologies, and hence, different formative conditions.

Group C - The J_s-T curves for the Group C C2 chondrites are shown in Fig. 5. We suspect that the Al Rais, Haripura, and Renazzo meteorites are inhomogeneous and therefore that the J_s-T curves given in Fig. 5 may not necessarily be representative of these meteorites as a whole. Due to the high saturation magnetization of metallic iron and the extreme sensitivity of our system, we were constrained to use very small samples (less than 1 mg) of those meteorites, such as Renazzo, which generally contain abundant metallic iron. This practice, of course, accounts for dissimilar results obtained from two samples of the same meteorite, if that meteorite is inhomogeneous. It is also probable that the inhomogeneity observed in the samples of Al Rais and Haripura is the combined result of larger grain sizes in these than in other C2 meteorites and the small size of the samples measured.

The J_s-T curve for one sample of Al Rais (Fig. 5a) is indicative of a single magnetic component--metallic iron containing some nickel. From the particular temperatures at which magnetism is lost on heating and regained during cooling, the content of Ni can be estimated to be about 6 weight percent.

A second sample of Al Rais (Fig. 5b) appears to contain only pure magnetite. In neither case is there any evidence of troilite.

With one exception, all samples of Renazzo yielded J_s-T curves similar to that shown in Fig. 5c, indicating metallic Fe of low nickel content (less than 2%). The lone exception (shown in Fig. 5d) is typical of behavior observed in Group A C2 chondrites (sse Figs. 1 and 2), that is, the increase in J_s probably represents the alteration of troilite to magnetite.

ACKNOWLEDGEMENTS

Table 1: Upper Limit Determination of the Magnetite Content of Some C2 Chondrites.

Upper Limit for Wt. % Fe_3O_4		Sample Weight (mg)
BORISKINO*		
<0.86 ± 0.05**		0.20
<0.82 ± 0.05		2.27
weighted average	≤ 0.82 ± 0.04	
COLD BOKKEVELD		
≤ 0.60 ± 0.04		0.46
≤ 0.59 ± 0.04		0.47
≤ 0.45 ± 0.03		4.05
weighted average	≤ 0.48 ± 0.03	
ERAKOT		
≤ 0.36 ± 0.02		2.92
≤ 0.34 ± 0.02		2.59
weighted average	≤ 0.35 ± 0.02	
MIGHEI*		
≤ 0.33 ± 0.02		1.53
MURCHISON		
≤ 1.43 ± 0.04		0.39
≤ 1.16 ± 0.07		0.74
≤ 0.23 ± 0.01		1.10
weighted average	≤ 0.75 ± 0.04	
MURRAY		
≤ 0.64 ± 0.04		1.96
≤ 0.57 ± 0.03		3.36
weighted average	≤ 0.60 ± 0.04	
NAWAPALI		
≤ 0.40 ± 0.02		5.84
≤ 0.59 ± 0.04		2.53
weighted average	≤ 0.46 ± 0.03	

Table 1: (Continued)

Upper Limit for   Sample Weight (mg)
Wt. % Fe_3O_4

NOGOYA

$\leq$ 0.68 ± 0.04   1.78
$\leq$ 0.62 ± 0.04   1.08

weighted average $\leq$ 0.66 ± 0.04 %

SANTA CRUZ

$\leq$ 0.82 ± 0.05   2.80
$\leq$ 0.73 ± 0.04   0.83

weighted average $\leq$ 0.80 ± 0.05

* Run on whole samples

** Error is analytical only and does not include any attempt to evaluate
   sample inhomogeneity.

Table 2 . Magnetite Content of the Bells, Essebi, Kaba and Mokoia C2 Chondrites.

Wt. % Fe_3O_4		Sample Weight (mg)
BELLS		
13.29 ± 0.80*		3.93
13.30 ± 0.80		2.60
13.76 ± 0.83		0.88
. average	13.5 ± 0.8	
weighted average	13.4 ± 0.8	
ESSEBI		
7.70 ± 0.46		0.34
9.80 ± 0.60		0.82
9.18 ± 0.55		1.10
8.76 ± 0.53		0.55
10.64 ± 0.64		0.55
average	9.2 ± 0.6	
weighted average	9.4 ± 0.6	
KABA		
11.17 ± 0.67		5.62
11.50 ± 0.69		4.25
average	11.3 ± 0.7	
weighted average	11.3 ± 0.7	
MOKOIA		
4.18 ± 0.25		4.98
3.99 ± 0.24		4.49
4.20 ± 0.25		4.44
average	4.1 ± 0.3	
weighted average	4.1 ± 0.3	

*Error is analytical only and does not include any attempt to evaluate sample inhomogeneity.

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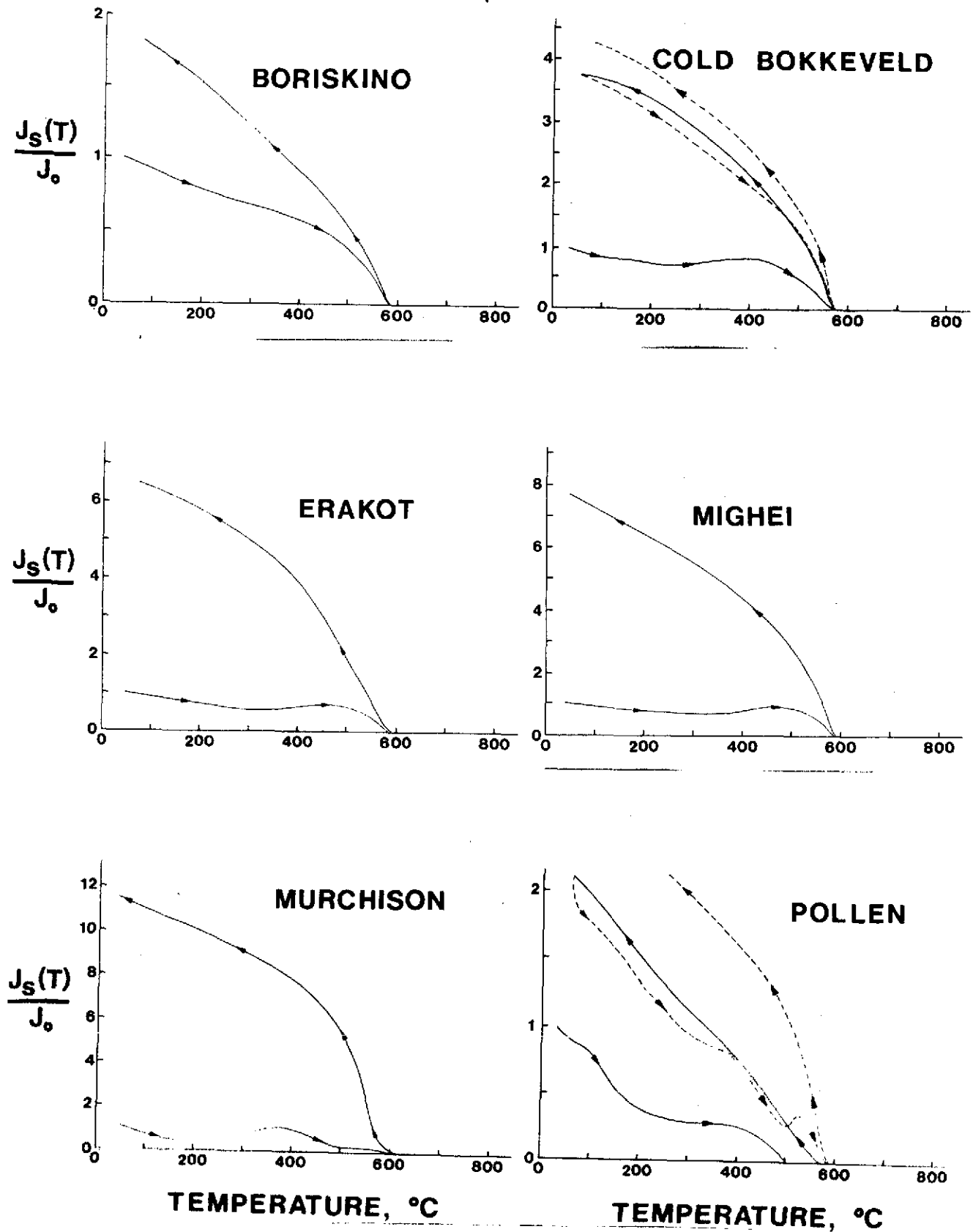[10] B. Mason, Meteoritics 6 (1971) 59.

Fig. 1: Saturation magnetization vs. temperature (J_s-T curves for six C2 chondrites. Note the large increase in magnetization as the samples cool, indicative of magnetite production. Both Cold Bokkeveld and Pollen were subject to two heating-cooling cycles (broken curves). Apparently one cycle is not adequate to allow complete production of magnetite. Eleven of the eighteen C2 chondrites show production of magnetite upon heating(see also Fig. 2).
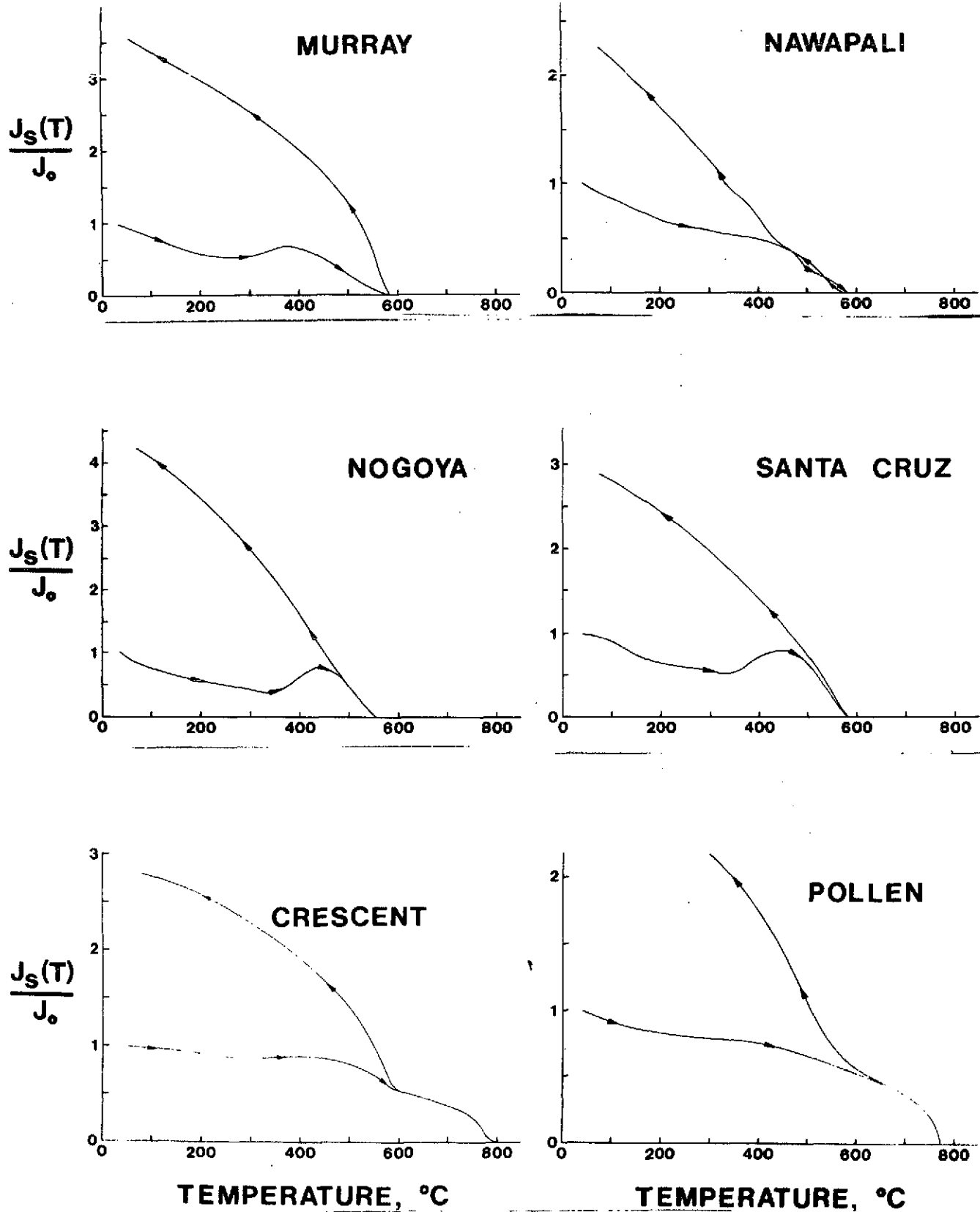
Fig. 2: Saturation magnetization vs. temperature (J_s-T) curves for six
C2 chondrites. See caption on Fig. 1. Both Crescent and Pollen
show evidence of low Ni iron as evidenced by the higher Curie
point (~770°C). Note that while the Pollen sample illustrated
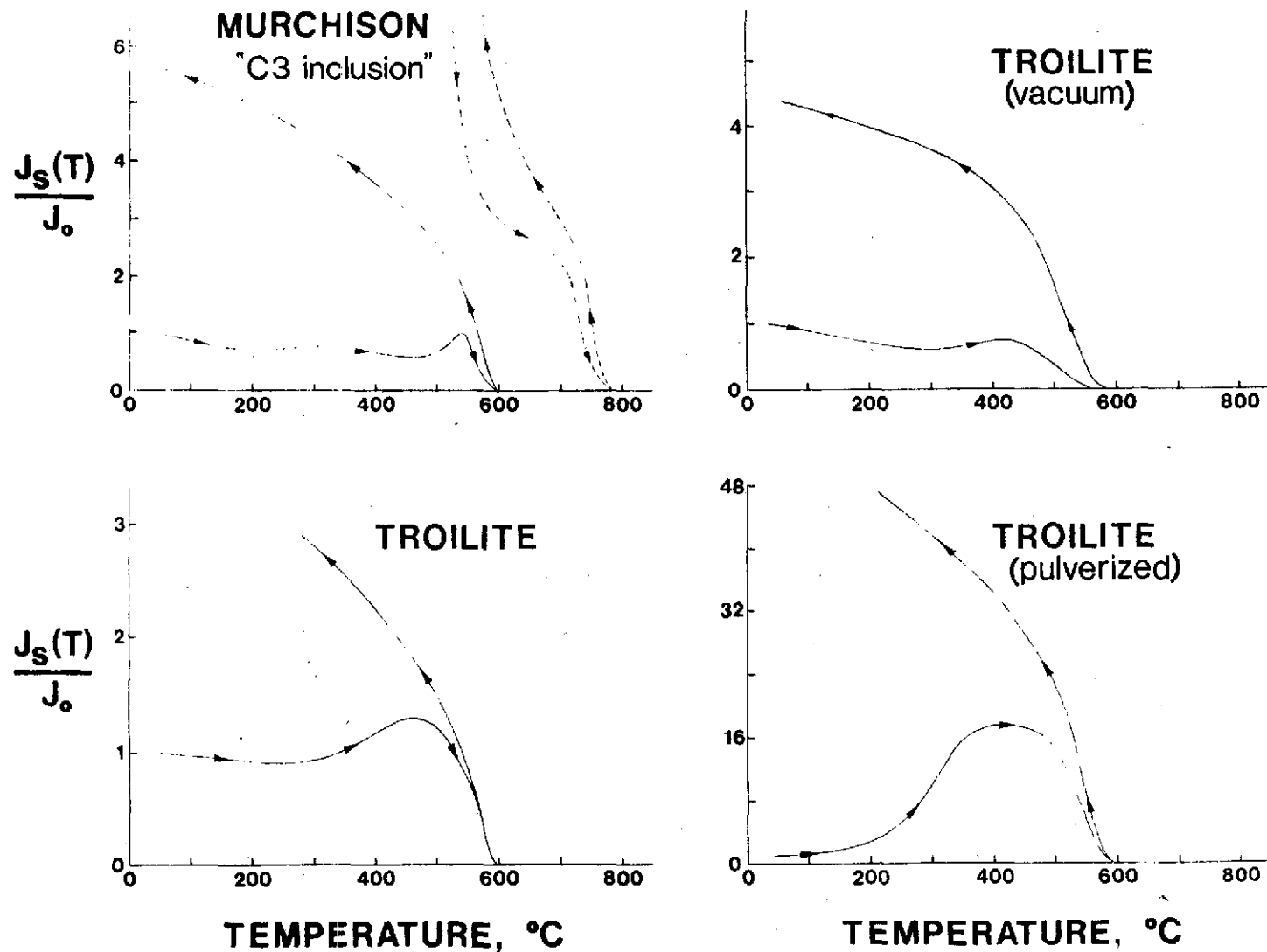in Fig. 1 contains no iron, both samples show magnetite production.

Fig. 3: Saturation magnetization vs. temperature (J_s-T) curves for a
C3 chondritic inclusion from the Murchison C2 chondrite and for
troilite. The troilite was run both with our gas atmosphere
(H_2 + CO_2 in N_2 carrier; see [1&3]) and under vacuum (~10^{-4} torr).
The high temperature portion(broken curve) for the
"C3 inclusion" was the result after intentionally reducing the
magnetite to iron. Since no lag in reacquisition was observed,
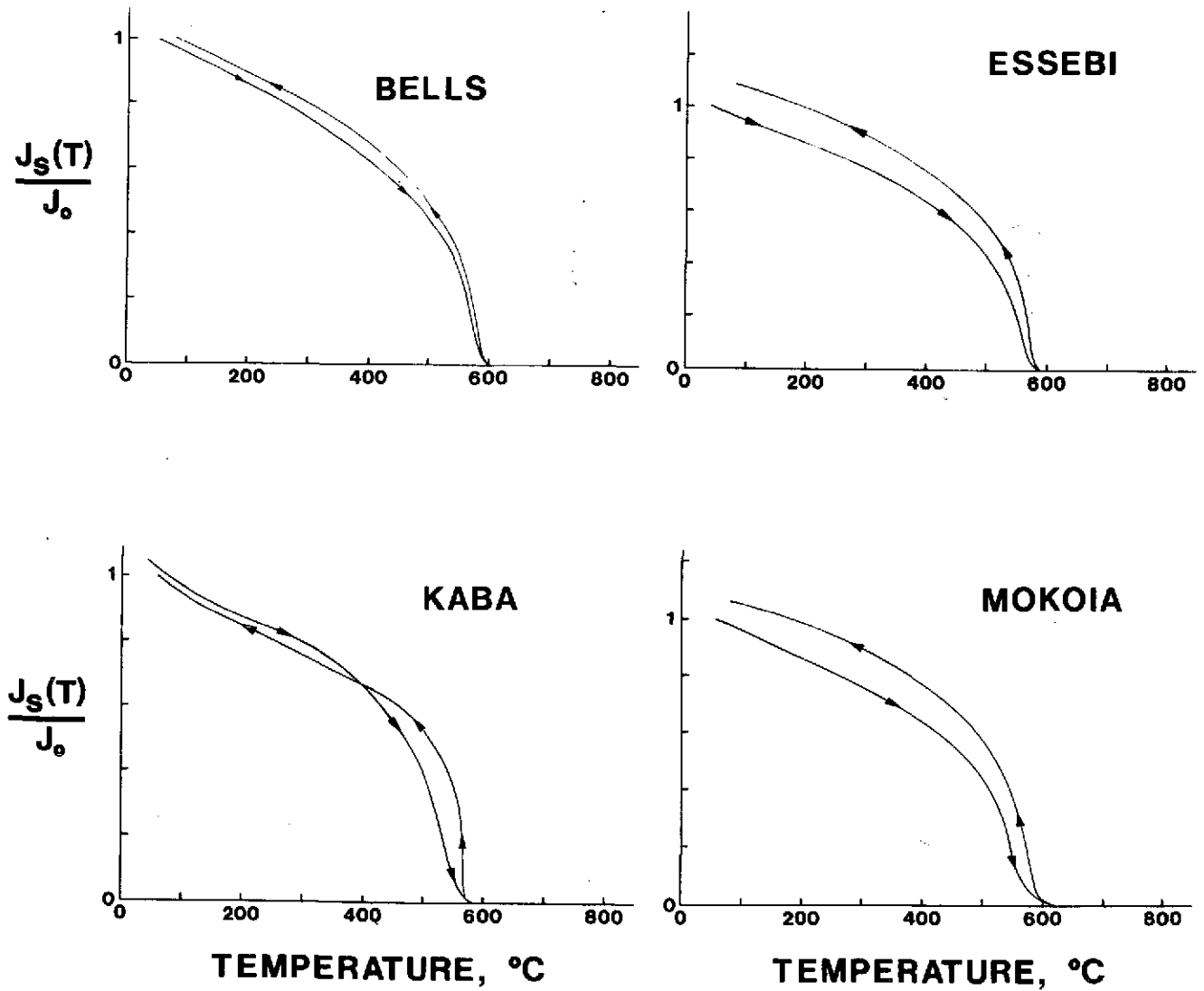the iron is of low Ni content ($\leq$ 2%).

Fig. 4: Saturation magnetization vs. temperature (J_s-T) curves for four C2 chondrites. Magnetite is quite dominant. Only minor magnetite production is indicated (Essebi and Mokoia) in contrast to Figs. 1, 2, and 3.
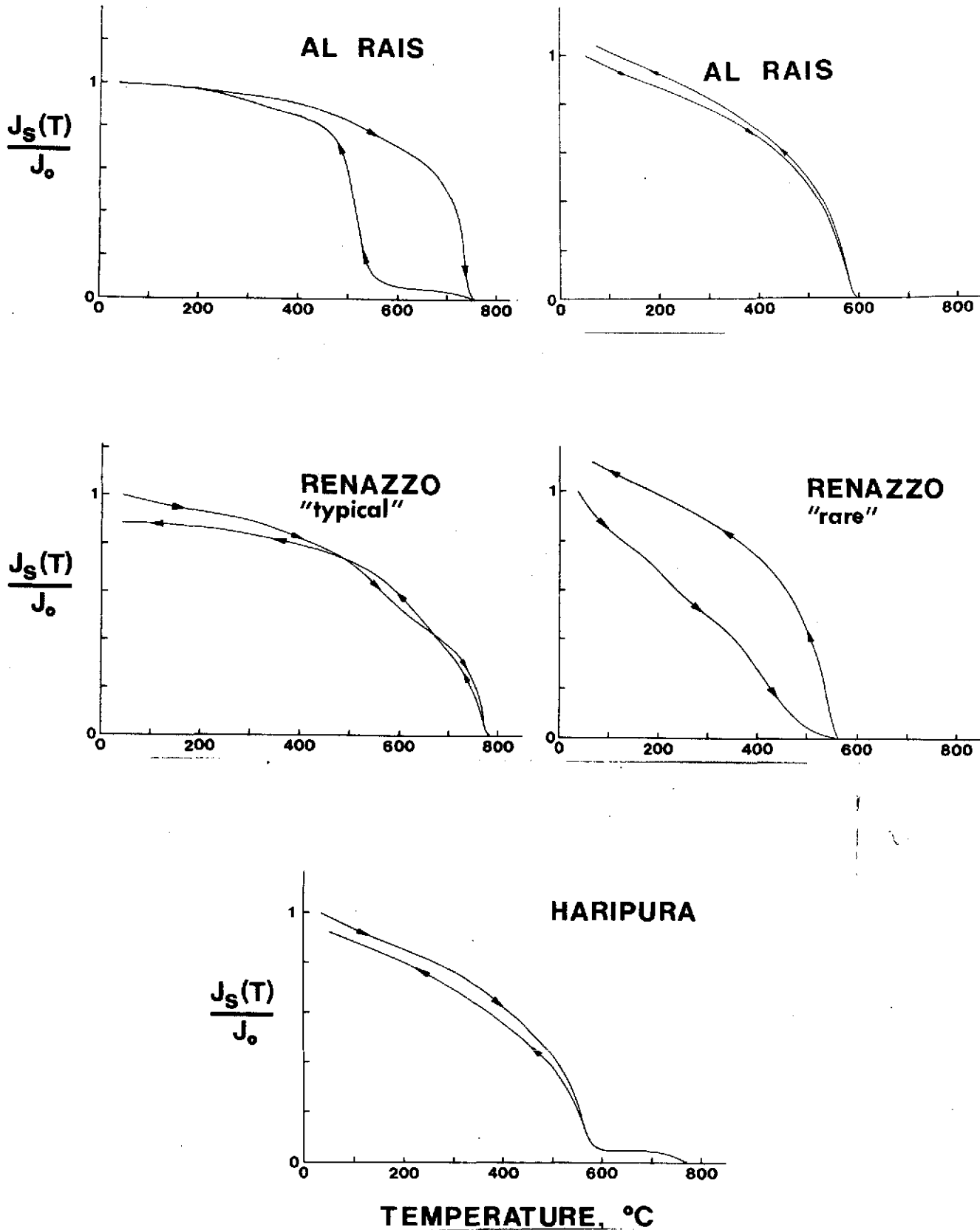
Fig. 5: Saturation magnetization vs. temperature (J_s-T) curves for the remaining three C2 chondrites. Neither of the Al Rais samples show significant evidence of magnetite production. The first Al Rais sample contains Ni-Fe, while the second contains magnetite only. The first sample of Renazzo is typical of many samples of Renazzo we ran and shows iron only ($\leq$ 2% Ni) with no evidence of magnetite production. One rare sample, however, seemed to contain a material with a Curie point < 580°C and showed magnetite production. Haripura contained primarily magnetite with a small amount of low Ni iron.