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THERMOMAGNETIC ANALYSIS OF METEORITES, 3. C3 and C4 CHONDRITES

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Abstract - Thermomagnetic analysis on all of the C3 and C4 chondrites, conducted under conditions of controlled oxygen fugacity, indicates the presence of a thermally unstable component in at least 5 of the C3 chondrites which upon heating results in magnetite production. This unstable component is most likely troilite (FeS). The presence of the unstable substance may affect the estimation of paleointensities in meteorites which contain it. Our results indicate that Grosnaja, Ornans, Kainsaz, Felix, and Warrenton are likely to be less complicated for paleointensity determinations than the other C3 chondrites. Both C4 chondrites should lead to reliable results.

1. INTRODUCTION

This paper is the third in a series of reports of our saturation magnetization vs. temperature (Js-T) analyses of samples of all the known carbonaceous chondrites. We reported the results of our studies on samples of the five C1 chondrites* in part 1 of this series [1]. The dominant magnetic phase observed in the C1 chondrites was magnetic, for which we obtained quantitative estimates ranging from 5 to 12 wt.% Fe_3O_4 for those five meteorites.

In part 2 of this series we presented the results of our studies on samples of all of the eighteen C2 chondrites [3]. Although all C2 chondrites are chemically similar with one another, as based on whole rock elemental analyses, we found considerable variation in the chemical state of iron in these meteorites. This, of course, contrasts to the situation in the C1 chondrites, where magnetite was the predominant state observed for iron.

In only five (Al Rais, Bells, Essebi, Kaba and Mokoia) of the eighteen C2 chondrites was magnetite found to be the major magnetic phase. (A second sample of Al Rais was found to contain metallic iron with about 6% Ni). Metallic iron was observed in five samples (Al Rais, Crescent, Haripura, Pollen and Renazzo). Eleven of the C2 chondrites, (including Crescent and Pollen) were most strikingly characterized by a lack of magnetic minerals (e.g.,<1% Fe_3O_4). Lacking a dominant magnetic phase, the thermomagnetic behavior of those eleven C2 chondrites was characterized by a pronounced increase in saturation magnetization which resulted from the formation of magnetite from troilite during the experiment. In spite of their chemical similarity, the thermomagnetic behavior of C2 chondrites was rather complex.

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*As in Parts 1 and 2, we employ the classification scheme for chondrites of Van Schmus and Wood [2].

The C3 chondrites appear to be considerably more heterogeneous within their group than are either the C1 or the C2 chondrites. Only two C4 chondrites are known, the Coolidge and Karoonda meteorites, and we include them with the C3's. In fact, Van Schmus [4] suggested that Karoonda should be reclassified from C4 to C5. Since the C4 chondrites may be derived from the C3 chondrites [2], it is reasonable to discuss them together. Thus we present in this paper the thermomagnetic analyses of all thirteen C3 chondrites and both C4 chondrites.

The equipment and technique used to measure the saturation magnetization as a function of temperature is the same as used previously in this series [1,3] and is discussed in detail by Larson, et al. [5]. The apparatus consists basically of a Cahn electrobalance, a furnace to heat the sample to ~800°C, and a moveable, 2500 - oersted permanent magnet. An essential feature of the system is the fugacity control. To minimize oxidation or reduction of the magnetic minerals 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 altered and monitored. The oxygen fugacity is 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 heating-cooling cycles to 600°C or 800°C required ~45 minutes and 60 minutes, respectively.

2. RESULTS AND DISCUSSION

In part 2, we found it convenient to arbitrarily subdivide the C2 chondrites into three groups in order to discuss the thermomagnetic behavior. We can also benefit from such a subdivision within the C3 and C4 chondrites according to criteria similar to that used for the C2 chondrites [3]: (A) those meteorites characterized by their low initial magnetite content and by pronounced magnetite production observed during the course of the experiment, (B) those meteorites, thermomagnetically similar to C1 chondrites, indicating magnetite as their major magnetic component and, (C) those meteorites which do not readily lend themselves to classification in either of the first two groups. Though we choose to subdivide C3 and C4 chondrites according to the same criteria as the C2 chondrites, there are both subtle and distinct differences observed within any group. We will discuss the above mentioned groups separately, and in doing so, will compare and contrast them to the thermomagnetic behavior observed in C2 chondrites in similar subgroups.

Group A. The J_s-T curves for those meteorites displaying magnetite production during the course of the experiment are shown in Fig. 1a-f. We begin our discussion with the thermomagnetic data for the Allende meteorite which is shown in Figs. 1a and 1b. The normal J_s-T curve for this meteorite is shown in Fig. 1a with two complete thermal cycles indicated, both run in the oxygen fugacity field for magnetite. The increase in saturation magnetization upon heating is characteristic of the oxidation of troilite to magnetite and pyrrhotite. Indeed, we observed this behavior in over half of the C2 chondrites [3]. Butler [6] and Banerjee and Hargraves [7] noted similar behavior in their thermomagnetic studies (conducted under vacuum) of the Allende meteorite. However, Butler attributed the increase in saturation moment to a "high temperature homogenization" of Ni-Fe alloys of grossly different composition. Butler stated, "Thermomagnetic analysis indicates that the ferromagnetic minerals in Allende consist of 95 wt.% taenite containing 67% Ni plus 5 wt. % taenite with 36% Ni." To determine whether the increase in saturation magnetization in our sample of Allende was the result of magnetite formation as we had observed in the C2 chondrites or "high temperature homogenization" of Ni-Fe alloys as proposed by Butler [6], we completed a normal J_s-T analysis on a powdered sample of Allende (Fig. 1b). Following that run, we heated the same Allende powder to 700°C in an intentionally produced reducing atmosphere and maintained those conditions for about fifteen minutes. The broken curve in Fig. 1b shows the high temperature portion of the J_s-T curve which was obtained following the reduction process. The broken curve indicates that the magnetic component now in Allende (after reduction) is metallic iron of low nickel content ($\leq$ 2% Ni) which was derived from the reduction of the magnetite (produced from oxidation of FeS) and by reduction of any FeS which remained after the normal J_s-T cycle. The magnitude of the saturation moment of the high temperature reduced component is greater than that which would have been produced from the Allende sample if the initial saturation magnetization had resulted entirely from magnetite. This experiment thus demonstrates that magnetite was produced during the J_s-T run prior to reduction. Several characteristics of the broken curve in Fig. 1b are inconsistent with Butler's hypothesis. If metallic iron with ~65% Ni was the result of the reduction (as expected from Butler's proposal): (1) The Curie temperature would not be expected to be ~770°C (the Curie point of pure iron) as we observed. 65% Ni in iron would yield a Curie temperature of ~610°C. (2) A $\gamma \rightarrow \alpha$ transition in the high-temperature portion of Fig. 1b is expected from Butler's proposal. The lack indicates iron with $\leq$ 2% Ni. (See Al Rais data, Fig. 5 in Watson, et al. [3] or Fig. 3f here for good examples of the $\gamma \rightarrow \alpha$ transition reflected in a J_s-T plot).

The thermomagnetic behavior of samples of the Arch, Efremovka, Leoville and Vigarano C3 chondrites (Figs. 1c-f, respectively) is similar to that of the Allende meteorite, indicative of no metallic iron component and being characterized by an increase in saturation magnetization during the experiment. Since these samples become more magnetic with heating, it is not possible here to identify the components responsible for the initial magnetization.

As we did with the C2 chondrites [3], we can ascribe upper limits of

Fe_3O_4 content for those C3 chondrites illustrated in Fig. 1 on the basis of saturation magnetization measurements at ambient temperature by assuming that the initial saturation moment is due entirely to magnetite. For Allende and Vigarano, determinations were made on aliquots taken from gently crushed 50-200 mg samples. The other meteorite samples were measured as small whole pieces. The upper limits of Fe_3O_4 content are shown in Table 1. Of these five meteorites only Allende and Vigarano are falls. The relatively high upper limits of magnetite content for Arch, Efremovka and Leoville may reflect magnetite formation from terrestrial weathering. Similarly, the increase in saturation magnetization for the finds may result in part from the reduction of terrestrially acquired hematite (Fe_2O_3) to magnetite (Fe_3O_4) since the samples were measured in the oxygen stability field for magnetite. The increase in saturation moment in the Allende and Vigarano samples most likely results from the oxidation of troilite during the experiment.

Group B. Our thermomagnetic data for samples of the Bali, Grosnaja and Ornans C3 chondrites and the Karoonda C4 chondrite are shown in Fig. 2a-d, respectively. The J_s-T curves for all these meteorites are quite reversible and their shape and Curie temperature (~590°C) indicate that magnetite is the dominant magnetic phase. Similar curves were seen for all five C1 chondrites and for five samples of the C2 chondrites [1,3]. Quantitative estimates of the magnetite contents of these C3 chondrites, as determined from ambient temperature saturation magnetization measurements are shown in Table 2. Also included are similar estimates for the C1 and C2 chondrites for comparison [1,3]. The Ornans and Karoonda data were obtained on aliquots taken from gently crushed samples. The Bali and Grosnaja samples were measured as small whole pieces. It should be noted that the grain sizes observed in the Grosnaja meteorite are comparatively large and as a consequence our data may not be representative of the meteorite as a whole. Error estimates recorded are based only on deviations observed when measuring a standard sample. The reported error does not reflect the possibility that some of the magnetization is affected by some magnetic component other than Fe_3O_4, e.g. pyrrhotite, nor was any attempt made to take into account sample inhomogeneity. We estimated in part 1 that for Orgueil, at least, pyrrhotite contributes 7% or less to the total saturation moment.

Group C. The thermomagnetic data shown in Fig. 3a-f respectively, for the Felix, Isna, Kainsaz, Lancé, and Warrenton C3 chondrites and the Coolidge C4 chondrite are all indicative of the presence of magnetite in addition to metallic iron. Of these meteorites the Isna sample (Fig. 3b) and the Lancé sample (Fig. 3c) are the only ones showing pronounced magnetite formation during the experiment with a suggestion of magnetite production appearing in the Felix data as well (Fig. 3a). The metallic iron components in our samples of Kainsaz (Fig. 3c) and Lancé (Fig. 3d) contain $\leq$ 2% Ni as indicated by the absence of a lag in reacquisition of magnetization (no $\gamma \rightarrow \alpha$ transition) upon cooling as well as the observed Curie temperature of ~770°C. This low nickel content in the metal is probably not representative of all of the metal in those two meteorites. Because of the high saturation moment of metallic iron and the extreme sensitivity of the thermomagnetic balance used, we were constrained to use quite small samples (<1 mg). For that reason sample inhomogeneity is likely to be more important. The low nickel content of the metal observed in the Kainsaz and Lancé samples suggests that this component may be of secondary origin, possibly produced from the reduction of magnetite prior to accretion.

If as Van Schmus and Wood [2] believe, the C4 chondrites were derived from the C3 chondrites, then we would perhaps expect that the unstable component may well have been entirely altered to magnetite during the process of converting

C3 to C4 material. We do not observe any unstable magnetic components (i.e., no magnetite production upon heating) in the C4 chondrites but with statistics involving only two samples, no conclusions can be drawn. It would be of interest to examine other more numerous classes (the LL, L or H chondrite groups) to see whether this suspected trend actually holds.

In view of the recent interest in paleointensity determinations on carbonaceous chondrites [6-8], we note that the data presented here and in paper 2 [3] suggest that considerable care be exercised in conducting paleointensity studies on C2 and C3 chondrites. Obviously, those samples containing the unstable component will be less suitable for paleointensity determinations on the magnetite component than samples lacking the noted magnetite production. The Ni-Fe component may yield valuable information; however, considerable care in experiment design should be exercised in regard to $\gamma \rightarrow \alpha$ recovery during remagnetization.

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Table 1 Upper Limit Determination of Magnetite Content of Some C3 Chondrites

Upper Limit for Wt. % Fe_3O_4	Sample Weight (mg)
<u>ALLENDE</u>	
$\leq$ 0.72 ± 0.04*	10.07
$\leq$ 0.73 ± 0.04	7.93
Weighted average $\leq$ 0.72 ± 0.04	
<u>ARCH</u>	
$\leq$ 2.20 ± 0.15	2.97
<u>EFREMOVKA</u>**	
$\leq$ 10.7 ± 0.6	5.37
$\leq$ 7.0 ± 0.4	3.34
Weighted average $\leq$ 9.3 ± 0.6	
<u>LEOVILLE</u>*	
$\leq$ 7.5 ± 0.5	2.64
$\leq$ 6.7 ± 0.4	2.50
Weighted average $\leq$ 7.12 ± 0.4	
<u>VIGARANO</u>	
$\leq$ 8.5 ± 0.5	3.20
$\leq$ 7.1 ± 0.4	1.33
$\leq$ 9.1 ± 0.5	2.95
Weighted average $\leq$ 8.5 ± 0.5	

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

**Run on whole samples.

Table 2 Magnetite Content of the Bali, Grosnaja and Ornans C3 Chondrites and the Karoonda C4 Chondrite. The Magnetite Contents of the C1 Chondrites [1] and Those C2 Chondrites [3] with Magnetite as the Principal Magnetic Phase are Included for Comparison.

Fe_3O_4 (Wt. %)		Sample Weight (mg)
C1 Chondrites [1]		
Alais	5.3 ± 0.4*	(Weighted Average of 11 determinations)
Ivuna	12.2 ± 0.9	(" " " 5 ")
Orgueil	11.9 ± 0.8	(" " " 7 ")
Revelstoke	7.2 ± 0.5	0.16
Tonk	9.4 ± 0.6	0.67
C2 Chondrites [3]		
Bells	13.4 ± 0.8	(Weighted Average of 3 determinations)
Essebi	9.4 ± 0.6	(" " " 5 ")
Kaba	11.3 ± 0.7	(" " " 2 ")
Mokoia	4.1 ± 0.3	(" " " 3 ")
C3 Chondrites		
BALI**	3.0 ± 0.2	0.36
GROSNAJA**	2.1 ± 0.1	3.42
	1.9 ± 0.1	9.62
Weighted Av.	2.0 ± 0.1	
ORNANS	4.5 ± 0.3	0.85
	4.3 ± 0.3	1.57
	4.2 ± 0.3	2.59
Weighted Av.	4.3 ± 0.3	
C4 Chondrites		
KAROONDA	8.2 ± 0.5	0.97
	7.6 ± 0.5	5.52
Weighted Av.	7.7 ± 0.5	

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

**Run on whole samples.

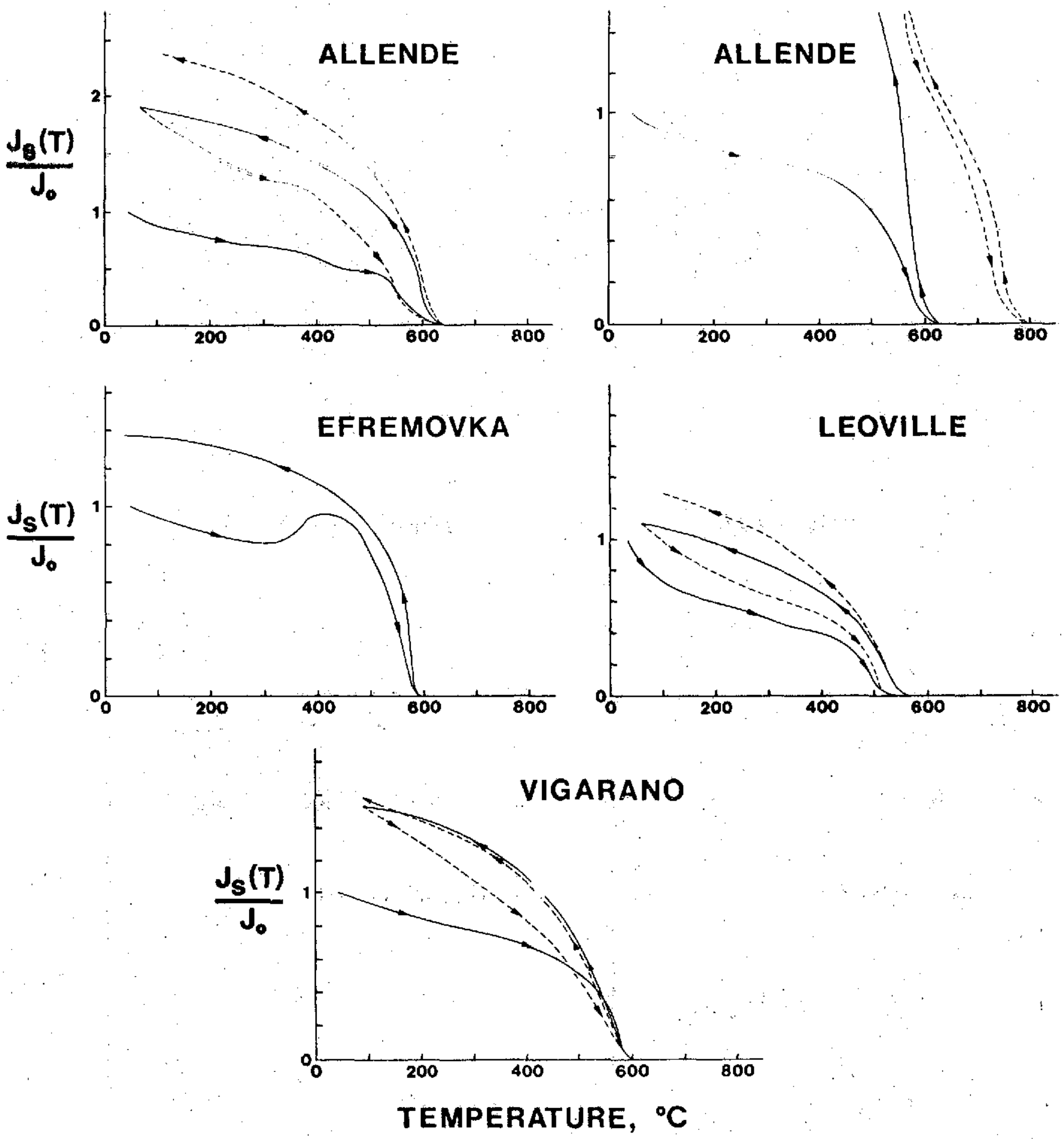

Fig. 1. Saturation magnetization vs. temperature (J_s-T) curves for four C3 chondrites. Note the large increase in magnetization as the samples cool, indicative of magnetite production. All of these except Eframovka were subjected to two heating - cooling cycles (broken curves). As with the Group A C2 chondrites [2], one cycle is not adequate to allow complete production of magnetite. Five of the eleven C2 chondrites show production of magnetite upon heating (see also Fig. 3).

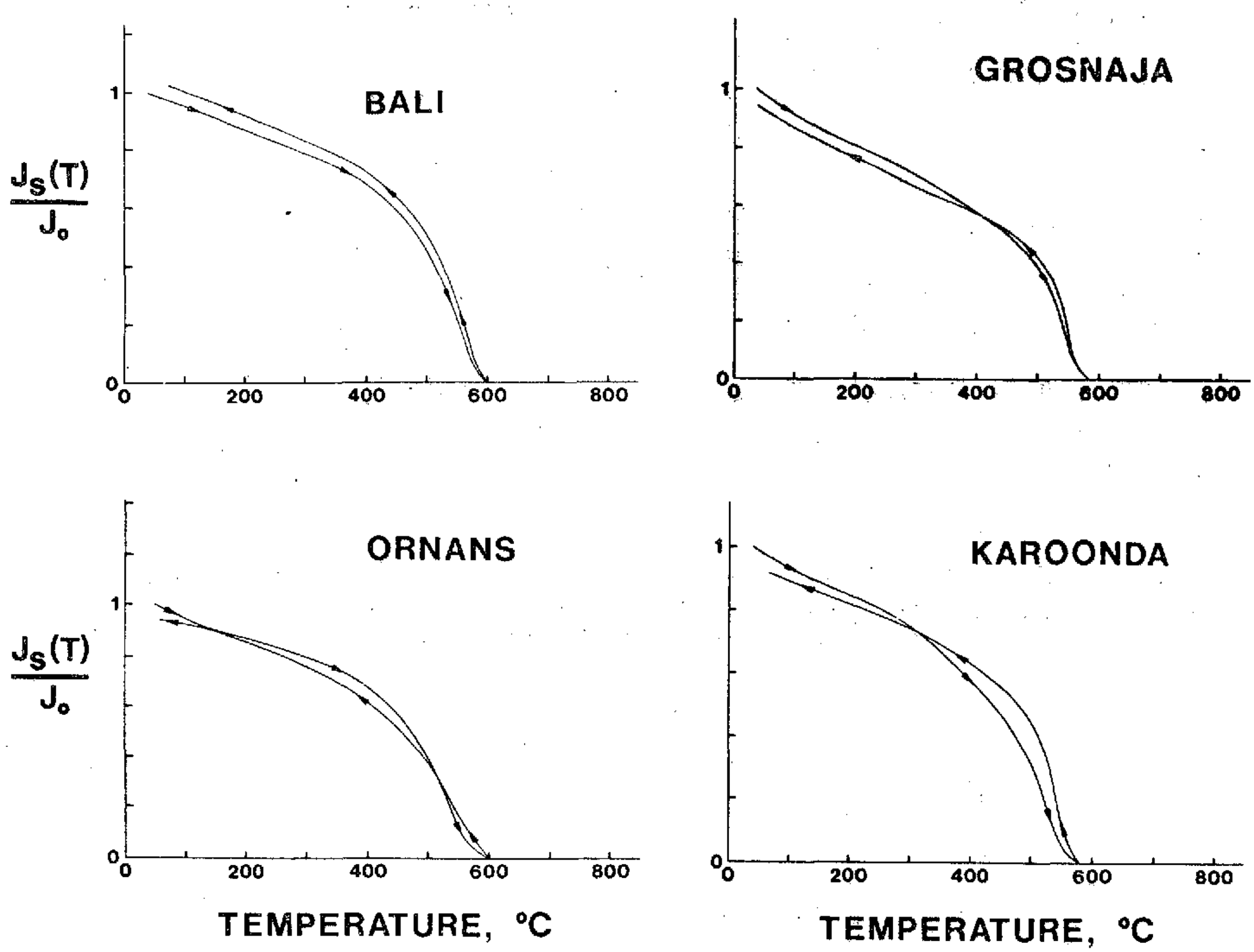

Fig. 2. Saturation magnetization vs. temperature (J_S-T) curves for three C3 chondrites and one C4 chondrite. Magnetite is quite dominant. No evidence for significant magnetite production is indicated in contrast to Figs. 1 and 3.

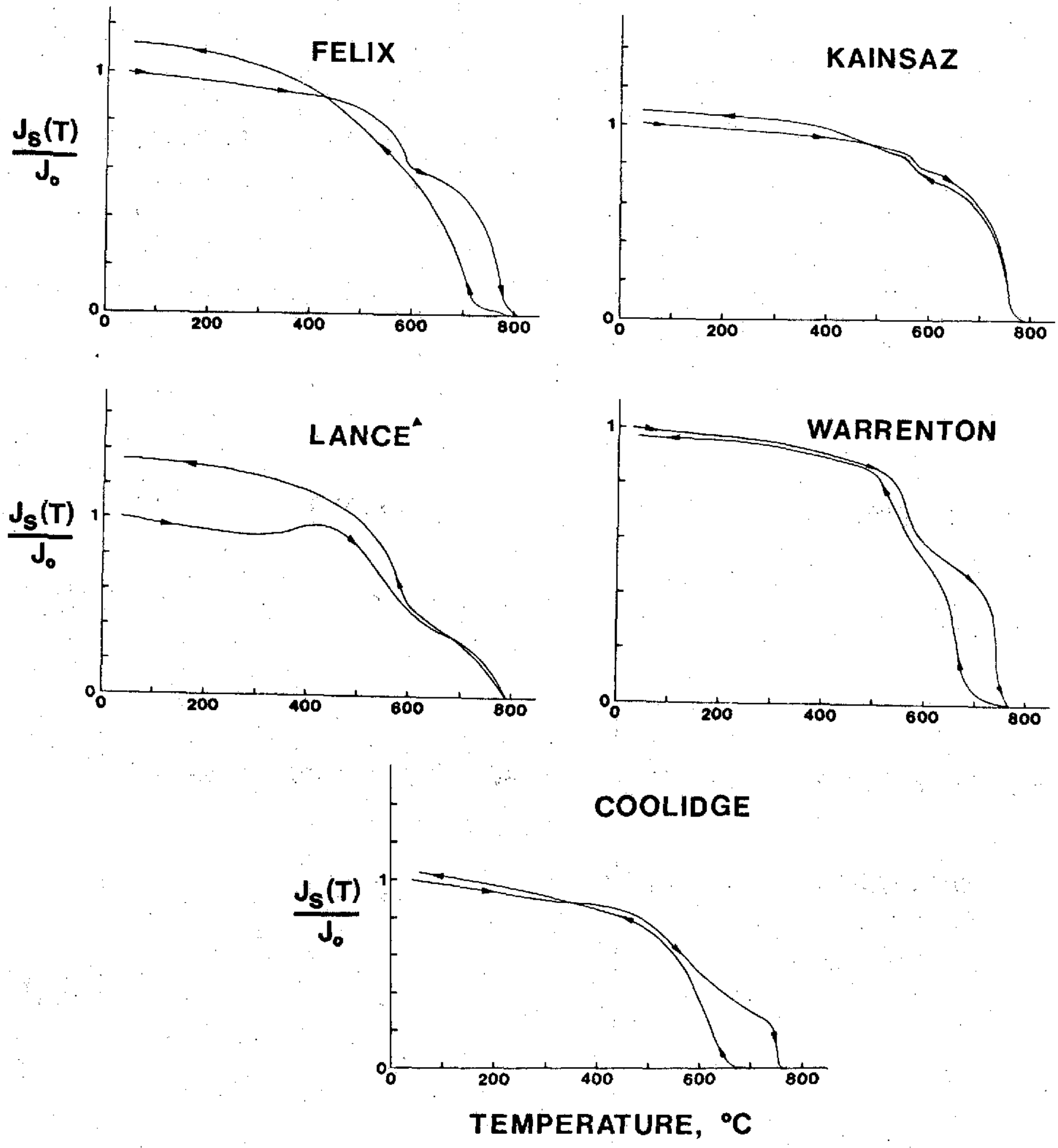

Fig. 3. Saturation magnetization vs. temperature (J_S-T) curves for four C3 chondrites and the remaining C4 chondrite. Felix and Lance' show evidence for slight magnetite production. No magnetite production was seen in the Kainsaz and Warrenton C3 chondrites or in the Coolidge C4 chondrite.