The observation

While measuring susceptibility versus temperature (χ-T) curves upon heating above room temperature (RT), a peak is sometimes observed between ~150 and 350 °C. The shape and intensity of the χ-T peak can vary substantially. Most often it takes the form of a gradual increase which then somewhat levels out before dropping at the high temperature side, creating an asymmetric plateau (or pedeplain, to be more exact, Fig. 1a, modified after Kontny and Grothaus (2017)). However, the peak may also be more subtle and rounded (Fig. 1b), and sometimes have a smaller tip within that, yet maintaining the fundamental characteristic increase at ~150 and decrease at ~350 °C. Notably, the feature only appears, or is most prominent, in weathered samples (e.g. Kontny and Grothaus, 2017).

This behavior is accompanied by other rock-magnetic observations: in saturation remanent magnetization versus temperature (M<sub>RS</sub>-T) curves decreases in magnetization occur at the corresponding temperatures (Van Velzen and Zijderveld, 1995), whereas hysteresis properties measured at different temperatures reveal a decrease in coercivity (B<sub>C</sub>, B<sub>CR</sub>) upon heating (Van Velzen and Dekkers, 1999), which is accompanied by an increase in high-field slope while M<sub>S</sub> remains unchanged.

The details

At first glance, when interpreting the susceptibility curves without any other knowledge of the sample nor other rock-magnetic measurements, the peak can be easily attributed to production of new magnetic minerals with higher susceptibility (magnetite) associated with alteration of the sample. However, this behavior has been observed in very different rock-types, from igneous to sedimentary and even soils, and in conjunction with other rock-magnetic and microscopic observations.

Production of new magnetic minerals does not necessarily explain the reduction of coercivity. Infact, for specimens that possess a large ~150 °C increase in susceptibility, hysteresis measurements do not show significant change in saturation magnetization over the same temperature range, yet they show a large drop in coercivity and an increase in low-field slope that matches the ac susceptibility pattern (Fig. 2). Significantly, the same phenomenon is sometimes observed in pure (but partially oxidized) magnetite samples.

These observations reasonably demonstrate that it is not the generation of new magnetite that is responsible for the increase at 150 °C, as would be logical to infer, for example, in samples containing abundant clay minerals or organic matter (OM), but instead is related to low-temperature oxidation, with formation of core-shell structures, and their behavior upon heating during the χ-T experiments. I further note that these structures are also abundant in many altered soils and paleosols containing clays and/or OM (more below).

The explanation

Low-temperature (LT) oxidation of magnetite (Fe<sub>3</sub>O<sub>4</sub>) occurs during weathering at atmospheric conditions, typically below 50 °C. Upon oxidation the composition gradually becomes that of maghemite (γ-Fe<sub>2</sub>O<sub>3</sub>), the fully oxidized endmember phase (e.g. O’Reilly, 1984; White et al., 1994).

The oxidation process starts at the surface of the grain where Fe<sup>2+</sup> is oxidized to Fe<sup>3+</sup> by either addition of oxygen or loss of Fe<sup>2+</sup>. Oxidation continues as a solid-state diffusion process that is driven by the oxidation gradient, leading Fe<sup>2+</sup> to diffuse from the interior of the grain to the surface and leaving behind a vacancy in its place. The process is temperature dependent and is very slow at room temperature (Askill, 1970). The end result is a strong oxidation gradient close to the grain surface, leading to the formation of an oxidized maghemite shell around an unoxidized magnetite core (O’Reilly, 1984). Further liberation of core Fe<sup>2+</sup> ions to the surface or to the
Visiting Fellow’s Reports

Pairing paleointensity results with coercivity spectra: providing support for selection criteria

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A few days into the new year of 2020, I arrived in Twin Cities, Minnesota for the first time, with an exciting rock magnetic project to be conducted at the Institute for Rock Magnetism. My research was focused on developing paleomagnetic data from the 1.1 Ga Beaver River diabase and its anorthosite xenoliths of the Beaver Bay Complex from the North Shore of Lake Superior, Minnesota. Before this trip, I had been developing directional and intensity data at the paleomagnetism lab at UC Berkeley. With the help of rock magnetic experiments at the IRM, I was hoping to decipher the cause of a variety of paleointensity results of my samples.

Retrieving paleomagnetic information from Precambrian rocks can aid in our understanding of the long-term evolution of the geodynamo. A recent paleointensity study by Sprain et al. (2018) reported a ca. 1.1 Ga paleomagnetic field strength similar to today based on the volcanics of the Midcontinent Rift System (MRS). That study suggested that this result is consistent with models wherein this time period of the Proterozoic is characterized by a strong geomagnetic field. However, to further evaluate the evolution of the geomagnetic field during the Precambrian, more paleointensity data are needed.

The hypabyssal intrusions of the ophitic Beaver River diabase (BRD) and the Ca-rich anorthosite xenoliths that it hosts are the targets of this study. The diabase contains abundant Fe-Ti oxides which are dominant carriers of paleomagnetic information. The nearly pure anorthosite xenoliths have potential for paleomagnetic investigation because plagioclase hosts can protect the exsolved magnetic minerals from post-formation alteration (Tarduno and Cottrell, 2005), and thus may faithfully record paleointensity information at the time of formation. A typical outcrop of anorthosite xenolith residing in the diabase and a hand sample of the anorthosite are shown in Fig. 1(A, B). Preliminary petrographic analyses show that the anorthosites are dominantly monomineralic with recrystallization textures (Fig. 1C). Crosscutting relationships together with high-precision geochronology dates from Swanson-Hysell et al. (2019) bracket the age of the BRD to be between 1091.61 ± 0.14 Ma (the age of the younger Silver Bay intrusions) and 1093.94 ± 0.28 Ma (the age of the Palisade rhyolite).

Most thermally demagnetized anorthosites and alternating field (AF) demagnetized diabase specimens have minimal secondary components and their magnetization is interpreted to be dominated by a primary thermal remanent magnetization. Characteristic magnetizations

Fig. 1: (A) A typical outcrop of an anorthosite xenolith residing in the Beaver River diabase. (B) A hand sample of anorthosite. The large reflective face at the bottom center is a cleavage plane of a centimetersize plagioclase crystal. The scale is 9 cm in total. (C) Cross-polarized light image of an anorthosite thin section. The second order birefringence of plagioclase indicates a high Ca content. The closely packed plagioclase crystals show recrystallization texture. (D) High-magnification SEM image of Fe-Ti oxides exsolved from a pyroxene crystal included in a plagioclase crystal. (E) Large, interstitial magnetite-ilmenite intergrowths between two plagioclase crystals. (F) A large Fe-Ti oxide grain with magnetite-ilmenite intergrowths next to a pyroxene in diabase. an: anorthite; px: pyroxene; mag: magnetite; ilm: ilmenite.
Fig. 2: (A) Site-mean directions of anorthosite and diabase plotted on an equal-area plot. (B) Calculated VGPs from the anorthosite and diabase plotted in context of a previously synthesized ca. 1.1 Ga Laurentia APWP from the Midcontinent Rift volcanics (Swanson-Hysell et al., 2019). VGPs from both lithologies fall close to the 1095 Ma pole position. (C) Example Arai plots for diabase. Most diabase and many anorthosite specimens were rejected by selection criteria due to the zigzagging behavior shown in the diabase example plot. (D) Example Arai plots for anorthosite. A typical anorthosite specimen that passes selection shows a straight Arai plot with a high paleointensity estimate before cooling rate correction. Note both specimens in (C) and (D) show dominantly single component magnetization in the inset orthogonal plots. The estimated field intensity is not cooling rate corrected.

from both lithologies yield indistinguishable site-mean directions and the virtual geomagnetic poles (VGPs) fall close to the 1095 Ma pole from the synthesized APWP of Swanson-Hysell et al. (2019), which is in agreement with the geochronological constraints (Fig. 2).

I conducted a comparative study of modified IZZI paleointensity experiments on both the diabase and anorthosite, with a group treated with low-field AF demagnetization after each in-field step and another group without. Paleointensity experiments for most diabase specimens result in non-ideal Arai plots often with poor pTRM checks, making them difficult to interpret for paleointensity estimates (Fig. 2). The experiments conducted on anorthosite samples, on the other hand, had a high success rate of > 50%. Moreover, the resulting success rate for the anorthosite group with the AF treatment is even higher. The straighter Arai plots are likely due to the AF steps mitigating the exhibition of pTRM tails often associated with non-ideal behavior of multi-domain grains that are demagnetized by the pre-treatment step. However, as the nearly pure anorthosite samples did not display dramatic alterations that are easily detectable with common petrographic techniques, a question rises as why some of the compositionally similar anorthosites passed the paleointensity selection results and some did not.

At the IRM, I was seeking the answer to this question with the help of the vibrating sample magnetometer (VSM) systems, including a newly installed Lake Shore VSM which greatly helped improve measurement resolution on samples with weak magnetizations (Fig. 3). Backfield demagnetization experiments were conducted and used to develop coercivity spectra (Fig. 3). The spectra were subsequently modeled to fit for the distributions of different populations of magnetic particles using a similar procedure as Maxbauer et al. (2016). Most spectra can be well approximated with models with one or two components with overlapping coercivity ranges (Fig. 3). The dominance of single-component distributions from

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Table: Common Mean Test

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The unmixed coercivity spectra likely suggests minimal alterations or formation of secondary magnetic mineral within the samples. By compiling the values of median destructive field (MDF) from all measured specimens and categorizing them in terms of their sister specimens’ paleointensity results, I found that the anorthosite samples that pass paleointensity selection criteria have distinctly higher median destructive field (MDF) than other groups.

Taken together, the rock magnetic experiment results support my paleointensity selection criteria in that specimens that produce straight Arai plots and have MDF values similar to stoichiometric single-domain magnetite are preferentially selected. The preliminary paleointensity results yielded consistent estimates. The cooling rate-corrected site-mean paleointensity estimate is about 40 µT, consistent with results from Sprain et al. (2018) that the Earth’s magnetic field strength at the Earth’s surface in the late Mesoproterozoic was close to that of today.

Acknowledgements
I thank Dario Bilardello, Peat Solheid, Mike Jackson, Josh Feinberg, and Bruce Moskowitz for their tremendous help of instrumental operations, data interpretations, and research guidance. I thank the IRM for the generous U.S. Visiting Student Fellowship. I thank Nicholas Swanson-Hysell at UC Berkeley for advising this research. Margaret Avery provided field assistance.

References


Rock magnetic properties of Paleocene-Eocene sediments from the Piceance Creek Basin, western Colorado

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Deposition during the Paleocene and Eocene in the Piceance Creek Basin of western Colorado records dynamics associated with the Paleocene-Eocene Thermal Maximum (PETM, ~56 Ma) – a global warming event associated with massive perturbations to the carbon cycle (McInerney and Wing, 2011). Fluvial systems in the Piceance Creek Basin changed during the PETM in ways that suggest discharge in river systems increased due to stronger seasonal rainfall events and/or increased mean annual precipitation (Foreman et al., 2012). Over the past several years, we have been working to develop new stratigraphic sections in the Piceance Creek Basin to develop more robust constraints for paleoclimate change during the PETM. One area of focus is on fine-grained deposition along the western margin of the basin in order to constrain paleoenvironmental and paleoclimatic conditions from floodplain environments. In this report, my aim is to introduce a simple model for paleosol development, share some of the magnetic data my students and I collected during two trips to the IRM (one as a visiting fellow in August 2019), and discuss how the rock magnetic properties help to reinforce our interpretations of pedogenic environments.

Depositional setting and paleosol types

Paleocene-Eocene deposits in the Piceance Creek Basin are assigned to the Wasatch Formation, which is subdivided into the Paleocene Atwell Gulch Member and Eocene Molina and Shire Members. The Atwell Gulch consists of lithofacies that are characteristic of fluvial, paludal, and lacustrine systems (Donnell, 1969; Johnson and Flores, 2003). Fine-grained deposits in the Atwell Gulch consist of organic-rich shales and paleosols. The brown-black shales are interpreted to be swamp, paludal, and shallow lake deposits (Donnell, 1969; Johnson and Flores, 2003; Foreman and Rasmussen, 2016). Paleosols are common and often associated with variable amounts of yellow, brown, and red mottling features. In the Molina Member, fluvial sand bodies and crevasse splay deposits are more common and paleosols develop atop overbank...
The PETM onset determined by field stratigraphic relationships. The paleosols. Stratigraphic members of the Wasatch Formation are indicated along the x-axis (IRM = isothermal remanent magnetization, ARM = anhysteretic remanent magnetization (IRM$_{20\,\text{Hz}}$)) were measured for all study specimens (n = 301). Intervals shaded in grey are known that better drained conditions should be associated with iron oxide mineralogy of Wasatch Formation paleosols in this drainage gradient, there are characteristic changes to soil color, geochemical conditions, and expected iron oxide mineralogy (see Figure 1). For more information on paleosol features and relationships between paleosols and climate and/or environmental conditions interested readers should refer to a recent review by Beverly et al. (2018).

For the purposes of this report, it is most relevant to consider how the depositional sequence of paleosol types are related to iron oxide mineral assemblages. The relationships between soil-formed iron oxide minerals and climate has been a topic of interest within the rock magnetic community for decades. For instance, it is well-known that better drained conditions should be associated with hematite while soils experiencing intermediate to poor drainage tend to accumulate more goethite (Kampf and Schwertman, 1983; Liu et al., 2013). In addition, many studies have evaluated the controls on magnetic enhancement in soils and paleosol sequences (reviewed in Maxbauer et al., 2016a; Orgeira et al., 2011). Magnetic enhancement is a phenomenon where topsoil magnetic susceptibility is enhanced relative to lower soil horizons due to the pedogenic production of ferrimagnetic magnetite and/or maghemite. It is expected that magnetic enhancement in most systems will increase with more soil moisture to a certain threshold, where more saturated soils in humid climates (greater than ~1200 mm of annual rainfall) have reduced magnetic enhancement (Maher and Thompson, 1995; Geiss et al., 2008; Balsam et al., 2011). Here, we use rock magnetic properties to constrain iron oxide mineralogy of Wasatch Formation paleosols in an attempt to apply these long-standing relationships to constrain paleoclimate conditions during the Paleocene-Eocene in western Colorado.

**Rock magnetic properties of Wasatch Formation sediments**

For all specimens in this study (n = 301), mass-dependent magnetic susceptibility ($\chi$, m$^3$kg$^{-1}$) was measured in an alternating field of 300 Am$^{-1}$ at a frequency of 465 Hz. Reported data for $\chi$ are the average of four replicate measurements. Anhysteretic and isothermal remanent magnetizations (ARM and IRM respectively) were measured for all specimen. ARM was acquired in a peak alternating field of 100 mT with a DC bias of 50 µT. IRM was imparted with three pulses of a 100 mT DC field. Data for all bulk properties are displayed in Figure 2 with respect to stratigraphic height in the Wasatch Formation. There is considerable variability in bulk properties – however most paleosol horizons (shaded grey in Figure 2) have weaker low-field remanence and susceptibility compared to overbank deposits serving as soil parent material (non-shaded intervals in Figure 2). A notable exception to this pattern is elevated remanence in paleosols at the base of the Molina Member (Figure 2) where ARM and IRM are both enhanced relative to their parent material, despite susceptibility remaining low.

In order to more effectively interpret bulk magnetic properties, a subset of samples from well-developed paleosol horizon samples were subjected to measurements of hysteresis properties and backfield remanence curves in saturating fields of 1 Tesla using the Princeton Measurement System Vibrating Sample Magnetometer (VSM). The most notable results from analyzing the hysteresis and backfield data are reported here in Figure 3. There is a considerable increase in coercivity for paleosols at the base of the Molina Member, where coercivity reaches ~400 mT from a background of <100 mT for Atwell Gulch paleosols. The increase in coercivity is associated with an increase in the ratio of remanent to saturation magnetization ($M_r/M_s$; Figure 3). Coercivity distributions for representative samples were derived from backfield remanence curves and decomposed to help identify magnetic mineral components (see Maxbauer et al., 2016b). Representative...
Coercivity spectra are displayed in Figure 3 – highlighting that Atwell Gulch paleosols display a mixed mineral assemblage while Molina Member paleosols are dominated by a single, high-coercivity component.

Magnetic mineral assemblages in Wasatch Formation paleosol horizons

To better constrain interpretations of magnetic mineralogy from paleosol layers we monitored room temperature remanence imparted with a 2.5 T field (RT-SIRM) using a Quantum Designs Magnetic Properties Measurement System (MPMS) on cooling and warming from 300 K to 20 K (see Figure 3). None of the paleosol samples measured showed a strong signature for the Verwey Transition in magnetite – confirming that the weak susceptibilities observed in paleosols in this sequence are due to low concentration of ferrimagnetic minerals, perhaps maghemite. Atwell Gulch paleosols appear to be dominated by goethite (see Figure 3), which demonstrates characteristic doubling of remanence on cooling during RT-SIRM experiments (Maher et al., 2004). Although, nanomaghemite often behaves similarly to goethite (Smirnov and Tarduno, 2000; Carter-Stiglitz, 2006) and is likely the low-coercivity component observed in the Atwell Gulch. Further, the only sample to display a slight transition around 225 K is a mottled-grey-mudstone in the Atwell Gulch (paleosol “B” in Figure 3), which likely reflects contributions from nanohematite. Molina Member paleosols generally display slight increases in remanence on cooling and lack appreciable change across the Morin (hematite) or Verwey (magnetite) transition temperatures. Increase in remanence on cooling and reduced or absent Morin transitions are noted from modern red soils and in Paleocene-Eocene paleosols from the Bighorn Basin (Maher et al., 2004; Maxbauer et al., 2016c). Taking the results of both VSM and MPMS measurements together, we interpret the increased coercivity and M_r/M_s observed in Molina paleosols to indicate a magnetic mineral assemblage that is increasingly dominated by hematite (top right panel of Figure 3) while magnetic properties in the Atwell Gulch reflect a more mixed combination of iron oxides.

Implications for Paleocene-Eocene paleoclimate

The rock magnetic data reported here support interpretations of drainage conditions based on field observations of mudstone facies in the Wasatch Formation. The Atwell Gulch is primarily dominated by a mixed-magnetic mineral assemblage dominated by goethite and a low-coercivity component (maghemite) that reflects both the multi-colored pedogenic mottling features observed in the field and poor drainage conditions of swamp and paludal environments. There is a rather abrupt shift to more well-drained paleosols at the base of the Molina Member – which is associated with a shift to red paleosol units that are dominated almost entirely by hematite, with the general absence of any low-coercivity component. The shift to well-drained, hematite dominated paleosols at the base of the Molina is reflective of a shift in early Eocene paleoclimates to more arid conditions. Drying in the early Eocene in the Piceance Basin is consistent with paleoclimate proxy records from the nearby Bighorn Basin (Wing et al., 2005; Kraus et al., 2007). In addition,
these findings support an overall arid to semi-arid climate punctuated by intense seasonal rainfall as the driving mechanism for fluvial system changes in the basin center of the Piceance Creek Basin (Foreman et al., 2012), rather than an overall increase in moisture. The lack of any appreciable low-coercivity component in the Molina Member further suggests dry climates where pedogenic production of magnetite/maghemite (and thus, magnetic enhancement) is limited (typical of climates with annual rainfall less than ~500 mm; Maher and Thompson, 1995; Geiss et al., 2008).

Ongoing work for this project aims to further constrain paleoclimate change in the earliest Eocene through additional geochemical proxies along with continued sedimentological work and the development of additional stratigraphic sections to further evaluate these interpretations.

Acknowledgments


\[ \text{ROTATING SHAFT} \]

\[ \text{CHALYBEATE WATER} \]

\[ \text{FIGURE 1} \]

“It seemed probable that the formation of the red skin is quite independent of the depth of the liquid on which it is formed [...] Further, if the wetting and drying are repeated, the layer should be progressively thickened [...] To test these ideas, some beads formed of short lengths of glass tube were threaded on a string to form a kind of necklace (figure 1). This necklace was hung on the pulley of an electric motor [...] The bottom of the necklace diped in a vessel of chalybeate water, and the free part of the length from the liquid to the pulley [...] was exposed to the radiation from an ordinary domestic heat stove, which dried it off. [...] The beads became yellow in say 15 min., then orange, then red by the thickening of the layer.”

**Current Articles**

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most are taken from INSPEC (© Institution of Electrical Engineers), Geophysical Abstracts in Press (© American Geophysical Union), and The Earth and Planetary Express (© Elsevier Science Publishers, B.V.), after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Current Articles section of the IRM Quarterly are always welcome.

**Anisotropy and Magnetic Fabrics**


**Archeomagnetism**


**Chronostratigraphy/Magnetostratigraphy**


Han, F., J. P. Sun, H. F. Qin, H. P. Wang, Q. Ji, H. Y. He, C. L. Deng, and Y. X. Pan (2020a), Magnetostratigraphy of the


Environmental Magnetism


**Extraterrestrial and Planetary Magnetism**


**Geomagnetism, Palaeointensity and Records of the Magnetic Field**


Lund, S., E. Platzman, and T. C. Johnson Paleomagnetic secular variation records from Holocene sediments of Lake Victoria (0.5 degrees S, 33.3 degrees E), Holocene, doi:10.1177/0959683619901214.


Paleomagnetism


region and kinematic reconstruction of its tectonic evolution since the Triassic, Gondwana Research, 81, 79-229, doi:10.1016/j.gr.2019.07.009.


Rock Magnetism and direct applications


Kubes, M., J. Leichmann, and M. Chlapaova Neof ormation of magnetite during selective metasomatism controlling large-scale positive magnetic anomalies within the Brunovistulian unit (Bohemian Massif), Mineralogy and Petrology, doi:10.1007/s00710-020-00696-x.


magnetite-maghemite interface is expected to be hindered as the oxidized shell becomes thicker with time (Ge et al., 2014).

In soils, the slow rates of diffusion ($10^{-12} - 10^{-20}$ cm$^2$/s, Sidhu et al., 1977; Tang et al., 2003) are further limited by the low temperature and circumneutral pH. The core-shell model was recently adopted by Ahmed and Maher (2018) for soils and paleosol sequences. They observed the presence of thin rims (1-4 nm thick) of amorphous Fe-bearing oxide material (interpreted as an oxidized maghemite shell) around the magnetite nanoparticles, and used the model to explain the stability of nanoscale magnetite particles over time periods exceeding 5 My (Fig. 3). Specific to soils, magnetites are typically coated with clay minerals, which form strong barriers to oxygen transport to the particles’ surface, and in time become the rate-limiting factor of the oxidation process.

Maghemite has the same crystal structure as magnetite (inverse cubic spinel) but the unit cell is smaller, so that upon oxidation the shell shrinks and is stretched over the core producing cracking. The resulting stresses act to increase the coercivity of the grain (e.g. Özdemir et al., 1993), making it more stable with respect to thermal activation and/or external magnetic fields, which is reflected in heightened unblocking temperature and suppression of magnetic susceptibility (Van Velzen and Dekkers, 1999).

The surface oxidation model was introduced to explain the behaviour in single domain (SD) grains (Knowles, 1981; Housden and O’Reilly, 1990), but the same surficial cracking also occurs in multi-domain (MD) particles (Appel, 1987). In magnetite the effect is easily produced under normal atmospheric conditions, and unless the temperature is increased or the conditions become more oxidizing, the core-shell structure may persist over geological time, as modeled by Ahmed and Maher (2018) for nanoparticles. According to Askill (1970) the diffusion constant for Fe$^{2+}$ in the crystal is 12 orders of magnitude higher at 150°C than at room temperature, although other studies indicate much smaller increases with temperature (Gapeev and Gribov, 1990, see also Fabian and Sheherbakov, 2020); this leads to a reduction of the large oxidation gradient built up by low-temperature oxidation, and if no further oxidation or reduction occurs at the grain surface, the heating promotes diffusion of iron and vacancies, leaving a more homogeneously oxidized grain with a low overall oxidation degree, i.e. the average oxidation degree of the thin oxidized shell and the large unoxidized core. In other words, the heating step anneals the stress within the maghemite shell and reduces the coercivity of the grain.

For a more in-depth discussion of the annealing of point defects from the magnetite and titanomagnetite lattice, the reader may refer to studies of the magnetic after-effects (MAEs) (e.g. Castro and Rivas, 1999; Walz et al., 2007, and references therein).

Figure 2. VSM data versus temperature (note both °C and K scales) acquired by Mike Jackson at the IRM on a Bishop Tuff specimen during two progressive (red and green symbols) and one repeat (cyan) heating cycles (blue symbols are the measurements on cooling after the first heating step). A) Mass-normalized low-field slope ($\chi$; showing the characteristic, non-reversible peak; B) coercivity data showing the sudden decrease in $B_c$ coincident with the increase in $\chi$; C) Saturation magnetization ($M_s$) remains ~constant over the temperature interval across which both the susceptibility peak and the drop in $B_c$ occur, despite a decrease in $M_b$ between the two heating curves to 600 °C.

Fig. 3. Shrinking-core model simulation of the soil magnetite oxidation reaction by Ahmed and Maher (2018). (A) Schematic representation of a reacting soil ferrite particle (initial particle radius $R_0$) with unreacted magnetite core ($r_c$), maghemite oxidation rim and an associated clay film (at $t$, $R_c = r$). (B) Shrinking-core model simulation using pH = 8.0, $P_{O_2} = 0.001$ atm, $T = 15$ °C, air-filled porosity ($\theta$) = 0.5, and variable $R_c$ between 5 and 20 nm. (C) Shrinking-core model simulation using $R_c = 10$ nm, $T = 15$ °C, $P_{O_2} = 0.001$ atm, $\theta = 0.5$, and variable pH between 3.0 and 9.0.
The practicality

It was proposed by Van Velzen and Zijderveld (1995) and Van Velzen and Dekkers (1999) that the post heating coercivity likely reflects that of the grain before oxidation (the OG) and that mild heating may therefore be used as a tool for determining the effects of low temperature oxidation. Van Velzen and Zijderveld (1995) further excluded that the decrease of the coercivity cannot be due to other factors, for example demagnetization of goethite during the same heating step. Likewise, low-temperature oxidation may result in overlap of the coercivity spectra of oxidized magnetite and those of hematite and goethite, and heating to 150 °C can reduce the overlap aiding in discrimination between these phases. Short of inverting to hematite, pure maghemite of course is fully oxidized and, therefore, cannot increase its coercivity further: heating to 150 °C may thus help to discriminate between maghemite, oxidized magnetite and magnetite (Van Velzen and Dekkers, 1999) and can be very useful in conjunction with the observation of the characteristic “humps” in the RTSIRM cooling and heating curves of maghemitized samples (Özdemir and Dunlop, 2010).

Back to the χ-T> RT curves, segmented incremental heating and cooling runs are particularly informative. Fig. 4 shows such an experiment performed by Kontny and Grothaus (2016) for the same specimen reported in figure 1a. The specimen is a shocked andesite that is visibly fractured (at least microscopically) and contains titanomaghemite. The experiment was performed in argon atmosphere to limit oxidation upon heating. For this specimen, the irreversible increase in susceptibility starts around 125 °C and ends above ~150 °C, where the curves become reversible. Above 350 °C the susceptibility starts to decrease irreversibly, up until 450 °C, and the resulting peak was termed the “maghemite bump” by these authors. These features are common across rock types and sediments, and the increase in susceptibility can be entirely attributed to the annealing of maghemite rim stresses, as described above, whereas the decrease corresponds to inversion of (ti)maghemite to (ti)hematite (e.g. Stacey and Banerjee, 1974; Dunlop and Özdemir, 1997). Gimme the phase with the humps and a bump.

Acknowledgement

I thank Mike for sharing the “maghemite bump” data he collected (or “beaks” as he refers to them), and providing valuable input and constructive criticism to this short article. I also thank Bruce Moskowitz for his thorough review and thoughtful suggestions.

References


O’Reilly W., 1984: Rock and Mineral Magnetism, Blackie,
From the IRM

Last month Mike Jackson retired from his position as polymath Facilities Manager and Research Professor after 25 unabated years at the IRM. Please join us in congratulating Mike for his outstanding scientific achievements and selfless dedication to the IRM and to the many visitors he has worked with over this past quarter of a century. Mike’s relentless genius has been over-arching and doubtlessly caused a transformative hermeneutic of rock magnetism and its applications. The legacy of Mike’s research speaks for itself and no list would do it any justice: a few highlights include his seminal contributions to magnetic anisotropy, the sagacious inclination shallowing corrections, the dexterous detection of remagnetizations in carbonates and redbeds, the erudite investigation of malleable Curie temperatures in titanomagnetics, the unparalleled development of an extraordinarily elegant magnetic thermal fluctuation tomography, the facile-processing of complex rock-magnetic data through the monumental IRM database, the marvelous didactic Quarterly articles, the perception of listening to baroque music on a loop, and, of course, the brilliant rediscovery of pigs drawn whilst-blindfolded. We wish Mike the very best in his next endeavours and sincerely congratulate him for his well deserved retirement!

In savagely impartial alphabetical order, Bruce, Dario, Josh, Max, Peat, and Subir