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Wasp-waisted hysteresis loops: Mineral magnetic characteristics and discrimination of components in mixed magnetic systems

Andrew P. Roberts, Yulong Cui, and Kenneth L. Verosub
Department of Geology, University of California, Davis

Abstract. Rock magnetic studies of complex systems that contain mixtures of magnetic minerals or mixed grain size distributions have demonstrated the need for a better method of distinguishing between different magnetic components in geological materials. Hysteresis loops that are constricted in the middle section, but are wider above and below the middle section, are commonly observed in mixed magnetic assemblages. Such "wasp-waisted" hysteresis loops have been widely documented, particularly with respect to rare earth permanent magnets, basaltic lava flows, remagnetized Paleozoic carbonate rocks, and an increasingly wide range of other rocks. Our modelling, combined with a review of previous work, indicates that there are several conditions that give rise to, as well as magnetic properties that are characteristic of, wasp-waisted hysteresis loops. First, at least two magnetic components with strongly contrasting coercivities must coexist. This condition can arise from either mixtures of grain sizes of a single magnetic mineral, or a combination of magnetic minerals with contrasting coercivities, or a combination of these two situations. Second, materials that give rise to wasp-waisted hysteresis loops will have relatively high ratios of the coercivity of remanence to coercive force (B_{cr}/B_c) because B_c is controlled by the soft (low coercivity) component, whereas B_{cr} is controlled by the hard (high coercivity) component. Third, values of $B_{cr}/B_c \geq 10$ usually only occur for strongly wasp-waisted loops when the low coercivity component comprises an overwhelmingly large fraction of the total volume of magnetic grains. Fourth, a given mixture of superparamagnetic and single-domain (SD) grains is more likely to give rise to wasp-waisted hysteresis loops than an equivalent mixture of SD and multidomain grains. Fifth, our results provide empirical confirmation that the total magnetization of a material is the sum of the weighted contributions of each component, in the absence of significant magnetic interaction between particles. Thus to contribute significantly to wasp-waisted behavior, a mineral magnetic component must give rise to a significant portion of the total magnetization of the rock. As a result, minerals with weak magnetic moments such as hematite need to occur in large concentrations to cause wasp-waistedness in materials that also contain ferrimagnetic minerals. We outline a method for determining the magnetic components that can give rise to wasp-waisted hysteresis loops. This method is based on high- and low-temperature magnetic measurements that are used to identify the dominant remanence-bearing mineral/s and on mineral magnetic techniques that are used to discriminate between different magnetic domain states. The method is illustrated with several examples from archaeological, geological, and synthetic materials.

Introduction

Rock magnetic analyses have become a fundamental part of paleomagnetic studies in recent years because of the need to determine the rock magnetic basis for paleomagnetic observations. As a result, geological materials that comprise mixtures of magnetic minerals and/or mixtures of magnetic grain sizes are being recognized more frequently. Work on complex rock magnetic systems has demonstrated the need for a better method of distinguishing between different magnetic components in a rock. For example, perhaps the most definitive means of determining magnetic grain size information is the measurement of the magnetic hysteresis properties [e.g., *Day et al.*, 1977]. The four commonly determined hysteresis parameters are (Figure 1): M_s, the saturation magnetization, M_{rs}, the saturation remanence, B_c, the coercive force, and B_{cr}, the coercivity of remanence. When the magnetic mineralogy is dominated by (titano) magnetite, the ratios M_{rs}/M_s and B_{cr}/B_c are widely used to determine the domain state and relative variations in magnetite grain size. Interpretive ambiguities can arise, however, because a sample comprising a mixture of grain sizes of a single magnetic mineral, or a mixture of different magnetic minerals, can sometimes give rise to hysteresis loops that are similar to those of a population of grains of uniform composition and identical size [*Parry*, 1982].

Interpretation of hysteresis parameters can become more complicated when, as is common in many studies, hysteresis loops are constricted in the middle section but are wider above and below the middle section [*Radhakrishnamurty and Sahasrabudhe*, 1965a, b, 1967; *Wasilewski*, 1973; *Becker*, 1982; *Otani et al.*, 1986; *Thompson and Oldfield*, 1986; *Heisz and Hilscher*, 1987; *Jackson*, 1990; *Jackson et al.*, 1992, 1993; *Borradaile et al.*, 1993a, b; *Pick and Tauxe*, 1993; *Radhakrishnamurty*, 1993; *Channell and McCabe*, 1994; *McCabe and Channell*, 1994]. Such loops are often referred to as

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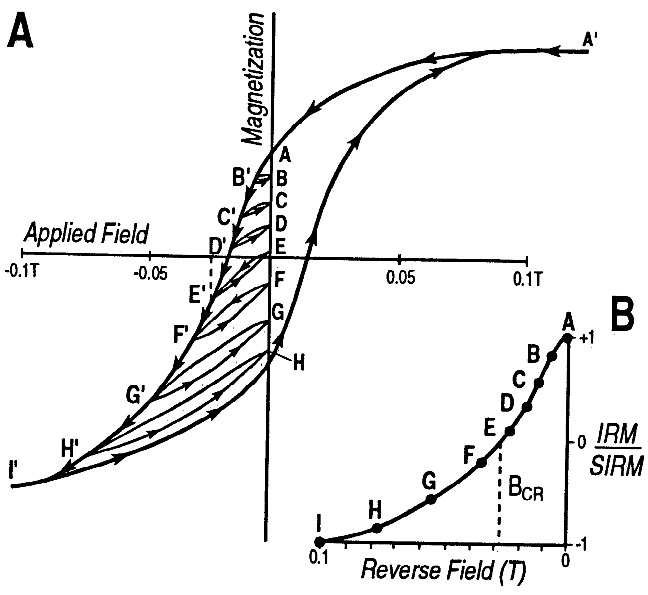

Figure 1. Magnetic hysteresis parameters. (a) Magnetic hysteresis properties of a sample subjected to a forward saturating field (A') followed by fields of decreasing strength and a series of reverse fields (B' to I'). The changes can be measured as a series of minor hysteresis loops (B'B, C'C, ..., H'H). The outer envelope marks the major hysteresis loop of the material. The magnetization at A' is the saturation magnetization (M_s) and the remanent magnetization at A is the saturation remanence (M_{rs}). The point at which the magnetization is reduced to zero (i.e., between D' and E') is the coercive force (B_c). (b) Measurements of the remanent magnetizations (A to I) left after application of each back field (minor loops). The reverse field which reduces the remanence to zero (i.e., between E and F) is the coercivity of remanence (B_{cr}). Modified after *Thompson and Oldfield* [1986].

"wasp-waisted" hysteresis loops. Wasp-waisted loops result from a bimodal (or multimodal) population of magnetic grains that have widely different coercivities. Coercivity contrasts arise from mixtures of grain sizes of a single magnetic mineral or from a combination of magnetic minerals with markedly different coercivities. Wasp-waisted hysteresis loops have been widely documented in the literature, the earliest references to which are associated with heat-treated high permeability metallic alloys [*Gumlich*, 1920; *Elmen*, 1928]. Some of the best-known modern examples are rare earth permanent magnets [*Becker*, 1982; *Chikazumi*, 1986; *Otani et al.*, 1986; *Heisz and Hilscher*, 1987]; basaltic lava flows [*Radhakrishnamurty and Sahasrabudhe*, 1965a, b, 1967; *Radhakrishnamurty*, 1993]; remagnetized Paleozoic carbonate rocks [*Jackson*, 1990; *Jackson et al.*, 1992, 1993; *Channell and McCabe*, 1994; *McCabe and Channell*, 1994] and submarine basaltic glasses [*Pick and Tauxe*, 1993, 1994].

A significant amount of work has been done on materials that display wasp-waisted hysteresis loops in the permanent rare earth magnet industry because constriction of the hysteresis curve drastically reduces the maximum energy produced by a magnet. *Heisz and Hilscher* [1987] reviewed three explanations for the origin of this type of behavior, including: (1) superposition of hard and soft magnetic phases, (2) oxidation of the surface layers of a magnetically soft material, and (3) spin reorientation which results in changes in the magnetic structure below 135 K. The first two of these mechanisms are applicable in the temperature ranges encountered in geological contexts and are therefore pertinent to the discussion outlined in this paper.

In our work in the Paleomagnetism Laboratory at the University of California - Davis (UC-Davis), we have encountered several examples of materials that display wasp-waisted hysteresis loops (Figure 2 and Table 1). These include Bulgarian archaeomagnetic samples (Figure 2a); Pleistocene lake sediments from Butte Valley, northern California (Figure 2b); synthetic greigite of mixed grain size (Figure 2c); lower Pleistocene glaciomarine sediments from Hole 10, Dry Valley Drilling Project, Antarctica (Figure 2d); and Paleozoic carbonate rocks from the Great Basin Cordillera that were remagnetized during the Kiaman reverse polarity superchron (Figure 2e) [cf. *Gillett et al.*, 1993]. Wasp-waisted hysteresis loops may even be characteristic of the extensively remagnetized Paleozoic carbonate strata of North America and England [*Jackson*, 1990; *Jackson et al.*, 1992, 1993; *Gillett et al.*, 1993; *Channell and McCabe*, 1994; *McCabe and Channell*, 1994]. In this paper we discuss the mineral magnetic characteristics of wasp-waisted hysteresis loops and we outline a rationale for discriminating between the mixed mineral magnetic components that give rise to wasp-waisted hysteresis loops.

Mixtures of Magnetic Grain Sizes

Even though all of the hysteresis loops shown in Figure 2 are wasp-waisted, they all have distinctly different shapes. This observation demonstrates that while the hysteresis behavior is controlled by M_{rs}, M_s, and B_c, these parameters are not sufficient to specify the curvature of the demagnetizing portion of the loop for $0 > B > B_{cr}$. Clearly, there is other information that can be derived from the hysteresis loops, namely, the curvature. The curvature may reflect variations in the distribution of coercivities and hence grain sizes in the sample. In an effort to obtain additional information concerning the distribution of coercivities, *Jackson et al.* [1990] performed Fourier analyses on hysteresis loops. Similar approaches that enable a fuller characterization of samples need further consideration. For example, quantification of the "degree of wasp-waistedness" could prove to be an important discriminant. We do not develop this issue explicitly here; however, it is an area that needs further work.

Several authors [e.g., *Wasilewski*, 1973; *Becker*, 1982] have suggested that wasp-waisted loops may arise when the (nonconstricted) hysteresis loops from different magnetic components are summed, as shown in Figure 3a. *Wasilewski* [1973] tested this idea by placing together two samples with markedly different coercivities and obtained a wasp-waisted hysteresis loop. This principle of additivity was also invoked by *Becker* [1982] to explain wasp-waisted hysteresis behavior observed from a permanent rare earth magnet (Figure 3b). *Bean* [1955] and *Parry* [1980, 1982] showed that, in the absence of magnetic interactions between particles, the magnetization in a given field is simply the sum of the magnetization of the isolated particles in that field (nonadditivity will result at concentrations of a few percent, by volume, as is evident in the work of *Hejda et al.* [1994]). We have used this principle to extend the work of *Wasilewski* [1973] by measuring separate samples of known narrow grain size, using the same applied field at each step. Because of this measurement procedure, we

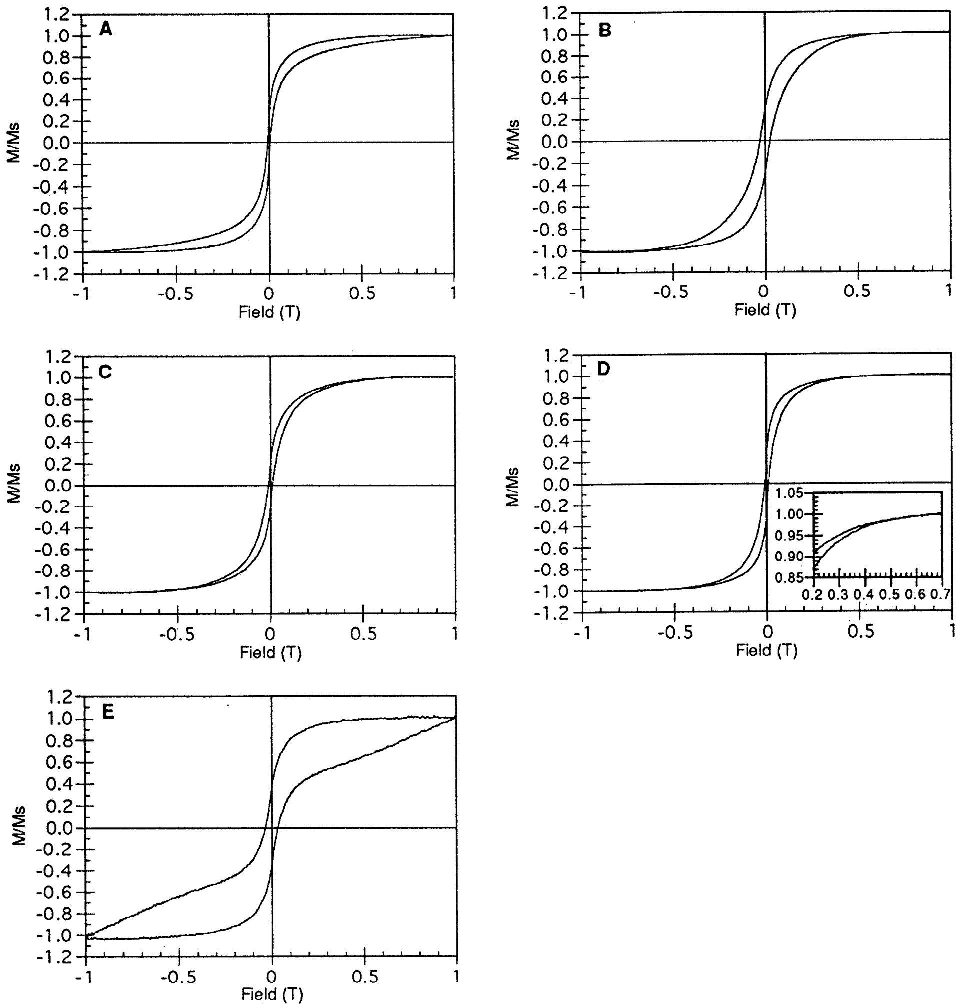

Figure 2. Examples of wasp-waisted hysteresis loops from (a) Bulgarian archaeomagnetic sample (BULG 1371); (b) Pleistocene lacustrine sediment from northern California (BV1675); (c) synthetic greigite sample (SYN93A); (d) lower Pleistocene glaciomarine sediment from DVDP Hole 10, Dry Valleys, Antarctica. The inset shows the open nature of loop above fields of 0.3 T, indicating the presence of a high-coercivity phase; and (e) remagnetized Paleozoic carbonate rock from the Great Basin Cordillera (BKDR4A). The hysteresis parameters for these samples are shown in Table 1.

Table 1. Hysteresis Parameters of Samples for Which Hysteresis Loops Are Shown in Figure 2

Sample	M_s, 10^{-7} A m^2	M_{rs}, 10^{-7} A m^2	M_{rs}/M_s	B_c, mT	B_{cr}, mT	B_{cr}/B_c
A. BULG1371 Bulgarian Archaeomagnetic sample	9.03	1.66	0.184	6.53	73.9	11.3
B. BV1675 Lake sediment	13.9	4.03	0.290	26.9	113	4.2
C. SYN93A Synthetic greigite	23.7	4.36	0.184	11.0	55.6	5.1
D. DVDP 10 - 126.0 Glaciomarine sediment	83.9	21.0	0.250	10.2	42.1	4.1
E. BKDR 4A Remagnetized Paleozoic carbonate rock	0.548	0.189	0.345	33.8	499	14.8

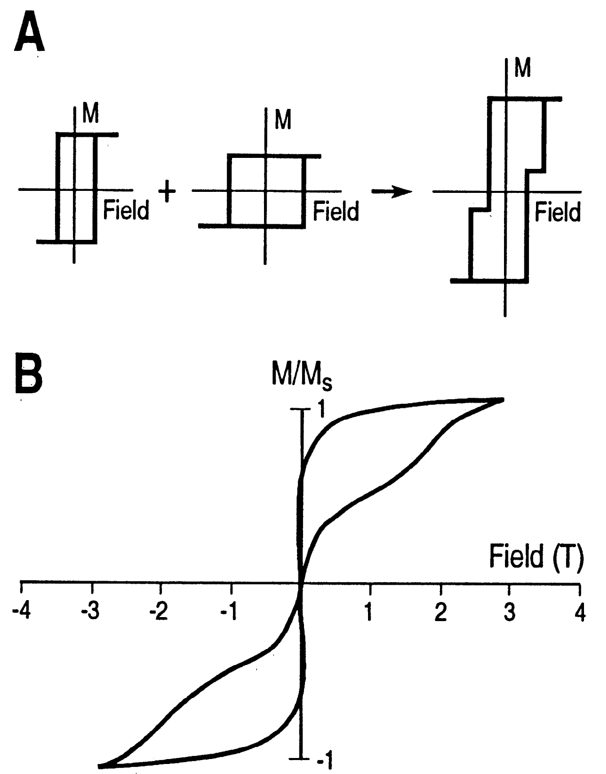

Figure 3. (a) Wasp-waisted hysteresis behavior resulting from addition of hysteresis loops with contrasting coercivities, as suggested by *Becker* [1982]. (b) Empirically obtained hysteresis loop from a $Fe_{70.5}B_{15.5}Tb_7La_7$ rare earth magnet with an oxidized surface layer, after *Becker* [1982].

can mathematically add the magnetizations at each field value to create a composite hysteresis loop. We can then compare the loop with that obtained by measuring a composite sample, as done by *Wasilewski* [1973].

In Table 2 we show the magnetic hysteresis parameters for samples with known grain size distributions, as measured on a Princeton Measurements Corporation Micromag Alternating Gradient Magnetometer at the UC-Davis Paleomagnetism Laboratory. Hysteresis parameters were measured for pseudo-single-domain (PSD) and multidomain (MD) magnetite, single-domain (SD) greigite and SD hematite. In Table 3 we show the magnetic hysteresis properties of mixtures of the samples from Table 2. The first set of values in Table 3 was obtained by direct measurement, and the second set was calculated by mathematically summing the magnetizations shown in Table 2. In Figure 4 we show the hysteresis loops for the original samples as listed in Table 2, along with the hysteresis loops obtained for each composite sample (cf. Table 3). These data demonstrate that it is possible to obtain wasp-waisted hysteresis loops by mixing magnetic components that have strongly contrasting coercivities. In Figure 5 we show the hysteresis curves obtained from the composite samples together with the curves determined by summing the magnetizations. The agreement between the two curves is good in each case. The degree of misfit between the hysteresis parameters is given in Table 3. The misfit between the curves (Figure 5) is small at low field values but increases as the sample nears saturation. In nearly all cases the mathematically derived magnetizations in Table 3 are higher than those determined empirically. This is probably due to increased interaction between particles in the measured composite samples and a concomitant increase in self-demagnetization as saturation is approached at higher field values. Nevertheless, the misfit is generally small (within 5%).

Our results provide empirical confirmation that the total magnetization is the sum of the weighted contributions of each component, when the effects of particle interaction are minimized. Our results contrast with those of *Hejda et al.* [1994], who were unable to demonstrate additivity of the contributions from individual magnetic components because of magnetic interactions. Additivity of the magnetic components is an important result because it provides a means for determining the contribution of a subset of magnetic grains to the total magnetization of a material. For example, data from magnetic minerals that have been extracted from geological materials are often treated with distrust because most extraction procedures are biased toward strongly ferrimagnetic grains or toward certain grain sizes. If the hysteresis properties of a rock are determined before extraction and subsequently on the extract as well as the residue, then the effectiveness of the extraction procedure can be assessed. Caution should be exercised in such work, however, because magnetic interactions between particles can give rise to significant nonadditivity. Regardless of this, the additivity of magnetic components is important because it means that minerals with weak magnetic moments, such as hematite and goethite, need to occur in significant abundances to cause wasp-waistedness in rocks that contain ferrimagnetic minerals.

Characteristics of Wasp-Waisted Hysteresis Loops

As shown above, wasp-waisted hysteresis loops result from a mixture of magnetic components with contrasting coercivities. Such a mixture will result in a bias of the magnetic parameters toward one or another constituent [*Parry*, 1980], producing distinctive wasp-waisted shapes. The degree of wasp-waistedness is dependent on the relative contribution of each

Table 2. Magnetic Hysteresis Properties of Pure Samples of Known Narrow Grain Size

Sample	Domain State	M_s, 10^{-6} A m^2	M_{rs}, 10^{-6} A m^2	M_{rs}/M_s	B_c, mT	B_{cr}, mT	B_{cr}/B_c
Magnetite	fine PSD	2.32	0.92	0.397	38.4	57.7	1.5
Magnetite	PSD	1.80	0.29	0.162	8.7	18.6	2.1
Magnetite	MD	9.07	0.08	0.008	1.2	14.4	12.0
Magnetite	MD	7.67	0.09	0.011	1.4	12.0	8.8
Hematite	SD	1.98	1.19	0.602	150	230	1.5
Greigite	SD	0.81	0.45	0.557	53.8	69.4	1.3

Table 3. Comparison of Measured and Calculated Hysteresis Properties of Mixtures of the Samples Listed in Table 2

Sample		M_s, 10^{-6} A m^2	Misfit, %	M_{rs}, 10^{-6} A m^2	Misfit, %	M_{rs}/M_s	Misfit, %	B_c, mT	Misfit, %	B_{cr}, mT	B_{cr}/B_c
Hematite + PSD magnetite	Measured	4.06		1.63		0.402		44.0		189	4.3
	Calculated	4.30	+5.6	2.11	+22.8	0.491	+18.1	40.6	-8.4		
Hematite + MD magnetite	Measured	10.90		1.32		0.121		17.5		230	13.1
	Calculated	11.05	+1.4	1.27	-4.2	0.114	-5.8	18.3	+4.4		
Hematite + greigite	Measured	2.66		1.59		0.596		97.9		168	1.7
	Calculated	2.79	+4.7	1.64	+3.2	0.588	-1.3	99.7	+1.8		
MD + PSD magnetite	Measured	9.80		0.99		0.101		11.5		57	5.0
	Calculated	9.99	+1.9	1.01	+2.1	0.101	0	12.5	+8.0		

component. Values of B_c and B_{cr} for a mixture of low-coercivity and high-coercivity components will be intermediate between those for the two separate components, however, B_c is largely controlled by the soft (low-coercivity) component while B_{cr} is largely controlled by the hard (high-coercivity) component [*Wasilewski*, 1973; *Day et al.*, 1977; *Nagata and Carleton*, 1987]. Because B_c values of the mixture are relatively low and B_{cr} values are relatively high, B_{cr}/B_c can increase to anomalously high values in materials with coexisting soft and hard coercivity components.

For uniform dispersions of MD grains, B_{cr}/B_c values are usually about 4.0-5.0 [*Day et al.*, 1977; *Dunlop*, 1981]. *Wasilewski* [1973] showed that with bimodal distributions of coarse and fine grains, values of B_{cr}/B_c of up to 7.0 could be achieved. When significant contributions are made to SD assemblages by MD or superparamagnetic (SP) grains, B_c is reduced much more significantly and B_{cr}/B_c values can reach 10 or greater. The B_{cr}/B_c values for the MD grains used in our study (Table 2) are higher than expected. The higher values may be due to minor surface oxidation that would increase the value of

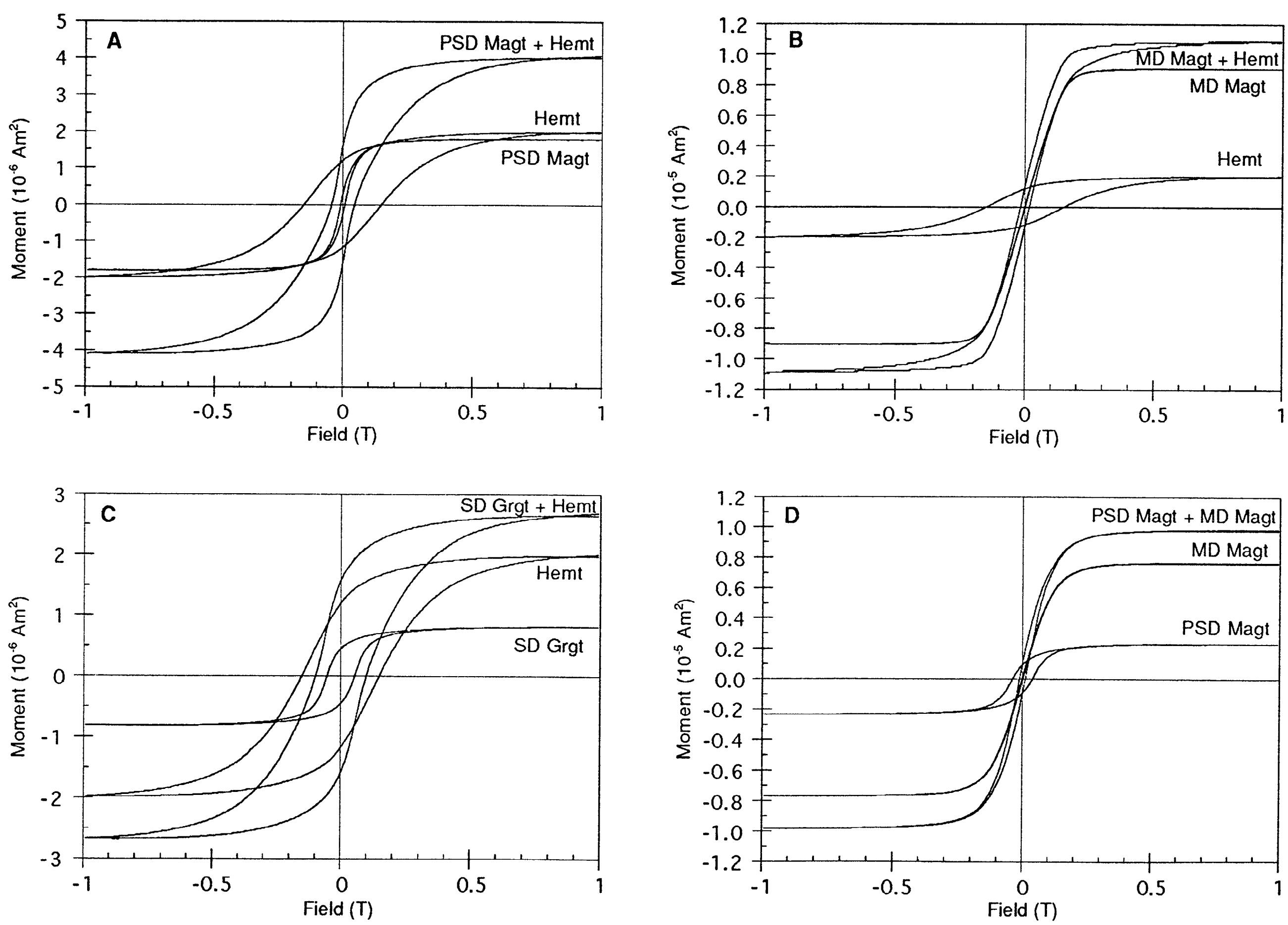

Figure 4. Hysteresis loops for two pure samples of known grain size, shown with the composite loop obtained by measuring both samples together. Loops are listed from lowest to highest moment: (a) PSD magnetite, hematite, PSD magnetite + hematite; (b) hematite, MD magnetite, MD magnetite + hematite; (c) SD greigite, hematite, SD greigite + hematite; and (d) PSD magnetite, MD magnetite, PSD + MD magnetite. The hysteresis parameters for these samples are listed in Table 2 and can be matched by comparing M_s values.

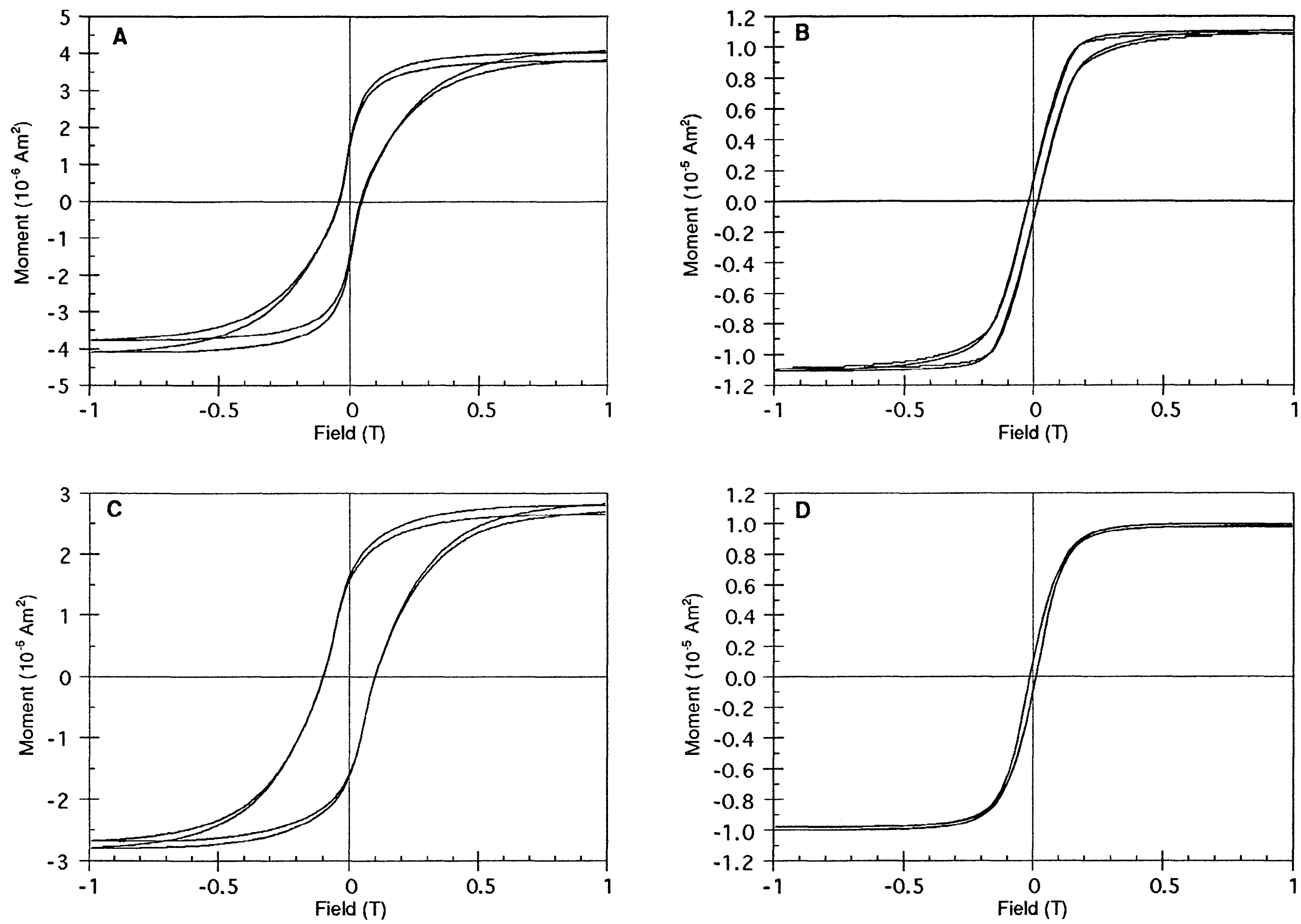

Figure 5. Comparison of hysteresis loops obtained from measurement of composite samples with those obtained by summing moments from each component measured separately. In each case the loop with the greatest value of M_s is that obtained by mathematically summing two separate loops. (a) PSD magnetite + hematite; (b) MD magnetite + hematite; (c) SD greigite + hematite; and (d) PSD magnetite + MD magnetite.

B_{cr}. However, the low values of B_c, the shape of the hysteresis loops, and the low M_{rs}/M_s ratios of these samples indicate that the remanence is dominated by MD behavior.

Other workers have also observed anomalously high values of B_{cr}/B_c. *Nagata and Carleton* [1987] observed values of B_{cr}/B_c up to 32 in terrestrial igneous rocks, and in some lunar rocks and chondrites they commonly observed values exceeding 30. In extreme cases, *Nagata and Carleton* [1987] observed values of more than 100, where significant proportions of hyperfine SP grains coexist with SD grains. *Parry* [1982] found that large ratios of B_{cr}/B_c ($\geq$ 10) occur only when the low-coercivity component represents an overwhelmingly large fraction of the total volume of magnetic grains. *Bean* [1955] and *Kneller and Luborsky* [1963] showed that a given fraction of SP grains lowers the overall coercivity of the mixture much more than an equal fraction of MD grains (Figure 6). This observation suggests that a given mixture of SP + SD grains is more likely to give rise to wasp-waisted hysteresis loops than an equivalent mixture of SD + MD grains.

This brief review suggests that the larger the coercivity contrast in a sample, the higher B_{cr}/B_c will be, and the more wasp-waisted the hysteresis loop will be. As shown by *Kneller and Luborsky* [1963] and *Wasilewski* [1973], the

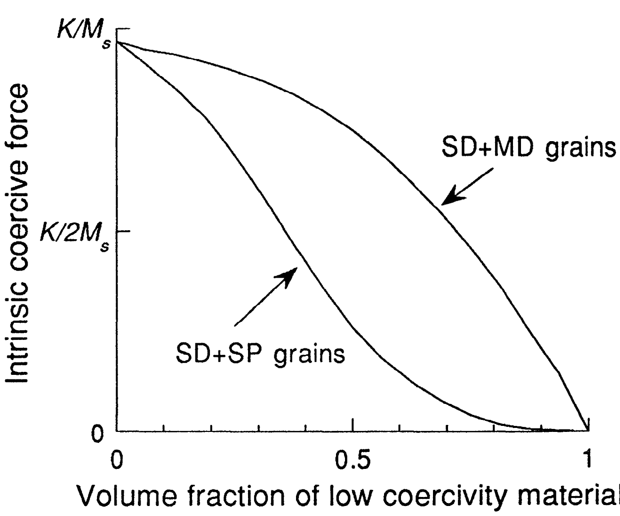

Figure 6. Coercive force distribution derived from mixtures of single-domain particles with variation in volume fraction of low-coercivity material for SD + SP and SD + MD grains, from *Bean* [1955]. K is the magnetocrystalline anisotropy constant and M_s is the saturation magnetization.

following relationships generally hold for a mixture of soft and hard components:

$$B_{cr}/B_c\,(mixture) > B_{cr}/B_c\,(soft) > B_{cr}/B_c\,(hard), \quad (1)$$

$$M_{rs}/M_s\,(soft) < M_{rs}/M_s\,(mixture) < M_{rs}/M_s\,(hard). \quad (2)$$

The relationships in (1) and (2) can be seen to be true for the samples in Tables 2 and 3, except for the mixture of MD and fine PSD magnetite (Table 3 and Figure 4d).

The sample shown in Figure 4d is a mixture of fine PSD (i.e., almost SD) and MD magnetite, with the larger contribution coming from the MD component (M_s is three times larger for the MD component than for the PSD component). However, a wasp-waisted loop is not observed and relationship (1) does not hold. We believe that this observation supports the contention of *Parry* [1982] that MD grains must make an overwhelming contribution to the remanence of a sample in order to produce high B_{cr}/B_c ratios and the accompanying wasp-waisted hysteresis behavior. If this conclusion is correct, then the characteristically high values of B_{cr}/B_c (as high as 15 in some cases) in remagnetized North American Paleozoic carbonate rocks [*Jackson*, 1990] suggests that soft coercivity (MD or SP) magnetic grains comprise an overwhelmingly large fraction of the magnetic mineral distribution of remagnetized North American Paleozoic carbonate rocks.

Mixtures of coercivities can occur in different ways. As shown above, a mixture of grains of a uniform composition (e.g., magnetite) can give rise to coercivity contrasts if SD grains coexist with significant volumes of SP or MD grains. Mixtures of ferrimagnets with canted antiferromagnets (e.g., magnetite + hematite; greigite + hematite) can also give rise to wasp-waisted hysteresis loops (Figures 4a, 4b, and 4c; maximum coercivities are listed for naturally occurring magnetic minerals in Table 4). However, mixtures of coercivities can also occur by other mechanisms. For example, in sulfate-reducing sedimentary environments, magnetite undergoes dissolution and ferrimagnetic iron sulfides often form [e.g., *Canfield and Berner*, 1987; *Karlin*, 1990a, b; *Leslie et al.*, 1990; *Snowball and Thompson*, 1990; *Roberts and Turner*, 1993]. Ferrimagnetic iron sulfide minerals such as greigite commonly grow to stable SD size [*Roberts*, 1995], while SD magnetite grains are commonly dissolved completely or are reduced to SP size. Thus it is possible to have a bimodal grain size distribution with mixtures of different ferrimagnetic minerals. *Jackson et al.* [1992] suggested that a mixture of grain sizes of ferrimagnetic pyrrhotite and magnetite could account for wasp-waisted loops in remagnetized North American Paleozoic carbonates. Mixtures of coercivities can also arise in grains (derived from igneous rocks) with mixed compositions. For example, *Reynolds* [1977] studied the magnetic properties of titanohematite grains that lie within the ferrimagnetic range of the hematite-ilmenite solid solution series [cf. *Nagata*, 1961]. Wasp-waisted loops were subsequently obtained from these titanohematite grains [R.L. Reynolds, written communication, 1995] and may result from submicroscopic intergrowths of differing composition, as described by *Lawson and Nord* [1984]. Compositional variation within titanohematite grains is a possible explanation for wasp-waisted hysteresis behavior because significant variations in coercivity occur along the hematite-ilmenite solid solution series [*Nagata*, 1961].

The above examples demonstrate the need for a method to determine the mineralogy and grain size of the magnetic constituents in a rock in order to understand the origin of wasp-waisted hysteresis loops and their significance.

Determining the Cause of Wasp-Waisted Hysteresis Behavior

We have developed a method for identifying the mineral magnetic components that give rise to wasp-waisted hysteresis behavior. Some information concerning the coercivity distribution is present in the hysteresis loop itself. If the loop is closed (i.e., the magnetization is fully saturated) at 0.3 T (i.e., the maximum coercivity of most ferrimagnetic minerals such as magnetite; Table 4), then it is a positive indication that a high-coercivity mineral (e.g., hematite or goethite) is not contributing to the wasp-waistedness. In this case a bimodal grain size distribution is probably responsible for the observed behavior. The fact that the three wasp-waisted loops in Figures 4a, 4b, and 4c are open at fields above 0.6 T demonstrates that a high-coercivity mineral is present in significant amounts (in this case hematite). On the other hand, the loop for the sample with mixed grain sizes of magnetite (Figure 4d) is closed at 0.2 T. However, apart from the open or closed nature of the loop at certain field values, we can learn little about the cause of wasp-waistedness from the loop itself. To understand the cause of the coercivity contrast, we must ascertain whether the contrast is due to a mixture of magnetic minerals or to a bimodal grain size distribution of a single magnetic mineral. The first step in determining the cause of wasp-waist-

Table 4. Maximum Unblocking Temperatures and Maximum Coercivities for Common Naturally Occurring Magnetic Minerals

Magnetic Mineral	Maximum Coercivity T	Maximum Unblocking Temperature °C	Reference
Magnetite	0.3	575	*O'Reilly* [1984]
Maghemite	0.3	~350	*O'Reilly* [1984]
Titanomagnetite			
x = 0.3	0.2	350	*O'Reilly* [1984]
x = 0.6	0.1	150	*O'Reilly* [1984]
Pyrrhotite	0.5 - 1	325	*Clark* [1984] and *Dekkers* [1988a]
Greigite	0.3	~330	*Roberts* [1995]
Hematite	1.5 - 5	675	*O'Reilly* [1984] and *Lowrie and Heller* [1982]
Goethite	>5	60 - 120	*Strangway et al.* [1968] and *Dekkers* [1988b, 1989a]

Modified after *Lowrie* [1990].

ed behavior is therefore to determine which magnetic minerals are present in a sample (Figure 7).

Magnetic Mineralogy

Various types of thermomagnetic analysis are effective for discriminating between magnetic minerals (Figure 7). Of these, Curie point analysis is perhaps the most useful. However, few Curie balances are sensitive enough to allow measurement of whole rock samples, which usually makes it necessary to work with magnetic extracts. As noted above, this raises the question of whether the extract is representative of the magnetic grains in a rock. An alternate approach is measurement of the temperature dependence of magnetic susceptibility of whole rock samples, as outlined by *Hrouda* [1994]. Susceptibility bridges with temperature dependent attachments are becoming more common in paleomagnetic laboratories. However, where such equipment is not available, stepwise thermal demagnetization of a three-axis isothermal remanent magnetization (IRM) can be used to identify the magnetic minerals [*Lowrie*, 1990]. With this method, IRMs are imparted at successively lower fields on the three orthogonal axes of a sample. The IRMs are then thermally demagnetized in a stepwise manner. Thermal demagnetization of a three-axis IRM permits

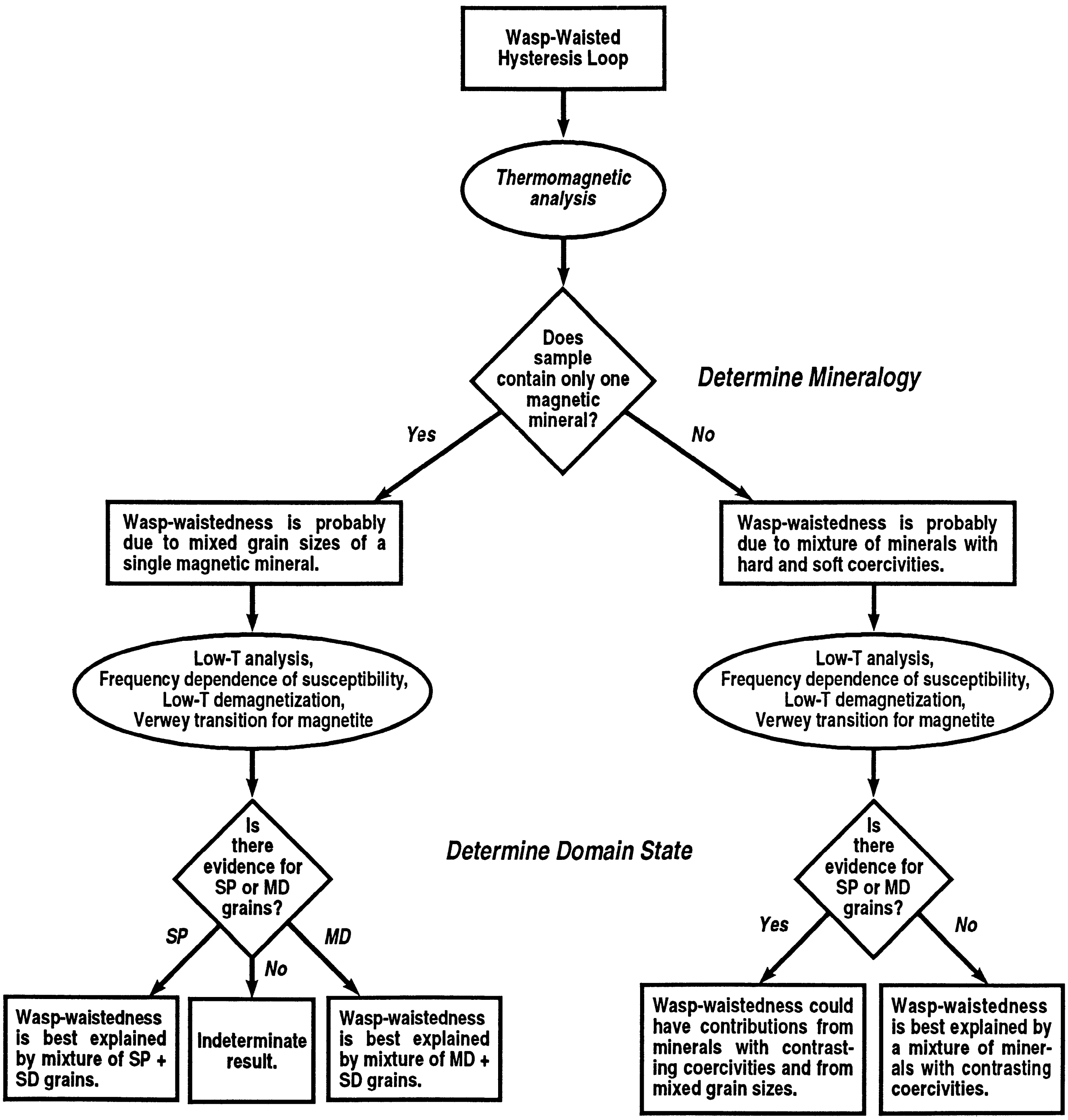

Figure 7. Flow diagram illustrating method for discrimination of the mineral magnetic components that give rise to wasp-waisted hysteresis behavior.

discrimination of thermomagnetic behavior over three ranges of coercivities and only requires conventional equipment that is available in most paleomagnetic laboratories. Diagnostic maximum unblocking temperatures and maximum coercivites are listed in Table 4 for a number of naturally occurring minerals. Ambiguities can arise, however, because several ferrimagnetic minerals have similar ranges of coercivities with maximum unblocking temperatures between 300° and 400°C (Table 4), including some titanomagnetites, maghemite, pyrrhotite, and greigite [e.g., *Lowrie*, 1990; *Roberts and Pillans*, 1993]. These problems can be partially resolved because greigite has particularly distinct thermomagnetic behavior [*Snowball and Thompson*, 1990; *Roberts and Turner*, 1993; *Reynolds et al.*, 1994] and magnetic extraction, coupled with Curie temperature or temperature-dependent susceptibility analyses, can resolve these difficulties. Low-temperature analysis is an excellent supplementary tool because several minerals undergo phase transitions at low temperatures, including pyrrhotite at 30-34 K [*Dekkers et al.*, 1989; *Rochette et al.*, 1990], the Verwey transition for magnetite at 110-120 K [*Verwey*, 1939; *Özdemir et al.*, 1993], and the Morin transition for hematite at ~250-260 K [*Morin*, 1950].

If different magnetic minerals with contrasting coercivities are identified by thermomagnetic analysis, then the wasp-waistedness can be explained as a mixture of these minerals (Figure 7). If only one magnetic mineral is identified, then it is necessary to undertake further rock magnetic characterizations in order to determine whether the wasp-waistedness is due to a distribution of magnetic grain sizes. The presence of two (or more) minerals with contrasting coercivities does not guarantee the absence of a bimodal grain size distribution of one (or more) components, which could contribute to the observed wasp-waistedness. It is therefore essential to determine whether a bimodal grain size distribution exists, particularly if only one magnetic mineral is present (Figure 7).

Magnetic Grain Size

A large number of magnetic granulometric techniques have been proposed in the literature. However, many of these techniques provide only a measure of the average mineral magnetic properties in a sample and are therefore useful only as relative indicators of grain size variation between samples. These methods tend to break down when a sample contains a mixture of grain sizes [e.g., *Lowrie and Fuller*, 1971; *Day et al.*, 1977; *Banerjee et al.*, 1981]. Grains of a given magnetic mineral can occur in three domain states: the single-domain (including pseudo-single-domain), multidomain, and superparamagnetic states. For a coercivity contrast (and wasp-waisted hysteresis behavior) to arise from a mixture of grain sizes of a single mineral, there must exist a mixture of either SD + SP or SD + MD grains. The granulometric methods emphasized in our approach are those which respond to restricted parts of the grain size spectrum and which enable discrimination between contributions from SP and MD components within a sample. SD grains are common to either type of mixture, therefore we do not seek to specifically identify SD grains.

Superparamagnetic (SP) grains. Low-temperature remanence measurements are particularly useful for determining the SP content of a sample. If there is a significant proportion of SP grains, an IRM that is induced at low temperatures will decrease during warming to room temperature as the fine particles thermally unblock and become superparamagnetic. The fraction of SP grains (f_{SP}) can be estimated by comparing the low-temperature IRM, say, that at liquid helium temperatures, with the room temperature IRM, as follows [cf. *Dunlop*, 1973]:

$$f_{SP} = \frac{M_{rs}(4.2K) - M_{rs}(300K)}{M_{rs}(4.2K)}. \quad (3)$$

Major changes in IRM due to transitions in crystalline structure or anisotropy (e.g., the Verwey transition) during the low-temperature run should be subtracted from these terms. The f_{SP} parameter will overestimate the SP content because it does not account for reduction in IRM due to temperature dependent changes in M_s from 4.2 K to 300 K. Despite this limitation, f_{SP} provides a useful maximum estimate of SP content.

The presence of SP grains can also be detected by measuring the frequency dependence of magnetic susceptibility [*Bloemendal et al.*, 1985]. Dual frequency susceptibility meters are commonly available and a measure of the frequency dependence of susceptibility is obtained by comparing the susceptibilities of a sample at low frequency and high frequency (typically over a tenfold frequency difference), as follows:

$$\chi_{fd\%} = \frac{[\chi(LF) - \chi(HF)]}{\chi(LF)} \times 100\%. \quad (4)$$

Large values of this parameter are indicative of a significant proportion of grains near the SD/SP boundary [*Bloemendal et al.*, 1985; *Thompson and Oldfield*, 1986]. *Mullins* [1977] puts an upper limit of about 8% susceptibility increase per tenfold increase in frequency; however, we have commonly observed values above 10% (see below). Values of $\chi_{fd\%}$ are directly proportional to the ratio of SP grains to magnetically stable (i.e., nonviscous or SD + MD) grains in a sample [*Bloemendal et al.*, 1985].

Multidomain (MD) grains. In addition to distinctive Curie points and Néel points, ferri/ferromagnets exhibit magnetocrystalline anisotropy transitions [*Fuller*, 1987]. Magnetite undergoes an anisotropy transition at ~130 K. MD magnetite grains lose much of their initial remanence when they are reheated to room temperature after being cooled below the anisotropy transition in zero field [*Ozima et al.*, 1964; *Kobayashi and Fuller*, 1968; *Merrill*, 1970]. *Mauritsch and Turner* [1975] used the presence of this transition to identify magnetite in ancient limestones which have magnetite concentrations as low as one part in 10^5.

The ratio of the amount of recovery or "memory" of remanence to the initial remanence is essentially 100% for SD grains whose remanence is pinned by shape anisotropy, but the ratio decreases with increasing grain size [*Dunlop and Argyle*, 1991] and is small for MD magnetite which is controlled by magnetocrystalline anisotropy. This so-called "low-temperature demagnetization" is therefore diagnostic of domain state for magnetite: the saturation IRM (SIRM) of MD grains will be demagnetized during low-temperature treatment, while SD grains will be relatively unaffected. Mixtures of MD and SD remanences in magnetite can be readily discriminated using this method. SP grains cannot contribute to the SIRM, thus this method is capable of discriminating between mixtures of SD + SP and SD + MD magnetite.

The presence of a Verwey transition in magnetite at 118 K has also often been taken to be an indicator of the presence of MD grains, because the transition is frequently observed to be suppressed in SD grains. *Özdemir et al.* [1993] studied freshly reduced magnetite grains and were able to detect a Verwey transition in SD grains; however, they noted a suppression of the transition with increasing oxidation. Pristine SD magnetite may not be common in natural environments, nevertheless, the interpretation of a Verwey transition as an indication of MD magnetite should be treated with caution.

Summary

Once the magnetic mineralogy and the range of grain sizes has been determined for a sample, the cause of the wasp-waisted hysteresis behavior should be discernible (Figure 7). If the sample contains only one magnetic mineral, then the wasp-waistedness can be attributed to mixtures of either SD + SP or SD + MD grains. If the sample contains two or more magnetic minerals, then two possibilities exist: wasp-waistedness may be due to either a mixture of magnetic minerals with contrasting coercivities or to a mixture of minerals plus a mixture of grain sizes.

Examples From Archaeomagnetic, Geologic, and Synthetic Samples

To demonstrate the proposed method for determining the sources of the coercivity contrasts that are responsible for wasp-waisted magnetic hysteresis loops in real samples, we use the materials shown in Figure 2 as examples.

Archaeomagnetic Samples, Bulgaria

Background. We have conducted mineral magnetic experiments on a number of samples from Bulgaria which were collected for archaeointensity studies by M. Kovacheva. A number of the samples were found to be unsuitable for archaeointensity determinations and mineral magnetic characterization was performed in order to understand better the archaeomagnetic results. The example shown in Figure 2a (sample BULG1371) is from a brick from a Medieval (14th century) church.

Results. The open nature of the hysteresis loop up to fields of 1 T (Figure 2a) and the results of IRM acquisition experiments (Figure 8a) demonstrate that this sample is not saturated even at fields exceeding 2 T. This behavior indicates the predominance of a high-coercivity mineral (Table 4). Temperature dependent susceptibility experiments indicate the presence of two magnetic minerals (Figure 8b). A major change in slope of the χ versus T curve at ~150°C is indicative of a mineral with a low Néel temperature, whereas the change in slope at ~540°C is probably indicative of the presence of a cation-substituted magnetite.

Three-axis IRM thermal demagnetization experiments (Figure 8c) confirm this interpretation. A large portion of the remanence is carried by the hardest component (0.4 - 2.5 T) which decreases dramatically in intensity below 150°C but persists to about 240°C. A soft component (< 0.1 T) is dominant at higher temperatures. The soft component is completely demagnetized between 500° and 550°C and is probably due to a ferrimagnetic cation-substituted magnetite with a Curie temperature of ~540°C (Figures 8b and 8c). The hard and intermediate components both demagnetize at low temperatures (Figure 8c) and are associated with the ~150°C Néel temperature phase indicated in Figure 8b. Low unblocking temperatures and hard magnetizations are usually associated with iron oxy-hydroxides such as goethite (α-FeOOH); however, goethite has maximum unblocking temperatures between 60° and 120°C (Table 4) [*Strangway et al.*, 1968; *Dekkers*, 1988b, 1989a]. Goethite dehydrates during heating at temperatures as low as 50°C [*Goss*, 1987], leading to complete transformation into hematite at about 250°C [*Wolska and Schwertmann*, 1989]. We interpret the thermal unblocking of the hard and intermediate components at temperatures up to 240°C to be due to the unblocking of goethite, accompanied by goethite dehydration, hematite formation, and partial unblocking of hematite. Above 240°C, the hard component appears to be fully converted to hematite, which has a maximum unblocking temperature between 650° and 700°C (Figure 8c).

No low-temperature phase transitions are evident (Figure 8d), as would be expected if the magnetic mineralogy comprises a mixture of goethite and surficially oxidized fine-grained magnetite [*Özdemir et al.*, 1993]. The low-temperature analysis demonstrates that a significant proportion of the remanence is blocked below room temperature (f_{SP} = 0.80). The value of f_{SP} may overestimate the SP fraction, however, because a unique characteristic of goethite is a continuous, but gradual, decrease in remanence when cycled from liquid nitrogen temperatures to room temperature [*Dekkers*, 1989b]. We therefore attribute only part of the low temperature remanence to thermal unblocking of SP grains, with the remainder being attributed to thermal unblocking of goethite. However, $\chi_{fd\%}$ values of about 10% confirm the inference from the low-temperature data that suggest a significant fraction of SP grains.

Following the method shown in Figure 7, the wasp-waisted behavior (Figure 2a) appears to be due to a contrast of coercivities between a (hard) goethite component and a (soft) cation-substituted magnetite component. A broad (or bimodal) grain size distribution of the magnetite component is also evident in the distributed blocking temperature spectrum (< 0.1 T component in Figure 8c) and in the significant SP fraction (Figure 8d). The large SP fraction probably contributes significantly to the particularly high value of B_{cr}/B_c observed for this sample (Table 1).

Lake Sediments, Butte Valley, Northern California

Background. Studies of the environmental magnetism of several lake sediment cores from part of the southern Cascade Range in northern California and southern Oregon have been undertaken in conjunction with palynological analysis to determine details of the paleoclimate history of that area [*Rosenbaum et al.*, 1994]. Magnetostratigraphic analysis of the 102-m Butte Valley core indicates that it spans at least the last 3 Ma. The Butte Valley sediments display several distinct rock magnetic properties. Periods of cool paleoclimate are characterized by high susceptibilities, low values of $\chi_{fd\%}$, and unconfined hysteresis loops that are indicative of pseudo-single-domain (PSD) magnetite grains. These samples also have consistently high values of the S parameter [*King and Channell*, 1991]

$$S = -\mathrm{IRM}_{-0.3\,\mathrm{T}}/\mathrm{IRM}_{1.2\,\mathrm{T}}, \quad (5)$$

which are indicative of a magnetic mineralogy that is dominated by a ferrimagnetic mineral such as magnetite. Periods of warmer, drier paleoclimate are characterized by low magnetic susceptibilities, high values of $\chi_{fd\%}$, and wasp-waisted hys-

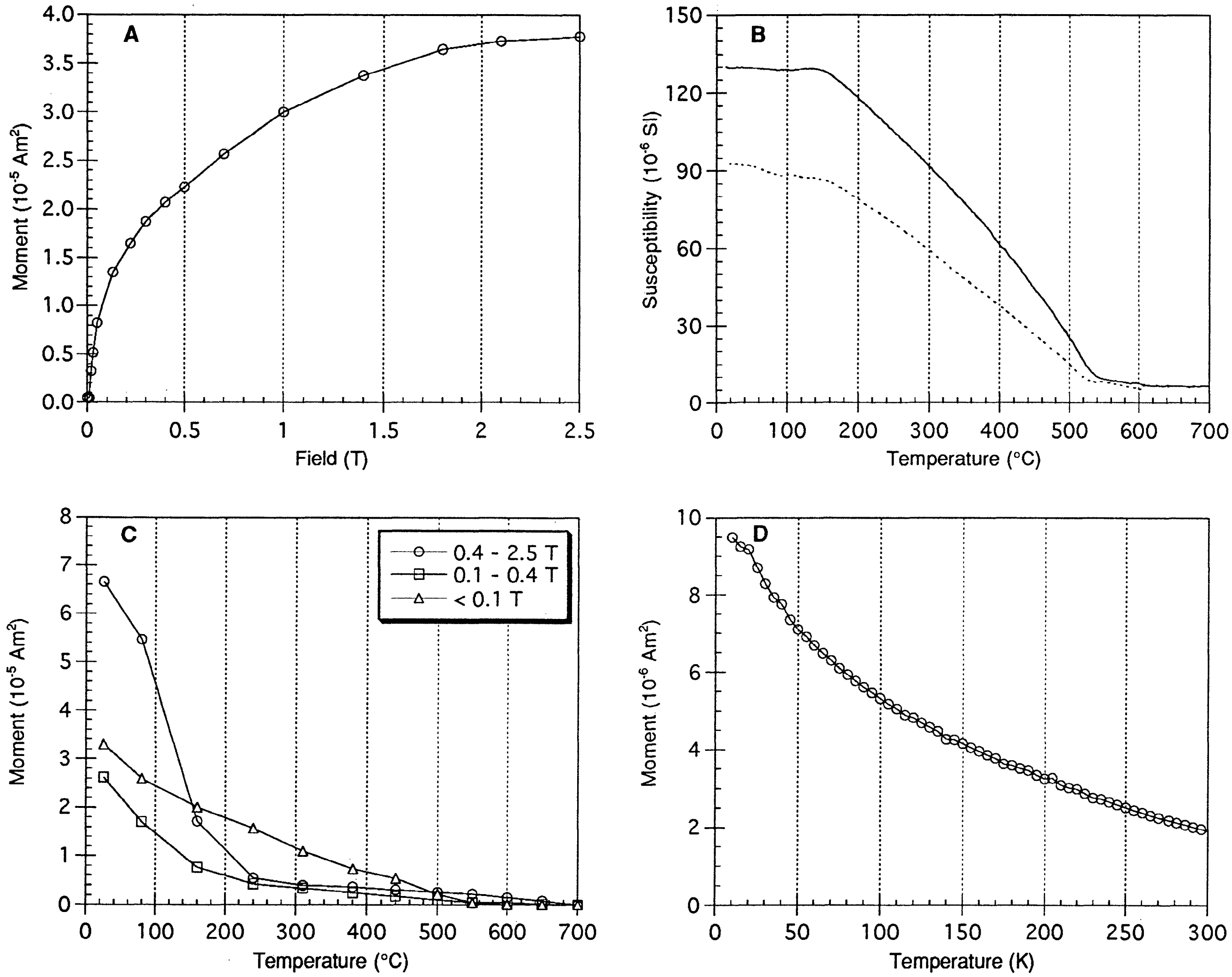

Figure 8. Magnetic characterization of Bulgarian archaeomagnetic sample BULG 1371: (a) acquisition of isothermal remanent magnetization; (b) temperature dependent susceptibility measurement (solid line, heating; dashed line, cooling); (c) thermal demagnetization of a three-axis IRM, with applied fields of 0.1, 0.4, and 2.5 T (coercivity ranges are shown on the figure); and (d) measurement of an IRM, applied at 5 K, as it warms to room temperature.

teresis loops (e.g., Figure 2b). These samples consistently have relatively lower values of the S parameter which are indicative of a magnetic contribution from a high-coercivity mineral such as hematite or goethite. The following analyses were carried out to determine the cause of wasp-waisted hysteresis behavior in a sample (BV 1675) from a depth of 58.2 m in the Butte Valley core.

Results. The hysteresis loop shown in Figure 2b is open at applied fields above 0.4 T, which indicates the presence of a high-coercivity mineral. This observation is consistent with an S value of 0.66 for sample BV 1675. Thermomagnetic analysis indicates that the magnetic assemblages of both warm and cold climate intervals are dominated by magnetite. Temperature dependent susceptibility measurements for sample BV 1675 (Figure 9a) do not indicate the presence of magnetic minerals other than magnetite. Measurements of temperature dependence of susceptibility are biased toward minerals with high magnetic susceptibilities, such as magnetite, and the presence of minerals with weak susceptibilities are less likely to be detected with this method. Nevertheless, as demonstrated in this paper, minerals with weak magnetic moments (such as hematite and goethite) must occur in significant amounts in order to give rise to wasp-waisted loops when other strongly magnetic minerals are present. Significant amounts of hematite have been observed optically in magnetic extracts of sediment from warm paleoclimate intervals in the Butte Valley core. Despite the lack of evidence for significant concentrations of hematite or goethite in the thermomagnetic data, we conclude that this experiment is ambiguous in this case because the presence of a high-coercivity mineral is strongly suggested by the hysteresis loop (Figure 2b) and the S parameter value for this sample, as well as by visual evidence for oxidized magnetic phases in other parts of the Butte Valley core where magnetic extracts were obtained.

Low-temperature measurements provide no further evidence for mixtures of magnetic minerals, as no low-temperature phase transitions are evident (Figure 9b). A large SP fraction (f_{SP} = 0.83) is evident in the major decrease in remanence after

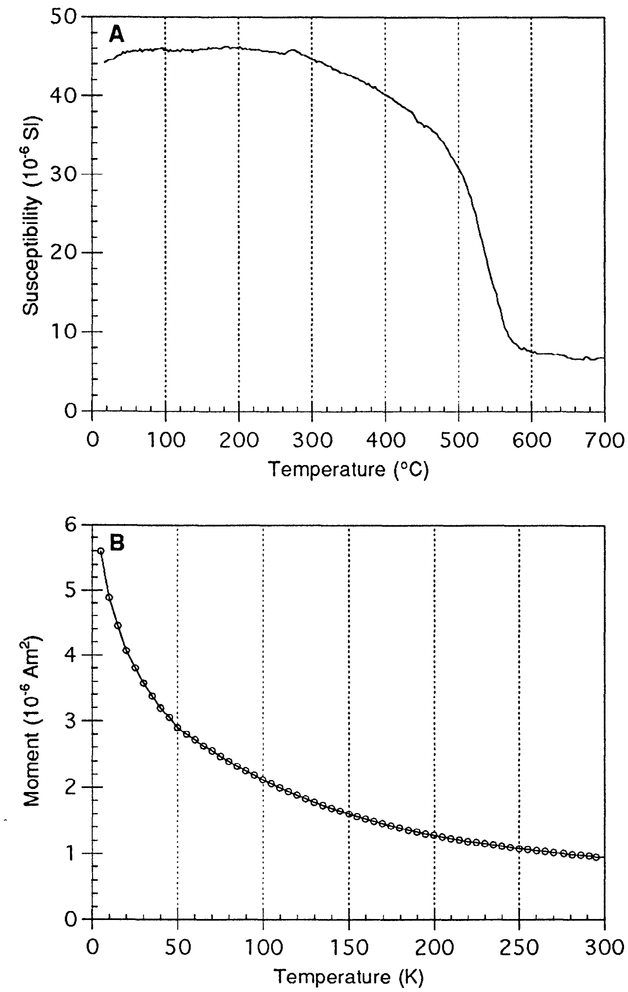

Figure 9. Magnetic characterization of Butte Valley lacustrine sediments. (a) temperature dependent susceptibility measurement and (b) low-temperature IRM measurement.

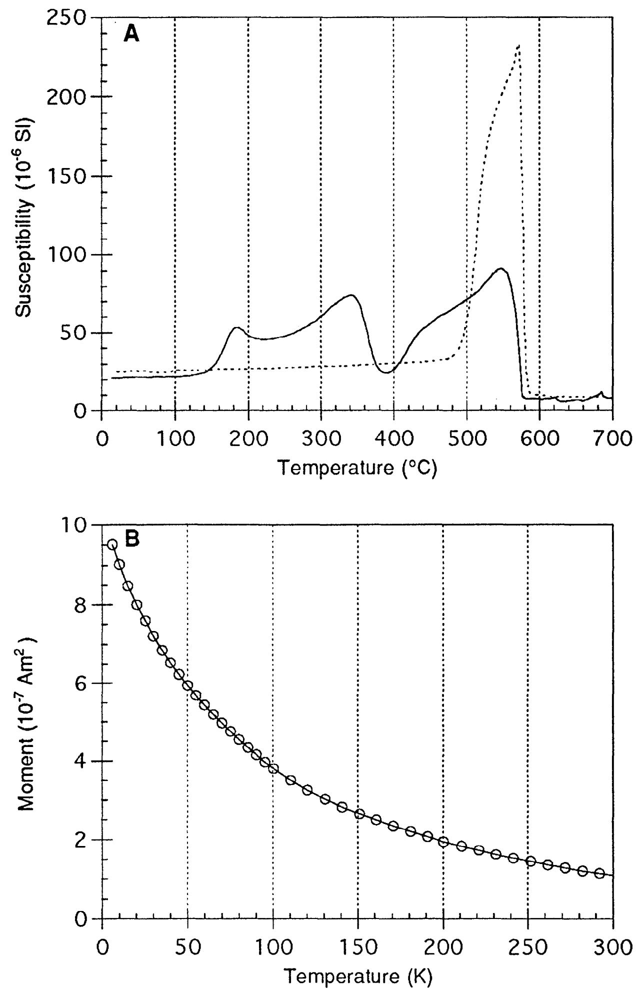

Figure 10. Magnetic characterization of synthetic greigite sample SYN93A. (a) temperature dependent susceptibility measurement (solid line, heating; dashed line, cooling) and (b) low-temperature IRM measurement.

warming from 4.2 K (Figure 9b). For the Butte Valley sediments, wasp-waisted hysteresis loops are observed only for samples with significant SP fractions, as indicated by $\chi_{fd\%}$ values generally greater than 7%. Unconstricted loops are generally observed for samples with $\chi_{fd\%}$ values up to 7%. Following the method in Figure 7, the most likely cause for wasp-waisted hysteresis behavior in the Butte Valley sediments (Figure 2b) is a mixture of SP + SD magnetite grains, although there is probably a contribution from a high-coercivity mineral such as hematite or goethite.

Synthetic Greigite

The synthetic greigite sample that produced the wasp-waisted hysteresis loop shown in Figure 2c was precipitated using a hydrothermal method that involves mixing ammonium ferrous sulfate (Mohrs salt) with a sodium sulfide solution, as described by *Uda* [1965] and *Snowball* [1991]. Thermomagnetic analysis of the synthetic sample reveals a Hopkinson peak at about 180°C, followed by further Hopkinson peaks at 340°C and 580°C (Figure 10a). The latter two Hopkinson peaks are attributed to the thermal breakdown of greigite which eventually forms magnetite, as indicated by the peak at 580°C. On cooling, the sample has converted entirely to magnetite (Figure 10a), which is typical for greigite [*Snowball*, 1991; ***Roberts and Turner***, 1993; ***Reynolds et al.***, 1994]. The Hopkinson peak at 180°C is probably due to formation of additional greigite. This temperature is frequently cited as the temperature of formation for hydrothermally synthesized greigite [*Horiuchi et al.*, 1974; *Snowball*, 1991]. The Hopkinson peak at 180°C is not surprising if the reagents in the initial synthesis did not completely react to form greigite.

Low-temperature SIRM measurements indicate a preponderance of SP grains in this sample, with a remarkably high value of f_{SP} = 0.89. This implies that up to nine-tenths of the low-temperature remanence is due to SP grains (Figure 10b). We attribute the large proportion of SP greigite grains in this sample to incomplete reaction during hydrothermal synthesis, which resulted in a large volume of hyperfine greigite grains. The thermomagnetic results indicate that no other magnetic phases are present.

We conclude (compare Figure 7) that the wasp-waisted behavior shown in Figure 2c is due to a mixture of SP + SD greigite. Wasp-waisted loops have not been obtained from natural greigite samples that have been extensively characterized by *Roberts* [1995], presumably because they contain much smaller proportions of SP grains (f_{SP} values range from 0.21 to

0.35 for the 12 natural samples analyzed). We conclude that the short time period over which the synthetic greigite was precipitated, compared to the much longer periods over which greigite forms in sedimentary environments, may have resulted in a much finer grain size distribution (with a larger proportion of SP grains) than is commonly encountered in natural sedimentary conditions. We subsequently heated the synthetic sample at 180°C for 1 hour and measured the hysteresis properties for this sample. The hysteresis loop was not wasp-waisted. This result supports our hypothesis of incomplete reaction during the initial hydrothermal synthesis: further heating at 180°C appears to have completed the reaction and has apparently diminished the contribution from the previously large population of SP greigite grains. The large fraction of SP grains therefore appears to be critical in causing the wasp-waisted hysteresis behavior in this sample.

Glaciomarine Sediment, Dry Valley Drilling Project, Antarctica

Background. The sample that produced the wasp-waisted hysteresis loop shown in Figure 2d comes from a fine-grained unit within an upper Pliocene to lower Pleistocene glaciomarine diamictite sequence at a depth of 126.0 m in Hole 10 from the Dry Valley Drilling Project, Antarctica [*McKelvey*, 1991].

Results. The loop in Figure 2d is open at field values of above 0.3 T, suggesting a contribution from a high-coercivity mineral. Thermomagnetic results indicate two Hopkinson peaks for this sample (Figure 11a). The peak at 40°C is followed by a major decrease in susceptibility to 100°C, whereas the peak at 490°C is followed by a major decrease in susceptibility to 570°C. These results are indicative of contributions to the remanence by a low Néel temperature mineral such as goethite (which gives rise to the open nature of the loop above 0.3 T), and a high Curie temperature mineral such as magnetite.

During low-temperature analysis, the magnetic moment does not drop sharply as it is heated from liquid helium temperatures to 50 K (Figure 11b), indicating that there is no significant SP fraction in this sample. A major change in slope of the remanence curve occurs above 50 K. We attribute the decay in remanence above 50 K to the presence of goethite [cf. *Dekkers*, 1989b]. A possible alternative interpretation is that the low Curie temperature mineral (Figure 11a) is a ferrimagnetic member of the ilmenite-hematite solid solution series [cf. *Nagata*, 1961]; however, this interpretation does not account so easily for the low-temperature behavior (Figure 11b). The absence of a Verwey transition indicates that the magnetite in this sample is either oxidized or is not in a MD state [*Özdemir et al.*, 1993]. In addition, the lack of evidence for SP magnetite grains suggests that the magnetite grains in this sample are of relatively uniform (SD) size. The wasp-waisted behavior shown in Figure 2d is therefore attributable to a mixture of goethite and magnetite, with no evident contribution to the coercivity contrast from a bimodal grain size distribution (compare Figure 7).

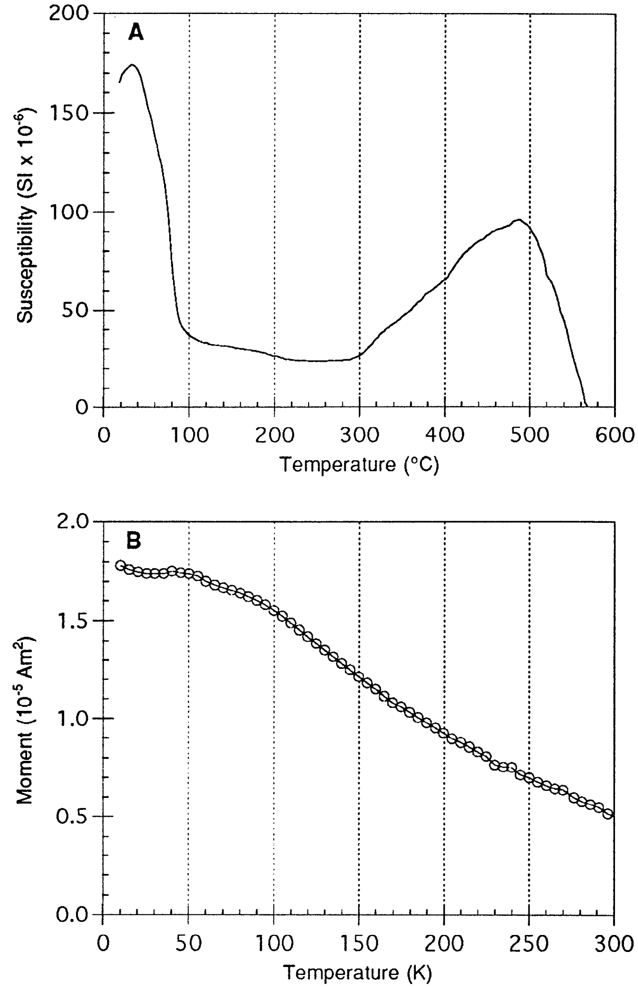

Figure 11. Magnetic characterization of DVDP 10 sample 126.0. (a) temperature dependent susceptibility measurement and (b) low-temperature IRM measurement.

Remagnetized Paleozoic Carbonate Rocks, Great Basin Cordillera

Background. *Gillett et al.* [1993] obtained wasp-waisted hysteresis loops from a number of remagnetized Paleozoic carbonate rocks from Nevada and Utah that were measured in the UC-Davis Paleomagnetism Laboratory. Their results are similar to those observed in other remagnetized Paleozoic carbonate rocks from North America and England [*Jackson*, 1990; *Jackson et al.*, 1992, 1993; *Channell and McCabe*, 1994; *McCabe and Channell*, 1994]. Preliminary data from the Great Basin Cordillera suggest that the magnetic carriers in these rocks are heterogeneously distributed on a millimeter scale and that they may be associated with stylolite-modified burrow fills and other features that may have acted as conduits for orogenic fluids in which magnetite precipitated [*Gillett et al.*, 1993]. The wasp-waisted hysteresis loops obtained from these rocks are largely determined from material in burrow fills.

Results. Of the examples shown in Figure 2, determination of the origin of wasp-waisted behavior from the carbonate rocks from the Great Basin Cordillera was the greatest challenge because of the low concentrations of magnetic minerals (compare M_s values in Table 1). A significant contribution is evident from a high-coercivity mineral because the loop remains open at applied fields of 1 T (Figure 2e). However, measurements of the temperature dependence of susceptibility from whole rock samples yielded no usable results because the magnetic susceptibility of the sample is too weak. S. L. Gillett and R. E. Karlin (written communication, 1994) have inferred from the unblocking behavior observed during thermal demagnetization that the magnetic mineralogy of the remagnetized samples from the Great Basin Cordillera is dominated by magnetite. If so, then a mixture of magnetite with the high-coercivity mineral inferred from Figure 2e would readily account for the observed wasp-waistedness. Low-temperature measurements do not elucidate the magnetic mineralogy because no low-temperature phase transitions are evident (Figure 12). A significant SP fraction is evident (f_{SP} = 0.79), based on the large decrease in magnetization as the sample warms between 5 and 50 K. We therefore attribute the wasp-waisted behavior (Figure 2e) to a mixture of a high-coercivity mineral such as hematite or goethite with a ferrimagnet (probably magnetite), with a contribution from a bimodal grain size distribution. The significant SP fraction probably contributes to the particularly high value of B_{cr}/B_c (Table 1).

Low concentrations of magnetic grains in the one remagnetized carbonate sample that we studied prevented us from unambiguously determining the origin of the wasp-waisted hysteresis behavior. This sample demonstrates the lower limit of the method outlined above. *Jackson et al.* [1992] also reported ambiguous results from weakly magnetized and remagnetized Paleozoic carbonate rocks. However, the method outlined above is clearly applicable to the important mineral magnetic problem of discriminating between mixed magnetic components that give rise to wasp-waisted hysteresis loops in relatively strongly magnetized samples. A means of making progress in understanding the rock magnetic origin of remagnetized carbonate rocks is to concentrate on the most strongly magnetized samples from a suite of remagnetized rocks and then to work on weaker samples once successful results are obtained from the relatively strongly magnetized samples.

Conclusions

Our results, combined with a review of previous work, indicate that there are several conditions that give rise to, as well as magnetic properties that are characteristic of, wasp-waisted hysteresis loops. First, at least two mineral magnetic components with strongly contrasting coercivities must coexist. Second, materials that give rise to wasp-waisted hysteresis loops will have relatively high values of B_{cr}/B_c because B_c is controlled by the soft (low coercivity) component, whereas B_{cr} is controlled by the hard (high coercivity) component. Third, values of $B_{cr}/B_c \geq 10$ usually only occur for strongly wasp-waisted loops in which the low coercivity component comprises an overwhelmingly large fraction of the total volume of magnetic grains. Materials with strongly wasp-waisted hysteresis loops will have high values of B_{cr}/B_c. Fourth, a given mixture of SP + SD grains is more likely to give rise to wasp-waisted hysteresis loops than an equivalent mixture of SD + MD grains (compare Figure 6). The examples given in this paper confirm that SP grains can be a significant contributor to wasp-waisted hysteresis behavior. Fifth, our results provide empirical confirmation that the total magnetization of a mineral is the sum of the weighted contributions of each component, in the absence of significant magnetic interactions between particles. Thus to be a significant contributor to wasp-waistedness, a mineral magnetic component must carry a significant portion of the total magnetization of the rock. Minerals with weak magnetic moments such as hematite therefore need to occur in large concentrations to cause wasp-waistedness in materials that also contain ferrimagnetic minerals.

The method outlined in Figure 7 has proved valuable in determining the magnetic components that give rise to wasp-waisted hysteresis loops. Examples of the use of this method demonstrate that wasp-waisted loops from natural materials can arise from mixtures of: a single magnetic mineral with a broad grain size distribution (Figure 2c); two minerals with strongly contrasting coercivities (Figure 2d); two minerals with strongly contrasting coercivities, plus a broad grain size distribution from one of the components (Figures 2a, 2b, and 2e). Our results demonstrate that, in general, this method should provide a basis for deriving a greater understanding of complex mineral magnetic systems and a better means of distinguishing between different magnetic components in a rock.

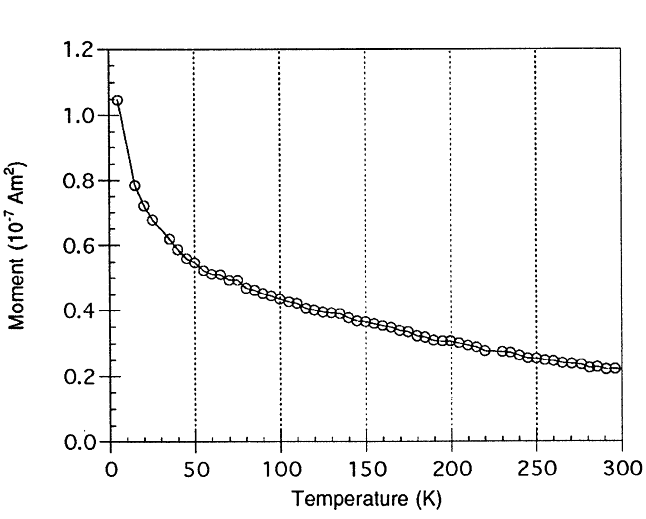

Figure 12. Low-temperature IRM behavior of remagnetized Paleozoic carbonate sample BKDR4A from the Great Basin Cordillera.

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Y. L. Cui, A. P. Roberts, and K. L. Verosub, Department of Geology, University of California, Davis, CA 95616. (e-mail: cui@geology.ucdavis.edu; roberts@geology.ucdavis.edu; verosub@geology.ucdavis.edu)

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