Notes on producing Day plots
from MicroMag VSM data

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1 Introduction

The Day plot (Day et al., 1977) has been a standard rock magnetic analysis technique for decades. It has been described in numerous papers and textbooks, but simple, practical guidance on taking the requisite measurements and generating the plot can be hard to find. These are some basic notes I made to provide such guidance and to collect relevant references, with particular emphasis on the following topics:

1. Magnetic units in the SI and cgs systems, and conversions between the two systems.

2. The definitions of the magnetic parameters used in the Day plot.

3. The data file format produced by the widely-used PMC MicroMag 3900 Vibrating Sample Magnetometer (VSM) (Princeton Measurements Corporation, 2009), and how the requisite parameters can be calculated by the Micro-Mag software and extracted from these files.[1]

The first two topics are of course relevant to many other areas of rock magnetism, and have been explained in several other publications, but I found it useful to summarize them here.

I wrote these notes for my own personal use, and am publishing them in the hope that they might be useful to others. They should be considered a work in (eternal) progress; corrections and additions are welcome.

2 Units in SI and cgs

Table 1 shows the units relevant to the Day plot. Note that the cgs and SI units are not directly equivalent. Converting directly between cgs and SI introduces inconvenient factors of 4π, so cgs units are usually converted to convenient *corresponding* (but not equivalent) SI units as follows:

- Convert the cgs magnetic field H (in oersted) to cgs magnetic induction B (in gauss). In practice, this is simply a relabelling: in cgs $B = H + 4\pi J$, and because we're measuring the field in free space, $J = 0$ and the equation becomes $B = H$. Thus, the quantity does not change. Next, convert this cgs magnetic induction (in gauss) to the SI magnetic induction (in tesla) by the equivalence $1\,\text{T} = 10^4\,\text{G}$.

- Convert the cgs magnetization J (in emu cm^{-3}) to cgs magnetic dipole moment per unit volume M (in emu cm^{-3}). Again, this is just a relabelling, because $J = M$ in cgs. Then convert

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[1]The material on data processing should also apply to the MicroMag 2900 AGM, which uses the same software and file format. As of 2017, both the 2900 and the 3900 have been discontinued. They have been succeeded by the 8600 and 7400-S series VSMs from Lake Shore Cryotronics, but I don't know whether the new instruments use the same data format.

Symbol	Quantity	SI units			cgs units
H	magnetic field	1	A/m	$= 4\pi \times 10^{-3}$	**oersted (Oe)**
B	magnetic induction	1	**tesla (T)**	$= 10^{4}$	gauss (G)
J	magnetization; magnetic polarization	1	tesla (T)	$= 10^{4}/(4\pi)$	**emu cm^{-3}**
M	magnetic dipole moment per unit volume	1	**A/m**	$= 10^{-3}$	emu cm^{-3}

Table 1: Units relevant to the Day plot in the SI and cgs unit systems, and the conversion factors between them. SI magnetic data is usually reported in terms of B and M, and cgs magnetic data in terms of H and J. These conventions are indicated in the table by the use of bold type for the preferred units in each system. Note that 'gauss' is sometimes used synonymously with emu cm^{-3} for J and M.

Symbols	Names	Definition	MicroMag field name
M_{r}, M_{rs}, J_{r}, J_{rs}, SIRM	saturation [isothermal] remanent magnetization	The remanence of a sample after removal of a saturating field.	Remanence
M_{s}, J_{s}	saturation magnetization, spontaneous magnetization	The maximum magnetization of a sample measured within a magnetizing field, after paramagnetic slope correction.	Saturation
B_{c}, H_{c}, $(B_0)_{\mathrm{c}}$	coercive force, coercivity	The direct reversed magnetic field that must be applied to reduce to zero the saturation magnetization that was imparted in the opposite direction.	Coercivity
B_{cr}, H_{cr}, H_{rc}, $(B_0)_{\mathrm{cr}}$	coercivity of remanence, remanent coercive force	The direct reversed magnetic field that must be applied and then removed to demagnetize to zero a saturation remanent magnetization that was imparted in the opposite direction.	Coercivity (remanent)

Table 2: Parameters used for the Day plot. The final column contains the verbatim label used for the parameter in a MicroMag data file.

the cgs magnetic dipole moment per unit volume (in emu cm^{-3}) to the SI magnetic dipole moment per unit volume (in A/m) by the equivalence $1 \text{ A/m} = 10^{-3} \text{ emu cm}^{-3}$.

There are many published guides to the confusing world of magnetic units. Payne (1981), Shive (1986), Moskowitz (1995), Butler (1992) (Appendix 1.1 to Chapter 1), and Stoner and St-Onge (2007) (Section 2.2) are all worth looking at. Shive (1986) is particularly concise, clear, and practically oriented.

3 Parameter definitions

Table 2 shows the parameters used in constructing a Day plot. In the literature there is considerable variation in the names and symbols used for the parameters, and in the capitalization and italicization of the letters that compose the symbols – sometimes even within the same publication. For the present work, I've standardized on upper-case italic letters with lower-case roman subscripts.

As the table shows, both M and J are used for magnetization, and both B and H for field. Strictly speaking, H and J should be used when data is presented in terms of field and magnetic polarization (as is usual for cgs); B and M should be used when data is presented in terms of induction and dipole moment per unit volume (as is usual for SI). These conventions are not always followed in practice. In any case, it's not a major concern for the Day plot, where the physical units cancel out and the plotted data represent dimensionless ratios. In the present work, I use M_r, M_s, B_c, and B_{cr}.

4 Definition of a Day plot

A Day plot plots M_r/M_s (on the y axis) against B_{cr}/B_c (on the x axis) (Figure 1). In the original paper by Day et al. (1977), the axes are linear, but logarithmic axes have also been used in the literature.

The y axis gives the *remanent* saturation magnetization divided by the *in-field* saturation magnetization, so we expect that the values will always be below 1 (and usually well below 1 for natural materials). Typically the axis range runs from 0 to 0.6.

The x axis gives the coercivity of remanence divided by the coercive force. Intuitively, we'd expect most values to be above 1 here: the coercivity of remanence has to be strong enough to reset the saturation remanence to zero, but the coercive force just has to be strong enough to hold the magnetization at zero while the field is being applied. Typically this axis starts at 0 or 1 and extends to somewhere from 5 to 10.

The Day plot is divided into behaviour regions (SD, PSD, MD) by horizonal and vertical lines. SD behaviour is inferred for samples that plot in the high-M_r/M_s, low-B_{cr}/B_c (top left) corner, MD behaviour for the low-M_r/M_s, high-B_{cr}/B_c (bottom right) corner, and PSD behaviour in the middle. At least two sets of values have been proposed for the limits; they are listed in Table 3.

Other values sometimes occur in the literature. For example, Thompson and Oldfield (1986) and Peters and Dekkers (2003) both appear to use 0.08 as the lower M_r/M_s limit. Evans and Heller (2003) note that the upper B_{cr}/B_c limit for SD behaviour has been 'rather arbitrarily' accepted as 1.5, and that 'it seems that it cannot exceed ~2'. Table 2 of Parry (1982) gives a more detailed interpretation of the parameter ranges, including expected results for mixtures of different magnetic grain sizes.

5 MicroMag VSM data file structure

A MicroMag data file is a text file with CRLF line terminators and ISO-8859-1 text encoding. Two types of data file are needed to obtain the parameters for a Day plot: the hysteresis file and the IRM file. Each of these file types can be post-processed with the MicroMag software after initial measurement to perform various operations (unit conversions, paramagnetic slope correction, mass normalization, etc.). Post-processing produces a file of the same format, but with various values added or changed.

The hysteresis file provides the M_r ('Remanence'), M_s ('Saturation'), and B_c ('Coercivity') parameters;
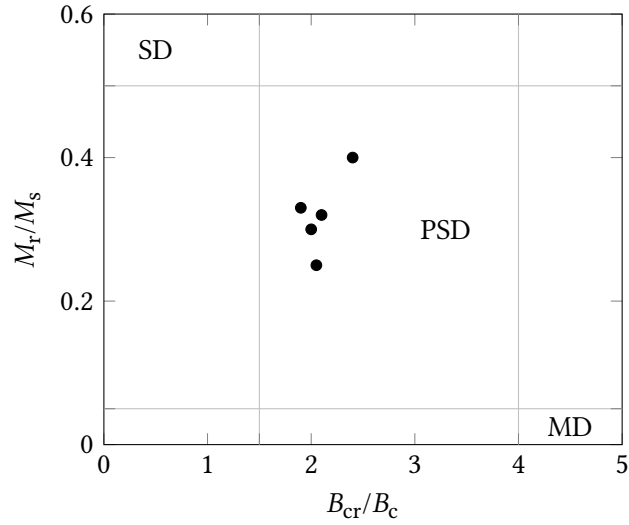
3

Figure 1: A Day plot with linearly scaled axes and the original Day et al. (1977) zone boundaries, showing several samples plotted in the PSD zone.

Source	B_{cr}/B_c lower	B_{cr}/B_c upper	M_r/M_s lower	M_r/M_s upper
Day et al. (1977)	1.5	4	0.05	0.5
Dunlop (2002a)	2	5	0.02	0.5

Table 3: Values for the zone boundaries in a Day plot.

Name of unit system	Field units Description	Header	Magnetization units Description	Header
cgs	oersteds	Oe	emu	emu
SI	amps per meter	A/m	amps per meter square meter *[sic]*	Am^2
Hybrid SI	Tesla	T	amps per square meter	Am^2

Table 4: Unit systems in MicroMag data files. Descriptions are taken verbatim from the manual (Princeton Measurements Corporation, 2009, section 4.14.2) (but see note in text); headers are as used in MicroMag output files.

Parameter	Value in cgs	Value in hybrid SI	Value in SI
Saturation	$12.910\,00 \times 10^{-3}$ emu	$12.910\,00 \times 10^{-6}$ Am^2	$12.910\,00 \times 10^{-6}$ Am^2
Remanence	636.5501×10^{-6} emu	636.5502×10^{-9} Am^2	636.5502×10^{-9} Am^2
Coercivity	121.5145 Oe	$12.151\,45 \times 10^{-3}$ T	$9.669\,818 \times 10^{3}$ A/m

Table 5: Magnetic parameters for a single sample in MicroMag's three available unit systems, measured in the 'hybrid SI' system and converted to the other two systems.

the IRM file provides B_{cr} ('Coercivity (remanent)'). The names in brackets are the textual labels that the MicroMag data file uses for these parameters.

Post-processing can, among other things, correct for the paramagnetic slope of a hysteresis curve and specify a mass for hysteresis or IRM measurements. For a hysteresis file, post-processing to apply a slope correction is essential for a meaningful M_{s} ('Saturation') value. For an IRM file, no post-processing is necessary for a Day plot: we just need the coercivity of remanence, which is accurately recorded in the original measurement file, and doesn't change if the sample mass is added in post-processing.

A VSM file can use any one of three possible unit systems. The unit system is specified in the first few lines of the file, and the units are explicitly stated in the column headers at the start of the list of measured magnetizations. The unit systems, as detailed in the MicroMag manual, are listed in Table 4.

The 'magnetization' units here aren't really magnetization units: they're magnetic moment units, since they're not normalized by volume (volume is not usually measured for a VSM sample). This doesn't matter for a Day plot, since we take the ratio of two magnetizations, so the volume would have cancelled out in any case. The unit definitions are a little confusing in the MicroMag manual. 'Amps per meter square meter' and 'amps per square meter' are presumably typos for the magnetic moment unit 'amp square meter' (Am^2) – and indeed this is what's specified in the column headers within the data files themselves when 'SI' or 'SI hybrid' units are used.

The unit system is set in the MicroMag software before measuring data or opening a previously measured file. The MicroMag software can convert the units during the post-processing step. In fact, it *will* convert the units automatically to whatever is currently configured in the settings, so it's important to check the settings before opening a file. When producing a Day plot, the workflow is simplified and the risk of mistakes reduced if all the input files use the same unit system.

6 Exploring unit systems and conversions in MicroMag files

To check the unit conversions performed by the MicroMag program, I measured a hysteresis loop for a sample (C5A35 from the NextData project) in the 'hybrid SI' system, then opened it in the program. I saved copies in the cgs and SI unit systems, then compared the hysteresis parameters from the three files. Table 5 shows the parameters in the three unit systems.

The magnetization values, saturation and remanence, are as they should be: identical in SI and hybrid SI (both using Am^2), and 1000 times larger in cgs (using emu) because $1\,\mathrm{Am}^2 = 10^3$ emu. Strangely, the rescaled cgs value for the remanence differs from the SI values in the last digit – perhaps the result of a rounding error in the MicroMag software.

What about the coercivity? It was originally recorded as an induction of $12.151\,45 \times 10^{-3}$ T in

```
MicroMag 2900/3900 Data File (Series 0016.002)
Direct moment vs. field; Initial magnetization; Hysteresis loop

INSTRUMENT
Configuration                 VSM
Temperature control           LHe Cryostat
Hardware version              0004
Software version              11/19/2010
Units of measure              Hybrid SI
Temperature in                Kelvin


...


PROCESSING
Background subtraction         No
...
Pole saturation                No
Slope correction              -9.666375E-06


...


CHARACTERIZATION
Initial slope                 +24.89977E-06
Saturation                    +3.241162E-06
Remanence                     +636.5501E-09
Coercivity                    +14.77686E-03
S*                            +39.20670E-03


...
                                             Adjusted        Adjusted
    Field            Moment     Temperature    Field           Moment
     (T)             (Am²)         (K)          (T)            (Am²)
+4.511724E-06,+21.33971E-09,+294.9284E+00,+4.511724E-06,+21.29610E-09
+9.753983E-03,+408.0768E-09,+294.9282E+00,+9.753983E-03,+313.7911E-09
...
```

Figure 2: Excerpts from a MicroMag hysteresis data file, post-processed to apply paramagnetic slope correction. Ellipses denote omitted sections.

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MicroMag 2900/3900 Data File (Series 0016.002)
Remanence curves:  IRM + DCD


INSTRUMENT
Configuration                 VSM
Temperature control           LHe Cryostat
Hardware version              0004
Software version              11/19/2010
Units of measure              Hybrid SI
Temperature in                Kelvin


...


CHARACTERIZATION
Initial slope                 N/A
Saturation                    N/A
Remanence                     +632.9187E-09
Coercivity (direct)           N/A
Coercivity (remanent)         +33.67905E-03
S* (direct)                   N/A
S* (DCD)                       -14.22482E-03


...


    Field          Remanence
     (T)             (Am² )
-214.3805E-09,-3.874648E-09
+19.93073E-03,+99.01363E-09
...
```

Figure 3: Excerpts from a MicroMag IRM data file. Ellipses denote omitted sections.

the 'hybrid SI' system.

To convert the 'hybrid SI' induction (in tesla) into an SI field strength in A/m, we divide by μ_0 (the permeability of free space), equal to $4\pi \times 10^{-7}$ in the SI system. This gives approximately $9.669\,817 \times 10^3$, a close (albeit not exact) match for the value in the MicroMag file saved with the SI unit system.

To convert the 'hybrid SI' induction (in tesla) into a cgs field strength in oersteds, we could start from our converted SI field in A/m and multiply by $4\pi \times 10^{-3}$ to get oersteds, giving 121.5145 Oe, which matches the result of the MicroMag conversion. More simply, we can first convert the 'hybrid SI' induction (tesla) to a cgs induction (gauss) by the equivalence $1\,\mathrm{T} = 10^4\,\mathrm{G}$, then trivially convert the resulting cgs induction to a cgs field by the simple equivalence $1\,\mathrm{G} = 1\,\mathrm{Oe}$. This gives $12.151\,45 \times 10^{-3} \times 10^4$, once again equal to the value of 121.5145 in the cgs file.

7 Applying the paramagnetic slope correction

The hysteresis loop as measured shows the combined response of all the minerals in the sample, including dia- and paramagnetic minerals. Typically a natural sample will have a combined ferromagnetic and paramagnetic behaviour. We can't get a meaningful M_s value out of this: the paramagnetic component doesn't saturate, so the reported 'Saturation' value is actually just the magnetization at the highest field the machine applied. The MicroMag software can fix this by fitting a straight line to the paramagnetic component (using the high-field ends of the curve where it dominates) and subtracting this line from the entire curve. The resulting curve flattens out at high field strengths, making it easy to determine the ferromagnetic *(s. l.)* saturation magnetization.

8 Ratio calculation: worked example

The relevant parts of a MicroMag hysteresis file and the corresponding IRM file are reproduced in Figure 2 and Figure 3 respectively. Note that both files are using the same unit system (Hybrid SI), and the hysteresis file has been slope corrected. The headers of the data sections at the end provide additional confirmation that the files are using the same units. Taking the 'Remanence', 'Saturation', and 'Coercivity' values from the hysteresis file, and the 'Coercivity (remanent)' value from the IRM file, we can calculate the parameter ratios as follows:

$$B_{cr}/B_c = \frac{33.679\,05 \times 10^{-3}}{14.776\,86 \times 10^{-3}} = 2.279175$$

$$M_r/M_s = \frac{636.5501 \times 10^{-9}}{3.241\,162 \times 10^{-6}} = 0.1963956$$

This sample will thus plot in the PSD zone of the Day plot.

9 Further reading

Parry (1982) presents experimental rock magnetic results for magnetite of various origins and grain sizes with the aim of modelling mixtures of domain configurations corresponding to points on a Day plot.

Thompson and Oldfield (1986): hysteresis loops are described in Section 2.3, and the Day plot in Section 4.7 ('General magnetic properties of natural materials').

Dunlop (2002a,b) significantly develops the Day plot, and presents new mixing curves with the power to more thoroughly characterize samples by means of M_r/M_s and B_{cr}/B_c.

Evans and Heller (2003), Section 2.6.5: one of the more comprehensive and comprehensible introductions to the Day plot and its practical application.

Roberts et al. (2011) is not primarily focused on explaining the Day plot as such, but is a good demonstration of its application. It also contains useful rock magnetic background information, including a glossary.

10 References

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11 License