The fourth Summer School on Rock Magnetism has just come to an end, and just like all other Summer Schools before it was a lot of fun to host: At the IRM we are very grateful to all the participants who contributed in making it so successful, despite having advanced the program by a full year!

The format of the summer school consisted of ten days of morning classes and afternoon lab sessions. The majority of the morning lectures was delivered by Bruce Moskowitz, with specific classes taught by Josh Feinberg, Mike Jackson and Dario Bilardello. Additionally, we were lucky to receive a visit and a guest lecture on Paleointensity by Lennart de Groot, from the Fort Hoofddijk laboratory in Utrecht. Classes covered all main aspects of magnetism, from the underlying physics of electron spin, orbital configurations and (super) exchange to the applications of paleomagnetism and environmental magnetism, and provided a very solid foundation for the applied component of the course: for many students this was the first course entirely dedicated to rock magnetism, which boosted the students’ understanding of magnetic techniques in geoscience research.

Eighteen participants travelled to Minnesota from as far as Indonesia for our short course, representing eleven nationalities and traveling from seven countries. Each participant brought much enthusiasm and different expertise to the IRM, which contributed to making the course varied and comprehensive. The Summer Schools on Rock Magnetism are specifically tailored to the interests of the participating students: as part as the application we ask students for their research interests, allowing us to design appropriate laboratory projects that encompass the gamut of research backgrounds. The 2016 students’ research interests varied broadly and encompassed very diverse research topics, including nuclear and mining waste, corals, soils and sediments, biomagnetism, diagenesis, stratigraphy, magnetic fabrics and serpentinites. Based on these topics, four projects on Environmental Magnetism (led by Peter Solheid), Archeomagnetism and Paleointensity (led by Josh Feinberg), Sedimentary Magnetism (led by Dario Bilardello), and Volcanic Remanence Carriers (led by Mike Jackson), were specifically put-together, giving the summer school participants a means of putting into practice the material covered in the morning classes, with a focus on their specific interests.

Group photo at the Interstate State Park, view of Minnesota from the 1.1 Billion year old basalts.

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Visiting Fellow Report

Cohenite - a stable magnetic carrier in iron meteorites.

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Iron meteorites offer the best constraints on thermal and magnetization history of early solar systems because most are remnants of the oldest bodies, which accreted and melted in <1.5 Myr, forming silicate mantles and iron-nickel metallic cores [1]. Among the important magnetic minerals of iron meteorites kamacite (α-Fe cell with less than 6% of Ni) and taenite (γ-Fe cell with more than 20% of Ni), ferrimagnetic cohenite (Fe$_{2.95}$Ni$_{0.05}$C) shows an exceptional magnetic behavior. According to Sugiuara and Strangway [2] cohenite carries the most stable component of natural remanent magnetization in the Abbe meteorite and, therefore, may be able to memorize signals from a strong magnetic field in the early solar system. The cohenite (an analogue to cementite Fe$_3$C in steels) has an orthorhombic symmetry and a Curie temperature ($T_c$) of 210 °C [2]. Interestingly, cohenite exhibits very prominent magnetic domain patterns already visible under an optical microscope using a ferrofluid [3]. This behavior makes cohenite predestined to study the in-situ thermomagnetic behavior. As the Asylum Research MFP-3D magnetic force microscope (MFM) at the IRM has a heating stage at ambient conditions, it was possible to observe the magnetic domain structure in cohenite of the Morasko iron meteorite [4] by heating above $T_c$ and back to room temperature. The MFM cantilevers are made from silicon or silicon nitride coated with CoCr. The MFP-3D collects high-pixel-density images (up to 5k x 5k) with high-speed data capture up to 5 MHz.

Our data visualize the high thermomagnetic stability of cohenite when it is annealed to 210°C under ambient conditions. We also observed no smeared magnetic structures in cohenite, no zig-zag shaped plates in kamacite or tiny rims at the cohenite-kamacite interface in the initial state (see images at 23°C in Fig. 2). We interpret this observation as evidence that after the impact with earth, the meteorite was not heated above 210°C. Therefore, the observed magnetic domain structures probably were recorded in stellar atmospheres. More studies are needed to understand the complex MFM structures of cohenite as well as their stability after eating to 700 °C.

Acknowledgements

We are grateful to M. Jackson, P. Solheid and E. Khakhalova from the IRM for their assistance with MFM experiments and helpful discussions. This work was car-

Figure 1. Cohenite revealed by Bitter colloid in Morasko meteorite. (a) Cohenite grains (arrows) in a Fe-Ni matrix. (b) A flexuous globular cohenite grain. The white box marks the interfacial area studied by MFM. (c) Magnified view showing elongated dark rows, bright island-shaped stripes and branched, dislocation-shaped rows (arrows).

Figure 2. MFM imaging of a cohenite-kamacite interface during heating and cooling runs around Curie point. Yellow arrows marks the position of the reference branched shaped feature. Red arrow marks strong magnetic contrast within the tiny rim area. Please refer to online version for color. The shown scale bar is the same for all images.

When the polished piece of the meteorite is covered with a ferrofluid colloid, numerous mm-sized cohenite grains can be recognized (s. arrows in Fig. 1a). Frequent-
Low-temperature magnetic properties of synthetic titanomagnetites and the mysterious effects of super-glue.

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Titanomagnetite(TM)-bearing igneous rocks are widely used in palaeomagnetic studies, which makes the TM solid solution, Fe\textsubscript{3-x}Ti\textsubscript{x}O\textsubscript{4} (0 ≤ x ≤ 1) one of the most important series of natural magnetic minerals. However, many aspects of TM mineral magnetism remain poorly understood to date. It was shown that the Curie temperatures (T\textsubscript{C}) of natural Mg\textsuperscript{2+}- and Al\textsuperscript{3+}-bearing TM samples strongly depend on thermal history (Bowles et al. 2013). For some samples those changes in T\textsubscript{C} were accompanied by drastic changes in the low-temperature properties. As a non-destructive characterisation method for TMs, low-temperature measurements have been used in various studies. However, the effects of substitutional elements (such as Mg and Al) on the low-temperature magnetic properties have not been studied in detail up to date. Therefore we have measured low temperature magnetic properties of synthetic TM samples with varying Ti-contents, varying cation substitution of Mg\textsuperscript{2+} and Al\textsuperscript{3+} and different thermal histories to improve our understanding of the low temperature behavior of natural samples.

Several studies have been conducted on the low temperature behavior of TMs (Radhakrishnamurty and Likhite, 1993; Torres et al. 1997; Walz et al. 1997; Moskowitz et al. 1998; Carter-Stiglitz et al. 2006; Church et al. 2011). They all noted systematic changes in the magnetic properties with Ti-content. At temperatures of 50-80 K in low-Ti (x<=40), an isotropic point (Ti) has been observed which correlates with a shift of a peak in susceptibility. This shift depends on the frequency and differs in magnitude for different Ti-compositions (Radhakrishnamurty and Likhite, 1993). The same phenomenon was observed by Carter-Stiglitz et al. (2006) and ascribed to thermally activated electron hopping within the B site. Over the same temperature interval, Torres et al. (1997) and Walz et al. (1997) describe a magnetic relaxation, varying with amount of Ti. Moskowitz et al. (1998) find that, in addition to the frequency-dependence, the low temperature susceptibility depends progressively more on temperature the higher the amount of Ti. This leads them to suggest that for TMs with Ti-contents of x < 0.4 the low-temperature behavior depends on both electron and lattice relaxation as well as the impact of isotropic points on the magnetic properties.

For the experiments conducted at IRM we synthesized TMs in the compositional range of TM25-TM60 with varying amounts of Mg\textsuperscript{2+} and/or Al\textsuperscript{3+} substitution of up to 0.12 per formula unit. All of the synthetic samples, with exception of a pure TM60 and a TM50 with 0.6 Mg\textsuperscript{2+} and Al\textsuperscript{3+} substitution per formula unit, show significant changes in T\textsubscript{C} when annealed at temperatures between 325-400°C for 10-10\textsuperscript{3}h. At IRM we used the Magnetic Property Measurement System (MPMS) to measure low temperature susceptibility as function of temperature and frequency, as well as low temperature remanence of our sample. A common artefact when measuring RT remanence on warming in the MPMS are sudden jumps in the data (see Fig.1), which are thought to arise from shifting of individual grains of the sample (all our samples were in powder form).

In order to immobilize the individual grains and in hope of avoiding these artefacts, we mixed in some...
drops of superglue with the sample powder when preparing the MPMS specimen. However, we weren’t aware of the full scope of ramifications caused by the addition of superglue:

Figure 2 shows a comparison of the FC, ZFC and RT remanence curves of a TM40 sample before (Fig. 2a) and after (Fig. 2b) adding super-glue. The shapes of both, the FC and ZFC remanence change distinctly: where there are two changes in slope (at around 70K and 130K) before adding the glue only the one at 70K remains after the glue was added. Additionally the shape of the RT remanence curve on cooling changes from a kind of concave shape to a convex one.

Also very drastic are the changes in low temperature susceptibility (Fig. 3): The overall susceptibility seems to have dropped significantly after adding the glue. The frequency dependence of susceptibility between ~40-120K is preserved but the sharp change in slope at 130K is completely absent in the specimen after the addition of the glue. Additionally the susceptibility becomes frequency dependent again around 270K.

The distinct frequency-independent kink in susceptibility at 130k (before adding the glue) matches with the second slope change in the FC and ZFC remanence curves and is described by Church et al. (2011) as the upper remanence decay temperature associated with Ti. The absence of both, the kink in susceptibility and the upper change in slope in the remanence curves suggests that adding super-glue to the sample somehow suppresses the isotropic point, i.e. inhibits electron hopping within the octahedral (B) site. However, the exact mechanism underlying this phenomenon remains unknown. We would therefore advise future users to refrain from adding super-glue to their specimens.

References

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 ISI Web of Knowledge, 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.

Biomagnetism


Environmental magnetism and Climate


Bandaru, V. L., P. B. Gawali, P. T. Hanamgond, and D. Kannan (2016), Heavy metal monitoring of beach sands through environmental magnetism technique: a case study from Vengurla and Aravalie beaches of Sindhudrug district, Maharashtra, India, Environmental Earth Sciences, 75(8).


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Fundamental Rock and Mineral Magnetism


High Pressure, Extraterrestrial and Planetary Magnetism


Magnetic Fabrics and Anisotropy


Fellitti, F., E. Dall'Olio, and G. Muttoni (2016), Determining flow di-
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Pallomagnetism


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Gladysheva, O. G., and V. V. Popov (2016), Paleomagnetic study of the Tunguska catastrophe epicenter, Geomagnetism and Aeronomy, 56(2), 229-238.

Hassan, R., R. D. Muller, M. Gurnis, S. E. Williams, and N. Flament (2016), A rapid burst in hotspot motion through the interaction of plate tectonics and deep mantle flow, Nature, 533(7602), 239-241.


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Hoshi, H., and K. Yamada (2016), Paleomagnetic study of Plio-Pleistocene sediments in the concentrated deformation zone along the eastern margin of the Japan Sea, Quaternary International, 397, 573-588.


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Gemai, K., N. M. Abd-El Rahman, B. M. Ghiath, and R. N. Aziz (2016), Integration of ASTER and airborne geo-
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Kamzin, A. S. (2016), Mossbauer investigations of Fe and Fe3O4 magnetic nanoparticles for hyperthermia applications, Physics of the Solid State, 58(3), 532-539.


Stratigraphy


Satolli, S., and A. Turri (2016), Early Cretaceous magnetostatigraphy of the Salto del Cieco section (Northern Apennines, Italy), Newsletters on Stratigraphy, 49(2), 361-382.

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Synthesis

Ferreira, N. M., M. C. Ferro, S. M. Mikhailov, F. M. Costa, J. R. Frade, and A. V. Kovalovsky (2016), Guidelines to design multicomponent ferrospinel for high-temperature applications, Rsc Advances, 6(39), 32540-32548.


Spider-pig drawn whilst blindfold by a 2016 Summer School on Rock Magnetism participant.
Environmental Magnetism

The Environmental Magnetism group looked at magnetic properties of lacustrine sediments from Sharkey Lake, from Southern Minnesota. The sediments from Sharkey Lake were cored by students at Carleton College in Northville MN and stored at the Lacustrine Research Center at the University of Minnesota, were re-sampled to determine down-core variations in magnetic properties in search of magnetic fingerprints of climate change and anthropogenic activity. Bulk susceptibility ($\chi$), ARM/$\chi$, SIRM/$\chi$, ARM/$\chi$, the S-ratio, as well as hysteresis parameters were evaluated in order to determine grain-size/domain-state and concentration variations of magnetic minerals. The magnetic mineralogy and coercivity distributions were also investigated. Main findings of the study are that the down-core variation in magnetic parameters delineate three portions of the core: a shallow section with softer and finer magnetite particles, likely biogenic; a larger mid section comprising harder and coarser particles, both magnetite and some siderite in the lowest portion; and a deeper section of softer and finer magnetite and siderite particles. Results were interpreted as indicating a reduction in grain-size (increased SP-SD) due to agricultural activity leading to increased erosion, with some potential down-core dissolution of magnetite.

Archeomagnetism and Paleointensity

The Archeomagnetism group searched for the 1000 BCE paleointensity spike in archeological artifacts from South America. The spike, known as the “Levantine spike”, was initially recognized in the Middle East, in Iran, Syria, Israel and Turkey, but was subsequently also observed in North America. This group specifically worked with artifacts from two Peruvian sites, with specimens younger, older, and of about 1000 years BCE. The study revolved around magnetic characterization and stability experiments to determine whether the specimens fit the requirements for a Thellier experiment (magnetite as magnetic carrier, PSD-SD grain-size range, little hematite and/or goethite, and no alteration during heating), and then proceeded to perform Pseudo-Thellier experiments. No evidence for the geomagnetic spike was observed from these experiments, yet it remained unclear whether the results of the experiments reflected true paleointensity variation or changes in magnetic mineralogy. However, the study proved that at least half of the specimens were suitable for a full Thellier paleointensity determination.

Sedimentary Magnetism

The DRM group looked at magnetic properties of natural sediments from North America and Brazil, evaluating the magnetic behavior of different magnetic mineralogies. A more in-depth project involved analyzing the magnetic remanence of a North American sediment that was re-deposited in the lab under varying field conditions: a constant 50 uT field intensity, and inclinations of 0°, 30°, 60° and 90°. The sediment was thoroughly characterized in terms of magnetic mineralogy and grain-size, through low and high temperature remanence and susceptibility analyses, measurement of hysteresis parameters and remanence acquisition/demagnetization experiments. Specifically, magnetic measurements allowed determining the stability of the dominant remanence carrying grains and their suitability for relative paleointensity estimates. The remanences measured were systematically shallower than the ambient field inclinations, with shallowing factors as small as 0.2, resulting in up to 45° of inclination shallowing, indicating substantial misalignment of the magnetic moments of the remanence carrying grains. Magnetizations were also found to be dependent on the settling field, with decreasing magnetizations for increasing field inclinations, observations that were also reflected in the relative paleointensity estimates.

Volcanic Remanence Carriers

Finally, the Paleomagnetism group looked at the magnetic remanence carried by volcanic rocks, and specifically 1.1 billion year old basalts and andesites associated with the North American Proterozoic failed rifting event. Specimens analyzed were from two sites from within the Lake Superior region, the Schroeder-Lutsen (SL) and the Michipicoten Island Formation (MIF) basalts, and detailed magnetic characterization revealed different magnetic composition among the basalts: the SL basalts possess multiple unblocking and disordering temperatures, around 600°C and close to 700°C, whereas the MIF basalts only possess one main unblocking temperature between 430°C and 530°C. Hysteresis loops and backfield curves confirm the importance of both ferromagnetic and antiferromagnetic remanence carriers: while the MIF basalts possess very narrow loops that close around 200 mT, the SL rocks possess much wider loops, which are constricted in the center and don’t close in fields up to 1 T. Un-mixing the coercivity distributions captured by the backfield curves also reflect the “softer” and “harder” magnetizations of the MIF and SL basalts, respectively. Integrating the high-temperature susceptibility data with low-temperature data acquired on the MPMSs, reveals that while the magnetizations of the MIF are carried by titanomagnetites, the SL basalts are highly oxidized and possess much maghemite and hematite. Additionally, this group’s study confirms the notion that for weakly anisotropic samples, the AMS fabrics are strongly affected by previously imparted high-field (de) magnetizations, showing that the order in which the experiments are conducted is critical for a successful study.

Field trip

Like the previous two Summer Schools, the destination for the weekend field trip was Taylor’s Falls, in the Interstate State Park. Here, 1.1 Gyr basalts crop out along the St. Croix river, and display giant pot-holes carved by discharge waters of Glacial Lake Duluth from the ice retreat at the end of the last glacial maximum (~11 kyr). Unfortunately, the weather was not as cooperative as in the past and the field trip was compromised by heavy rain. Additionally, and if that wasn’t enough,
intense road construction prevented us to visit the unconformably overlaying Cambrian Franconia Formation sandstone and hike the picturesque Curtain Falls trail. In fact, because of the road-construction we started the trip on the Wisconsin side of the Park, which was a first-time visit for all of us: this side turns out to be a little “wilder” in terms of scenery and much more picturesque, but with overall less impressive pot-holes, however, it does have a very nice picnic area which serendipitously sheltered us from an intense downpour. After the rain (and lunch) we decided to try our luck back in Minnesota to visit the “familiar” side of the Park: not too far into the park, however, the rain picked up again forcing the group to seek shelter and eventually decide to call it a day. Before hitting the road, a quick visit to a retro “Americana” ice cream and malts joint was the last stop, and added some sweetness to the trip.

Final dinner
As of tradition, on the final evening of the Summer School, the completion of the course was celebrated over a group dinner. This year’s dinner was held at a Mediterranean restaurant by the University, and provided one last opportunity for informal and friendly mingling among participants. We are big fans of tradition at the IRM, and in compliance with the most solid of traditions a brand new Pig Book was inaugurated for the occasion: everyone present took a stab at inking a pig whilst blindfold and we are all very glad to have the book as a memento of another fantastic summer school completed.

Scholarships
Last but not least, we’d like to acknowledge the 2016 recipients of the two scholarships generously provided by the GPE division of the American Geophysical Union, Louise Hawkins of the University of Liverpool, and Courtney Wagner of the University of Utah. Congratulations, again!

We would also like to remind colleagues that the scheduling of the IRM Summer School and Santa Fe Conference were inverted, and therefore the IRM Conference on Rock Magnetism is being planned for next year: more details to follow!

"The IRM Summer School gives you wings": Blindfolded pig-art by Gildo.
The Institute for Rock Magnetism is dedicated to providing state-of-the-art facilities and technical expertise free of charge to any interested researcher who applies and is accepted as a Visiting Fellow. Short proposals are accepted semi-annually in spring and fall for work to be done in a 10-day period during the following half year. Shorter, less formal visits are arranged on an individual basis through the Facilities Manager.

The IRM staff consists of Subir Banerjee, Professor/Founding Director; Bruce Moskowitz, Professor/Director; Joshua Feinberg, Assistant Professor/Associate Director; Mike Jackson, Peat Solheid and Dario Bilardello, Staff Scientists.

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The IRM Quarterly is published four times a year by the staff of the IRM. If you or someone you know would like to be on our mailing list, if you have something you would like to contribute (e.g., titles plus abstracts of papers in press), or if you have any suggestions to improve the newsletter, please notify the editor:

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