Magnetic Analysis of Soils from the Wind River Range, Wyoming

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MAGNETIC ANALYSIS OF SOILS FROM THE WIND RIVER RANGE, WYOMING

BY

EMILY QUINTON

A THESIS SUBMITTED TO
THE FACULTY OF THE ENVIRONMENTAL SCIENCE PROGRAM
IN CANDIDACY FOR THE BACCALAUREATE DEGREE
WITH HONORS IN ENVIRONMENTAL SCIENCE

ENVIRONMENTAL SCIENCE PROGRAM

HARTFORD, CONNECTICUT
MAY 4TH, 2011
MAGNETIC ANALYSIS OF SOILS FROM THE WIND RIVER RANGE, WYOMING

BY

EMILY QUINTON

Honors Thesis Committee

Approved:

Christoph Geiss

Jonathan Gourley

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Date: 5/6/2011
In lieu of an 'in person' signature, please consider this message as a full acceptance of this thesis my Emily E. Quinton.

Sincerely, Dr. Dennis Dahms

--

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"Research is to Teaching as Sin is To Confession; Unless you participate in the Former, You have nothing to say in the Latter."

    - John Slaughter, National Science Foundation.
Table of Contents

Abstract 1
Introduction 2
Methods 4
Results and Discussion 9
Conclusions 26
Acknowledgements 27
Bibliography 28

Tables

1: Magnetic parameters used in this study 8

List of Figures

1: Map of Wyoming and Red Canyon 5
2: Magnetic properties of WIN10B (Holocene) 10
3: Magnetic properties of WIN10A (Pinedale) 11
4: Magnetic properties of WIN10D (late Bull Lake) 12
5: Magnetic properties of WIN10E (early Bull Lake) 13
6: Magnetic properties of WIN10C (Sacagawea Ridge) 14
7: Hysteresis loop for WIN10A 5-10 cm and Day Plot 16
8: Variations of magnetic properties with age 18
9: XRD analyses for two representative samples 21
10: Comparison of hematite abundance from coercivity proxies 22
11: Modified L-ratio vs. HIRM300 and coercivity summary 25
Abstract

In order to constrain the rate of magnetic enhancement in glacial fluvial sediments, we investigated modern soils from five fluvial terraces in the eastern Wind River Range, Wyoming. Profiles up to 1.2 m deep were sampled in five cm intervals from hand-dug pits or natural riverbanks exposures. These profiles include soils from fluvial terraces correlated to Sacagawea Ridge, Bull Lake and Pinedale-age glacial advances and one Holocene profile. Soil ages range from approximately >500 ka to modern. To characterize changes in magnetic properties we performed a variety of rock magnetic analyses. Abundance and grain size of magnetic minerals were estimated through measurements of magnetic susceptibility, anhysteretic remanent magnetization and isothermal remanent magnetization. We also examined the absolute and relative contributions of ferrimagnetic magnetite/maghemite and antiferromagnetic hematite to the magnetic signal through measurements of “hard” isothermal remanent magnetization, S-ratios and magnetic coercivity distributions. Magnetic enhancement of the A-horizon as well as an increase in fine-grained material occurred mostly in and not prior to the Bull Lake profiles. A loss of ferrimagnets and an increase in antiferromagnetic minerals occurred in older soil profiles, suggesting the conversion of ferrimagnetic magnetite or maghemite to weakly magnetic hematite with progressing soil age. Absolute and relative hematite abundance increases with age, making it a useful proxy for soil age. All coercivity proxies are consistent with each other, which suggests that observed changes are representative of real changes in hematite abundance rather than shifts in coercivity distributions, even though the modified L-ratio varies widely.
Introduction

In the past rock-magnetic studies of soils have successfully applied to a range of questions in geology as well as soil science. These studies have various goals but utilize the same basic measurements to characterize the iron-bearing magnetic minerals present in soil. Some of the first studies (e.g., Kukla et al., 1988) aimed to delineate soil horizons and quantify the degree of soil development in loess-paleosol sequences on the Chinese Loess Plateau. More recently, Grimley et al., (2004; 2008) utilized changes in magnetic susceptibility to delineate the extent of hydric soils. Several authors (e.g., Singer et al., 1992; Grimley et al., 2003; Vidic et al., 2004) correlated soil age and pedogenic development within the increase of ferrimagnetic minerals in the upper soil horizons and used these correlations to estimate rates of magnetic enhancement or to constrain the duration of soil development.

Soil-magnetic analyses have also been used to understand the relationship between a given soil profile and its parent material, sediment provenance, and to characterize erosion rates (e.g., Dearing et al., 2001; Spassov et al., 2005). A correlation of the magnetic signal and precipitation can be used to reconstruct past changes in climate, particularly variations in precipitation (Heller and Liu, 1986; Maher et al., 2003b; Virina et al., 2000; Maher and Thompson, 1995; Han et al., 1996). Each of these studies posed questions that often necessitate further study across varied locations and pedogenic conditions. For example, the models and correlations that link magnetic enhancement to climate are specific to a limited region, and the process of magnetic enhancement and its causes are still poorly understood. Singer and Fine (1989) examined various pedogenic processes, while others (e.g., Maher et al., 2003a; Geiss and Zanner 2007) correlated modern climate with pedogenic enhancement in modern soils. Dearing
et al., (1996) as well as Blundell et al., (2009) applied statistical analyses to a large national data set to pinpoint the factors most responsible for magnetic enhancement.

In addition, the rates of magnetic enhancement are only poorly constrained. Singer et al., (1992), from their study of California beach terraces, concluded that timescales of up to 100,000 years were required for significant development of ferrimagnetic minerals to occur. Maher and Hu (2006), on the other hand, suggested that magnetic properties might develop rapidly in loess, which is supported in a recent study by Geiss et al., (2009).

Lastly, the main pathways of magnetic enhancement are still under investigation. In many mid-latitude sites the formation of pedogenic magnetite and maghemite appears as the main cause of enhancement (Orgeira et al., 2011). In some soils, however, there is evidence that ferrimagnetic minerals are only an intermediate stage in the enhancement process and antiferromagnetic hematite is the end member (e.g., Torrent et al., 2006). Long-term soil development can be further complicated in sites that experience cyclical climate patterns, such as a succession of glacial and interglacial climates (Hall, 1999).

In this study, we carefully characterized the magnetic properties of five soil profiles from a chronosequence of the eastern flank of the Wind River Range to estimate rates and pathways of magnetic enhancement for soils that purportedly formed over the past <10,000 ka - 730,000 ka (Dahms, 2010). These soils developed under a mostly semiarid climate in gravel deposits derived from Triassic redbeds and are dominated by hematite. They offer the opportunity to investigate the effects of magnetic enhancement on soils developed in an unusual parent material over time spans up to more than half a million years.
Methods

Profile locations and site descriptions

In August 2010 we sampled five soil profiles (WIN 10 A through E) from fluvial terraces in Red Canyon, 10 miles South of Lander, Wyoming (Fig. 1). Our soils developed in Quaternary gravels derived from the Triassic redbeds of the Chugwater group. The soils are mapped as part of the Sinkson-Thermopolis soil association (Young, 1981). They are deep and well drained and contain a well-developed Bky horizon below approximately 36 cm depth. Mean annual precipitation for Lander is 230 mm/year with most precipitation occurring during spring and fall. The average annual temperature is approximately 6.5ºC, ranging from -7ºC during the winter to over 20ºC during the summer months (NOAA Satellite and Information Service, 4/27/2011).

Age estimates for these profiles are based on landscape position and range from Holocene, <10 ka (WIN10B), to Sacagawea Ridge, 730 – 610 ka (WIN10C). Terrace ages are estimated using terrace heights above modern streams, relative soil development, and correlations to regional soil/terrace chronosequences (Dahms, 2010). Four of the profiles were collected from shallow soil pits (WIN10A, C, D and E) while WIN10B was collected from a natural exposure. All profiles were described in the field following procedures outlined in the Soil Survey Manual (1993).

Samples were collected every five centimeters throughout the upper meter of the profile. The sampling interval was increased to 10 cm for the deeper part of the profiles in WIN10D and WIN10E. In the field samples were disaggregated by hand, passed through a two mm sieve and approximately 100 cm³ of soil were placed in plastic bags for further analysis.
Figure 1: Map of Red Canyon, near Lander, Wyoming.
In the laboratory samples were air-dried, homogenized and packed into weakly diamagnetic plastic boxes with a volume of 5.3 cm$^3$. Sample masses ranged between 6.3 and 9.5 g. For high-field analyses, which used a vibrating sample magnetometer (VSM), a select subset of samples was tightly packed into small gelcaps, which accommodated approximately 0.3 – 0.4 g of dried sample.

Loss on ignition (LOI) was used to determine inorganic and organic carbon content for the A- and Bk-horizon of each soil profile. We followed the procedure for LOI as set by Dean (1986). X-ray analyses were conducted for representative bulk samples to confirm the nature of the high-coercivity magnetic component. These analyses were performed using a PANalytical X’pert Pro diffractometer equipped with a rotating sample stage and X’celerator detector.

**Rock-Magnetic Analyses**

We performed rock-magnetic analyses to characterize the abundance, grain-size and mineralogy of the magnetic minerals present in the soil. Table 1 lists all magnetic parameters used in this study. We measured mass normalized magnetic susceptibility ($\chi$) using a KLY-4 Kappabridge susceptibility meter. Anhysteric remanent magnetization (ARM) was acquired in a peak field of 100 mT combined with a 50 $\mu$T bias field using a Magnon International AFD 300 alternating magnetic field demagnetizer. Isothermal remanent magnetization (IRM) was acquired through three pulses of a 100 mT field using an ASC-Scientific IM-10-30 pulse magnetizer. SIRM was acquired in three 2.5 T field pulses, followed by a backfield applied in three field pulses of -0.1 T and -0.3 T respectively. All remanence values were measured using an AGICO JR6 spinner magnetometer with a sensitivity of 2×10$^{-6}$ A/m.
These measurements were used to calculate S-ratios, \( S_{100\text{mT}} \) and \( S_{300\text{mT}} \), see Table 1 for definitions), as well as “hard” IRM (HIRM) to estimate the relative and absolute abundance of high-coercivity (“hard”) antiferromagnetic minerals, such as hematite or goethite. The modified L-ratio (Hao et al., 2008; Liu et al., 2007; Liu et al., 2010) was also calculated to aid in the interpretation of S-ratios and HIRM.

Magnetic coercivity distributions were determined through stepwise alternating-field (AF) demagnetization of an IRM, acquired in three field pulses of 1200 mT. The maximum AF demagnetization field was 300 mT. Coercivity data were fitted to cumulative log normal distributions using the methodology outlined by Geiss et al., (2008). These analyses were performed on a subset of samples. To extend coercivity distributions to higher demagnetization fields the same subset of samples acquired a SIRM in a 2 T field, followed by stepwise backfield (DC) demagnetization. These measurements were carried out using a Princeton Model 3900 Vibrating Sample Magnetometer (VSM). Only DC demagnetization curves are shown as AF demagnetization data do not capture the high-coercivity component present in our soil profiles and both methods yield equivalent information at low fields.

To characterize bulk magnetic properties, such as saturation magnetization and bulk magnetic grain size, hysteresis loops in applied fields up to 1.25 T were measured using the same VSM. Hysteresis data were corrected for para- and diamagnetic contributions. Coercivity of remanence \( B_{cr} \) was measured through backfield demagnetization in backfields up to 0.2 T.
Table 1: Magnetic parameters used in this study

<table>
<thead>
<tr>
<th>Name</th>
<th>Methodology</th>
<th>Magnetic Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass-normalized magnetic susceptibility ($\chi$)</td>
<td>Measured using a KLY-4 Kappabridge susceptibility meter. Units m$^3$/kg</td>
<td>Provides a rough estimation of the abundance of magnetic minerals in a given sample.</td>
</tr>
<tr>
<td>Anhysteric remanent magnetization (ARM)</td>
<td>Acquired in a peak field of 100 mT and with 50 µT bias field using a Magnon International AFD 300 alternating magnetic field demagnetizer. Units: Am$^2$/kg</td>
<td>Provides an estimate of the presence of small (0.05-0.06 µm) single-domain (SD) grains; sensitive to both the concentration and grain size of ferromagnetic minerals.</td>
</tr>
<tr>
<td>Isothermal remanent magnetization ($\text{IRM}_{100\text{mT}}$)</td>
<td>Acquired in a peak field of 100 mT and with 50 µT bias field using a Magnon International AFD 300 alternating magnetic field demagnetizer. Units: Am$^2$/kg</td>
<td>Estimates the abundance of all remanence-carrying ferrimagnetic (magnetite and maghemite) minerals; relatively independent of grain-size.</td>
</tr>
<tr>
<td>Saturation isothermal remanent magnetization ($\text{SIRM}_{2.5T}$)</td>
<td>Acquired in three 2.5 T field pulses using an ASC-Scientific IM-10-30 pulse magnetizer.</td>
<td>Indicates presence and abundance of all remanence carrying ferrimagnetic and antiferromagnetic (hematite) particles.</td>
</tr>
<tr>
<td>Backfield IRM</td>
<td>Backfield IRM. Acquired following acquisition of SIRM in three pulses of -100mT and -300mT, respectively using an ASC-Scientific IM-10-30 pulse magnetizer.</td>
<td>Used to calculate HIRM and S-ratios (see below).</td>
</tr>
<tr>
<td>“Hard” IRM HIRM$<em>{100}$ HIRM$</em>{300}$</td>
<td>$HIRM_{-x\text{mT}} = \frac{1}{2} (SIRM + IRM_{-x\text{mT}})$</td>
<td>Provides estimate of the absolute abundance of medium- and high-coercivity magnetic minerals.</td>
</tr>
<tr>
<td>S-ratio $S_{100\text{mT}} S_{300\text{mT}}$</td>
<td>$S_{x\text{mT}} = -\frac{\text{IRM}_{-x\text{mT}}}{\text{SIRM}}$</td>
<td>Provides information on the relative abundance of medium-coercivity SD particles ($S_{100\text{mT}}$) and high-coercivity minerals ($S_{300\text{mT}}$).</td>
</tr>
<tr>
<td>L-ratio</td>
<td>$L = \frac{HIRM_{300}}{HIRM_{100}}$</td>
<td>Reveals coercivity changes in the antiferromagnetic component; aids in the interpretation of HIRM variations.</td>
</tr>
<tr>
<td>Magnetic Coercivity Distributions:</td>
<td>AF demagnetization curves determined through stepwise AF-demagnetization in fields up to 300 mT using Magnon</td>
<td>Used to constrain the pedogenic component to determine the original of magnetic remanence.</td>
</tr>
<tr>
<td>AF demagnetization curves</td>
<td>AFD 300 alternating field demagnetizer.</td>
<td>By reaching a higher peak field the DC demagnetization curves can be used to determine the high-coercivity component, in this case, hematite.</td>
</tr>
<tr>
<td>DC demagnetization curves</td>
<td>Backfield demagnetization curves were determined using a Princeton Measurement Corporations MicroMag 3900 VSM up to a peak field of 2 T.</td>
<td>Hysteresis data provide a general characterization of a sample’s bulk magnetic properties, such as magnetic grain size or mineralogy.</td>
</tr>
<tr>
<td>Hysteresis loops and coercivity of remanence $B_{cr}$</td>
<td>Measured using a Princeton Measurement Corporations MicroMag 3900 VSM at a peak field of 1.25 T. $B_{cr}$ determined via single remanence curves.</td>
<td></td>
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</table>
Results and Discussion

Figs. 2 – 6 show magnetic properties for all studied soil profiles arranged in chronological order, beginning with the Holocene soil profile (WIN10B, Fig. 2). Because magnetic susceptibility and IRM are strongly correlated (n = 75, r² = .98), IRM data are not shown.

No significant magnetic enhancement occurred in the Holocene soil profile (WIN 10B, Fig. 2b). The soil developed in a fluvial terrace and variations in magnetic properties are predominantly due to changes in parent material.

The Pinedale soil profile (WIN 10A, Fig. 3) displays higher magnetic susceptibility in the Bk-horizon ($\chi = 8.9 \times 10^{-7}$ m$^3$/kg) than in the A-horizon ($\chi = \times 10^{-7}$ m$^3$/kg). This may suggest a depletion of ferrimagnetic minerals in the topsoil or the addition of additional, weakly magnetic material to the soil profile. HIRM$_{300}$ and S$_{300\text{mT}}$ (Fig. 3e and f) show fairly little change throughout the profile except for a slight decrease in HIRM$_{300}$ with depth and a slight increase in S$_{300\text{mT}}$ with depth. Magnetic coercivity distributions (Fig. 3g) show a small contribution by hematite to magnetic remanence (shaded in light red) that is most prominent in the A- and Bk-horizons.

Bull Lake aged profiles do show magnetic enhancement in the topsoil. For the late Bull Lake soil profile (WIN 10D, Fig. 4) moderate enhancement in the A-horizon is suggested by an approximate 100% increase in susceptibility between the Bk-horizon ($\chi = 3.4 \times 10^{-7}$m$^3$/kg) and the A-horizon ($\chi = 6.6 \times 10^{-7}$m$^3$/kg) (Fig. 4b). HIRM$_{300}$ decreases with depth throughout the Bk-horizon while S$_{300\text{mT}}$ increases correspondingly. DC demagnetization curves (Fig. 3g) show increased hematite concentrations (shaded in light red) compared to the Pinedale profile (Fig. 2), particularly in the A- and Bw-horizons,
Figure 2: Magnetic properties of soil profile WIN10B (Holocene). Magnetic susceptibility ($\chi$), ARM and ARM/IRM are proxies for the abundance of ferrimagnetic minerals (b, c and d respectively). HIRM$_{300}$ and S$_{300mT}$ provide an estimate of the absolute and relative abundance of high-coercive minerals, respectively (e and f). Magnetic coercivity distributions obtained from backfield demagnetization curves up to 2T further characterize the nature of the magnetic remanence (g). There are two components of the magnetic coercivity distributions: a soft component (constrained with two curves) and a hard component. The soil lithology legend (h) applies to Figures 1-5.
Figure 3: Magnetic properties of soil profile WIN10A (Pinedale). See caption for Figure 1 for more details and soil lithology legend.
Figure 4: Magnetic properties of soil profile WIN10D (Late Bull Lake). See caption for Figure 1 for more details and soil lithology legend.
Figure 5: Magnetic properties of soil profile WIN10E (Early Bull Lake). See caption for Figure 1 for more details and soil lithology legend.
Figure 6: Magnetic properties of soil profile WIN10C (Sacagawea Ridge). See caption for Figure 1 for more details and soil lithology legend.
Magnetic enhancement further increases for the A-horizon of the early Bull Lake soil profile (Win 10E, Fig. 5). $\chi$ increases by almost 1000% between the Bk-horizon ($\chi = 0.66 \times 10^{-7}\text{m}^3/\text{kg}$) and the A-horizon ($\chi = 6.0 \times 10^{-7}\text{m}^3/\text{kg}$). At this site, HIRM$_{300}$ and S$_{300\text{mT}}$ increase in the Bw- and A-horizons (Fig. 5e and f). Magnetic coercivity distributions show a large hematite component throughout the entire profile (Fig. 5g).

There is some enhancement of ferrimagnets in WIN10C (Sacagawea Ridge, Fig. 6b). $\chi$ increases slightly by approximately 20% between the Bk-horizon ($\chi = 4.4 \times 10^{-7}\text{m}^3/\text{kg}$) and the A-horizon ($\chi = 5.4 \times 10^{-7}\text{m}^3/\text{kg}$). HIRM$_{300}$ increased slightly in the Bw- and A-horizons while S$_{300\text{mT}}$ decreased in these horizons (Fig. 6e and f). Magnetic coercivity distributions indicate an increased hematite component in the Bw- and A-horizons (Fig. 6g).

Figure 7a shows a typical hysteresis loop for our soils (A-horizon, WIN10A). Loops close at magnetic fields between 0.35 and -0.35 T and have a rather normal shape (neither wasp-waisted nor pot-bellied (Tauxe et al., 1996). Figure 7b, shows a scatterplot of magnetization ratios ($M_r/M_s$) vs. coercivity ratios ($B_{cr}/B_c$) (Day et al., 1977; Dunlop, 2002). A-horizon samples (closed symbols) plot in the pseudo-single domain (PSD) field, while Bk-horizon samples (open symbols) are displaced towards higher coercivity ratios. A-horizon samples cluster tightly and do not follow a particular grain size trend. The displacement of Bk-horizon samples may either be due to a larger presence of hematite (Channel and McCabe, 1994) or the addition of super-paramagnetic (SP) particles (Dunlop 2002). If the abundance of SP particles were large then $\chi$/IRM ratios should be high as well, which is not observed in our samples.
Figure 7: a) Hysteresis loop for sample WIN10A, 5-10 cm. b) Plot of remanence ratio ($M_r/M_s$) vs coercivity ratio ($B_{cr}/B_c$) for all five soil profiles. Solid symbols represent samples from the A-horizon, open symbols represent all other horizons.
Magnetic Changes with Soil Age

In Fig. 8, various magnetic measurements are plotted as a function of age for typical samples from the A- (solid symbols) and Bk-horizon (open symbols) for all sites with the exception of the Holocene soil profile (whose magnetic properties are controlled by changes in lithology rather than age-dependent pedogenesis). Correcting Bk-horizon data for the presence of carbonates affected the overall magnitude of all concentration-dependent parameters but preserved the trends already observed in the uncorrected data. For clarity these data are omitted from Fig. 8.

Concentration-dependent parameters $\chi$ (Fig. 8a), IRM (not shown) and ARM (Fig. 8b) show a decreasing trend with age for the A-horizon. $\chi$ remains fairly constant between the two oldest sites (Early Bull lake and Sacagawea Ridge). ARM/IRM ratios (Fig. 8c) which increases with age from Pinedale to early Bull Lake, drop again in the Sacagawea Ridge profile. A general increase in $B_{cr}$ values (Fig. 8d) indicates accumulation of bulk coercivity with soil age. Corresponding trends in HIRM and $S_{300mT}$ indicate that the higher $B_{cr}$ values are due to both an absolute (HIRM increases with age) and relative ($S_{300mT}$ decreases with age) increase of high-coercivity hematite (Figs. 8e and f). The general decrease in $\chi$ and ARM with age in the A-horizons of our soil profiles may be due to a gradual loss of ferrimagnetic minerals or the conversion of ferrimagnetic minerals to weakly magnetic, antiferromagnetic hematite. The increase in ARM/IRM (Fig. 8c) for the magnetically enhanced Bull Lake profiles indicates that pedogenic enhancement is at least partially due to an accumulation of SD minerals.

In our soil profiles the A-horizons are magnetically enhanced only in the Bull Lake soils (Figs. 4 and 5). Based on their investigations of California beach terraces Singer and coworkers
Figure 8: Variations of magnetic properties with age. A-horizon samples: solid symbols, Bk-horizon samples: open symbols.
(1992) suggest that little magnetic enhancement is observed in soils younger than approximately 40 ka, which would explain the lack of magnetic enhancement observed in the Holocene and Pinedale soil profiles. The degree of magnetic enhancement increases significantly between the late and early Bull Lake profiles, as the early Bull lake soil likely experienced interglacial climatic conditions during the Sangamon that were more conducive to pedogenic enhancement.

Hall (1999) suggested that older soils in the Wind River Basin experienced significant deflation and loss of upper soil horizon material which would strip the older soil profiles of their magnetically enhanced horizons. Magnetic enhancement is a near-surface process and is usually most pronounced in the topsoil. Therefore, long-term deflation could explain the lack of magnetic enhancement in the Sacagawea Ridge soil profile.

In his study of similar soils Hall (1999) found no systematic trend in rubification of the Bt-horizon. In this study, we see a systematic change in coercivity parameters with $B_{cr}$ and HIRM increasing and S-ratios declining with age (Fig. 8d, e and f). Therefore, high-coercivity minerals do systematically increase in the older soil profiles. The increase in both relative and absolute hematite concentrations in older soils appears to contradict Hall’s earlier findings, but it should be kept in mind that Hall studied Bt-horizons, which are only weakly expressed in our soils and consistent hematite enhancement is only observed in the A-horizons. Furthermore, increased hematite production may not necessarily lead to further rubification if all grains are either already completely coated by hematite or neoformation of hematite results in enlarging existing hematite crystals rather than the formation of new red material.

To summarize the trends seen in the A-horizons of these soil profiles, we observe a loss of ferrimagnetic materials and an increase in antiferromagnetic hematite. Also, higher ARM/IRM ratios indicate that pedogenic ferrimagnets are created. This suggests that pedogenic
ferrimagnets are an intermediate stage with hematite as the stable end member (Torrent et al., 2006).

In the B-horizons $\chi$, IRM and ARM trends are less clear (Fig. 8a, b and c). Bk-horizon samples do not show consistent trends with age, even when magnetic parameters are corrected for the presence of carbonates. This may be due to the inhomogeneity of parent material or complex deflation history, which brings older material closer to the surface.

Estimates of Hematite Abundance

XRD analyses of representative samples (Fig. 9) confirm that the high coercivity component in our soil profiles is carried by hematite. Therefore estimates of high coercivity distributions can be used to quantify the abundance of hematite.

To assess the consistency of common magnetic coercivity proxies (S-ratios, HIRM and coercivity distributions), we compared relative hematite abundance estimates to $S_{300mT}$ values (Fig. 10a). The relationship between these two parameters is fairly linear, suggesting that in our case both methods yield comparable results and can be used to detect qualitative changes in the relative concentrations of high-coercivity minerals.

In Fig. 10b and c the absolute contribution of the high-coercivity component (hematite) to the magnetic remanence as determined by our analysis of magnetic coercivity distributions is plotted against HIRM$_{300}$, an alternative proxy for the absolute hematite abundance. Both parameters show a positive correlation. Figure 10b shows the correlation between coercivity distribution analyses and HIRM when coercivity spectra are fitted by two coercivity components. Such an analysis yields a good correlation between the two hematite proxies. When coercivity
Figure 9: XRD analyses for two representative samples from the Sacagawea Ridge soil profile. Diffraction peaks associated with quartz (Q), calcite (Cc) and hematite (H) are labeled.
Figure 10: Comparison of hematite abundance estimates from $S_{300 \text{mT}}$, HIRM$_{300}$ and coercivity distributions. a) Relative abundance estimates from coercivity distributions vs. $S$-ratio.
b) Absolute remanence contributions carried by hematite based on a two-component (high- and low coercivity component) fit of the coercivity distributions shown in Figs. 1 – 5 vs. HIRM$_{300}$.
c) Absolute remanence contributions carried by hematite vs. HIRM$_{300}$ but with coercivity distributions analyzed using a three-component (high-, medium-, low-coercivity) fit.
spectra are fit with three coercivity distributions, often a very broad medium-coercivity component is added. This improves the overall fit to the data but the added component overlaps significantly with the remaining low- and high-coercivity components and leads to a poorer correlation between the two proxies (Fig. 10c).

Liu et al., (2007) introduced the L-ratio (later, the modified L-ratio) to assess the validity of HIRM and S-ratios as proxies for the abundance of high-coercivity minerals (hematite and goethite). According to Liu et al., (2007), HIRM only reflects the abundance of high-coercivity minerals if the (modified) L-ratio remains fairly constant, otherwise, changes in HIRM are mainly due to changes in magnetic coercivity.

Fig. 11a shows the modified L-ratio plotted vs. HIRM$_{300}$ for all samples. This plot shows considerable variation in the L-ratio and very strong site-specific linear trends. According to Liu et al., (2007) Fig. 11a suggests that, in our case, HIRM is poorly suited to estimate changes in hematite abundance. Liu et al., (2007) suggested a detailed analysis of coercivity distributions (Fig. 2 – 5g) to further clarify the contributions of high-coercivity minerals to the magnetic signal because magnetic coercivity spectra do capture changes in magnetic coercivity more completely than single-valued parameters such as HIRM or S-ratios. Our comparisons show that both techniques yield comparable results (Fig. 10), confirming the usefulness of simple HIRM measurements when estimating hematite abundance even when the corresponding L-ratios show considerable variability.

Fig. 11b, shows that a two-component fit (which gave the best correlation between coercivity-distribution-based and HIRM-based estimates) separates the coercivity spectra into two low- and high-coercivity components that are fairly well defined (narrow range of Bh and Dp values) and well separated from each other. The distinct separation and relative homogeneity
of the two coercivity distributions are the reason why the two techniques yield comparable results, but our results suggest that the abundance of hematite is reasonably well quantified using HIRM and S-ratios even when L-ratios are not constant. It appears that all proxies for hematite abundance (HIRM, analysis of coercivity distributions) reflect true changes in the abundance of hematite in the studied soil profiles.
Figure 11: a) Modified L-ratio (Liu, 2007) versus HIRM$_{300}$ for all samples. Linear trends for specific sites are indicated on graph. b) Distribution width (Dp) versus log median coercivity (log Bh) for the modeled low- (pale blue symbols) and high-coercivity (pale red symbols) components as determined from a two-component fit analysis of magnetic coercivity distributions. Absolute remanence carried by these components is indicated by increasing symbol size.
Conclusions

The study shows that the magnetic properties of pre-Bull Lake soil profiles retain very little enhancement. In the late and early Bull Lake profiles magnetic susceptibility and ARM/IRM increase in the upper soil horizons, similar to soils studied elsewhere, for example, at the Chinese Loess Plateau. Enhancement occurs slowly, with no enhancement showing before 100 ka. There is no simple relationship between soil age and the degree of magnetic enhancement, and enhancement trends do not extend to our oldest soil profile (Sacagawea Ridge, WIN10C). Deflation over long time-scales may have stripped the fine-grained, magnetically enhanced topsoil of the Sacagawea Ridge profile.

With respect to age from the Pinedale through Sacagawea Ridge profiles, a loss of ferrimagnets and an increase in antiferromagnetic hematite occurred (Fig. 8). This suggests that pedogenic magnetite may only be an intermediate phase in the conversion of ferrimagnets to antiferromagnets, with hematite as the stable end product, as it has been suggested by Torrent et al., (2006).

A comparison of several hematite abundance proxies demonstrates that HIRM, S-ratios and magnetic coercivity distributions all indicate an increase in absolute and relative accumulation of hematite. It appears that HIRM is fine for indicating actual increases in hematite abundance even though the modified L-ratio is not constant for these soil profiles.
Acknowledgements

I would like to thank my thesis committee responsible for reading and assisting me with my thesis – Christoph Geiss, Dennis Dahms and Jon Gourley. Many thanks are owed to Dennis Dahms for showing me the best that Lander has to offer (in the form of the Lander Bar and the coolest coffee shop in the West) and for his help and guidance in the field. I owe a shout-out to my roommate/co-chair/“husband”, Giuliani, for giving me seven months of complete dibs on the lab computer up until the last 48 hours of this thesis being due. Most importantly, I would like to thank my adviser, Christoph Geiss, for his constant patience, good-humored encouragement and tolerance of my Pandora radio stations. He constantly motivates me against becoming a “slacka” and thanks to him – I have seen a systematic decrease in my gullibility over the last four years.

Trinity College’s analytical facilities are supported by grants from the National Science Foundation (MRI-EAR 0923043, MRI-CHE 0959526).
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29


