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Inside...

Gustaf Ising's Early Work on Magnetic Fabrics

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Andrea Biedermann's excellent article on magnetic fabrics (in what is destined—alas—to be the final IRM Quarterly to appear in printed form) jogged my memory and took me back to my first encounter with the subject in 1964, under the guidance of Don Griffiths and Roy King at the University of Birmingham. So I pulled out some ancient reprints, and with a little help from Google, discovered some facts that might be of interest to IRMQ readers. Roy King's seminal work on the inclination error is familiar to us all and is still widely quoted (King, 1955). It was a natural extension of research into detrital remanence then being pursued at Birmingham, building on the studies of Swedish varves that Don Griffiths had initiated in 1951 (Griffiths, 1953). Why varves? Why Sweden? What motivated Griffiths was the possibility of using annually-layered varves to determine the pre-observatory secular variation of the geomagnetic field. This had already been attempted in the U.S.A. using a 200-year sequence of varves (McNish and Johnson, 1938), but Sweden offered much longer sequences based on the classic chronology worked out by Gerhard De Geer (De Geer, 1912). Griffiths was well aware that the Swedish varves had already been studied by Gustaf Ising (1883-1960) at Stockholm University (Ising, 1943). It was the re-reading of this paper after so many years that piqued my interest. I had forgotten that Ising was just as interested in anisotropy of magnetic susceptibility (AMS) as in magnetic remanence, perhaps more so. He had started these studies in 1926, and by 1933 had established that the remanence was shallower than expected, and that the sediments had "a considerable anisotropy of susceptibility with the lowest value of susceptibility in the vertical direction". This early (earliest?) observation of magnetic fabric considerably pre-dates John Graham's comments about AMS (Graham, 1954). But there's more. Ising argued that AMS ought to be better than remanence as a recorder of the geomagnetic field. He questions the assumption that remanence (including TRM) "should have remained unchanged during the centuries, not to speak of geological ages". On the other hand, he puts forward a mechanism favouring AMS. He imagines ice sliding over bedrock and picking up "immense numbers" of grains and lithic fragments, "of which a fairly large proportion may be supposed to have got an elongated shape". After being transported into deep, quiet water they would be aligned by the ambient field, "like floating magnets", eventually leading to sediments carrying an AMS "that would not be affected by later field actions". His first experiments, in the summer of 1926, were carried out with a "simple induction balance". He found that the remanence of some natural clay samples was "easily measurable", but that the instrument was not sensitive enough to detect any anisotropy. He then built a torsional

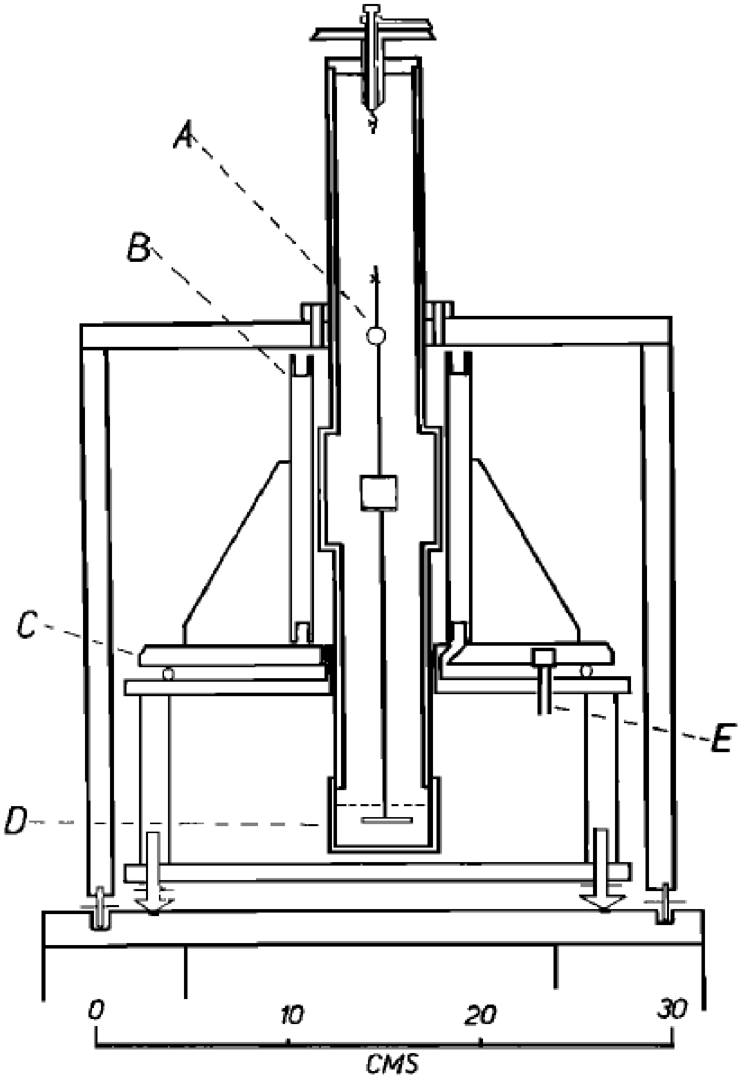

Fig. 1. The sensitive instrument. A, the suspended system; B, field coils; C, turntable; D, damping pot; E, remote control drive.

Original figure and caption from King and Rees (1962) depicting the torque-meter built following the design of Ising.

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Visiting Fellow Reports

Pyrrhotite in Albian Shales, Pyrenees.

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I have investigated the occurrence of pyrrhotite in metamorphic Albian marls from the Chainons Béarnais (North Pyrenees, France). In this retro-foreland, an earlier paleomagnetic study done by Oliva-Urcia et al., (2010) shows the prevalence of a high-temperature (HT) and a medium-temperature (MT) paleomagnetic components in Albian shales. The HT component is obviously carried by magnetite (T_{ub}~580°C). MT is carried by undetermined iron sulfides (T_{ub}~320°C). Since Oliva-Urcia et al. (2010) study, new data bring two major inputs. First, the maximum burial temperature was much higher than initially believed (<200°C), reaching more than 250°C and up to 400°C (Clerc et al. 2015). Albian shales are then within the greenschist facies. Second, most of folding took place during late Cretaceous extension and not during the Pyrenean orogeny (Lagabrielle, et al. 2010). My goal was to characterize the magnetic carrier nature of MT in light of metamorphic conditions, constrained by application of Raman geothermometer.

I conducted remanence studies at room temperature (hysteresis loop, FORC) and at low temperature (10-400 K, RT-SIRM, ZFC, FC). In addition, I performed thermal demagnetization of NRM and microscopic observations using NANOSCOPE III Magnetic Force Microscope. Thin section was prepared using 20 nm abrasive powder to obtain the best smoothed surface.

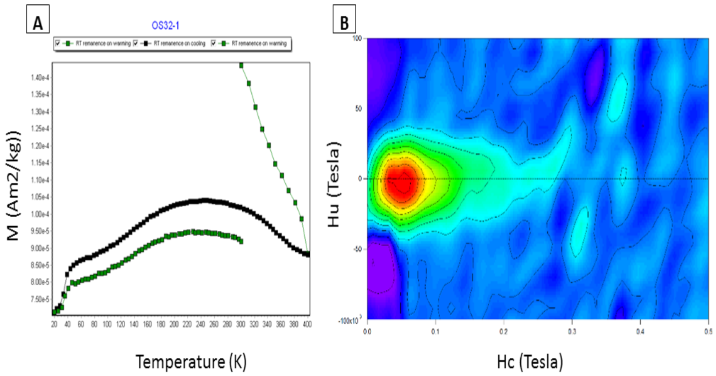

Figure 1. A) RT-SIRM cycling. Note the 400K demagnetization of RT-SIRM to remove goethite contribution. B) FORC diagram (smoothing factor 4). Both measures are done on the same Albian shales sample.

Strong weathering of some samples urged removal of the goethite contribution before running the cooling of RT-SIRM. I first applied a 2.5 T AC field at room temperature and demagnetized the sample at 400 K (Figure 1A). The goethite contribution can represent more than 40% of remanence. Once the goethite component is removed, a nice pattern of RT-SIRM on cooling displays a non-reversible Besnus transition at ~32 K, a firm indication of monoclinic pyrrhotite (Fe_7S_8) (Rochette, et al. 2011). The h/c ratio, near 0.9 in average, points for micrometer grains (Dekkers, 1989). The FORC (Figure 1B) displays non-interacting SD-type of pyrrhotite with a rather strong coercive field Hc near 50 mT. Using magnetic force microscope, we had the good chance to observe micrometric pyrrhotite SD to small MD (Figure 2). These pyrrhotites are generally embedded in calcite. All observations support therefore the presence of <10 µm monoclinic pyrrhotite in the Albian shales. Similar micrometric pyrrhotite have been observed in greenschist metamorphic argillaceous rocks (Appel, et al. 2012).

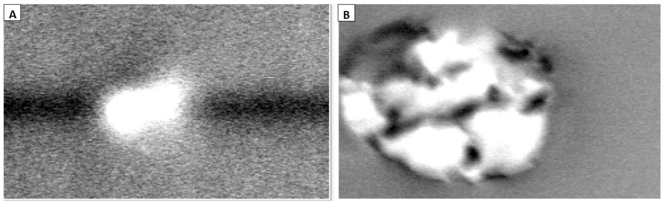

Figure 2. Magnetic force microscope (after application of a 2 T IRM) observation of Albian shales (same sample as Figure 1). A) SD monoclinic pyrrhotite; B) MD monoclinic pyrrhotite (nap-phase retrace). Each image is approximately 10 x 6 µm.

To constrain the metamorphic temperature of studied Albian shales, I used Raman spectroscopy carboniferous materials geothermometer (Beyssac, et al. 2002). For all samples experiencing Tburial >350°C±30°C, only monoclinic pyrrhotite is found without evidence of magnetite (as sample shown in Figure 1). This burial temperature corresponds therefore to the breakdown of magnetite into pyrrhotite (Rochette 1987). This metamorphic pyrrhotite has the potential to record thermo-remanence on cooling of metamorphic units below its Curie temperature (~320°C) (Appel, et al. 2012). I found that Albian marls carry a well-defined characteristic remanent magnetization of reverse polarity, as initially observed by Oliva-Urcia et al. (2010). This thermoremanent magnetization is essentially post-tilting, though declination and inclination are abnormal in some places. This suggests: 1) that this paleomagnetic component is imprinted after the main folding phase and 2) that this component is imprinted after the C34 long normal chron (~83 Ma), which is also the onset of compression in the Pyrenees. The paleomagnetic results are consistent with Lagabrielle et al. (2010) hypothesis of early folding of Chainons Béarnais during the late Cretaceous hyper extension (~100 Ma) and high thermal conditions (thermal gradient ~80°C/km) (Vacherat, et al. 2014). But upon the significance of these regional results for the Chainons Béarnais, this study allows to bracket for the first time the breakdown temperature of magnetite (~350°C) using Raman geothermometry in combination with rock magnetism.

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Post-deposition diagenesis indicated by mineralogy shifts from magnetic measurements.

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Oxygen deficiency has drawn wide attention for both paleo- and modern oceanographic studies to reconstruct atmospheric and oceanic oxygenation histories. To unveil oxygenation of the past, researchers have used iron speciation that is suggested to directly pinpoint anoxic conditions. Iron speciation has been commonly used on sedimentary rocks as a redox proxy to distinguish oxic, ferruginous (iron-rich anoxic water column) and euxinic (sulfide-rich anoxic) water columns on different time scales (Lyons and Severmann 2006). However, among the few applications of Fe speciation on marine sediments, little attention has been focused on Fe mineralogy shifts downcore in response to diagenesis and instantaneous events (e.g. flood layers and turbidites), which might obscure geochemical interpretations on ambient redox environments.

To address these concerns and provide new insights into post-deposition diagenesis, we examined a box core SPR0901-04BC (34º 16.895' N, 120º 02.489' W, 588 m water depth) retrieved in the Santa Barbara Basin (SBB) where suboxic (O_2<10 µmol/kg) and sporadically anoxic bottom waters prevail. This core was sampled at continuous 1 cm intervals to generate a total of 62 bulk sediment samples, which were then freeze-dried and ground to <75 µm for magnetic analyses.

During my visit to the IRM, low-field mass magnetic susceptibility (χ) was determined at 1-cm interval on an AGICO Kappabridge MFK1 Susceptometer at room temperature, followed by measurements of anhysteretic remanent magnetization (ARM), and saturated isothermal remanent magnetization (SIRM) on a 2G SQUID magnetometer. Magnetic hysteresis properties of bulk sediment samples were measured on a Princeton Measurements Corporation MicroMag VSM. Additionally, first-order reversal curves (FORC) (Pike 2003) are determined on selected samples at room temperature.

Temperature-dependent magnetic properties were also measured for selected samples for further identification of magnetic minerals. Low-temperature treatments were carried out with a Quantum Design MPMS for field cooling (FC), zero field cooling (ZFC) measurements and RTSIRM cycling (first imparting a saturation isothermal remanent magnetization at room temperature and then performing low temperature demagnetization). High-temperature measurements were performed to the same collection of samples on a Kappabridge High-Temperature Susceptometer to detect Fe sulfides that can be oxidized to magnetite at temperatures above 300 °C. For each sample run, ~200-300 mg of samples were weighed, heated from room temperature to 700 °C in the air and then cooled back to room temperature.

Our core shows a major transition in magnetic mineral concentrations and mineralogy with depth. Within the uppermost 35 cm, concentration-dependent parameters

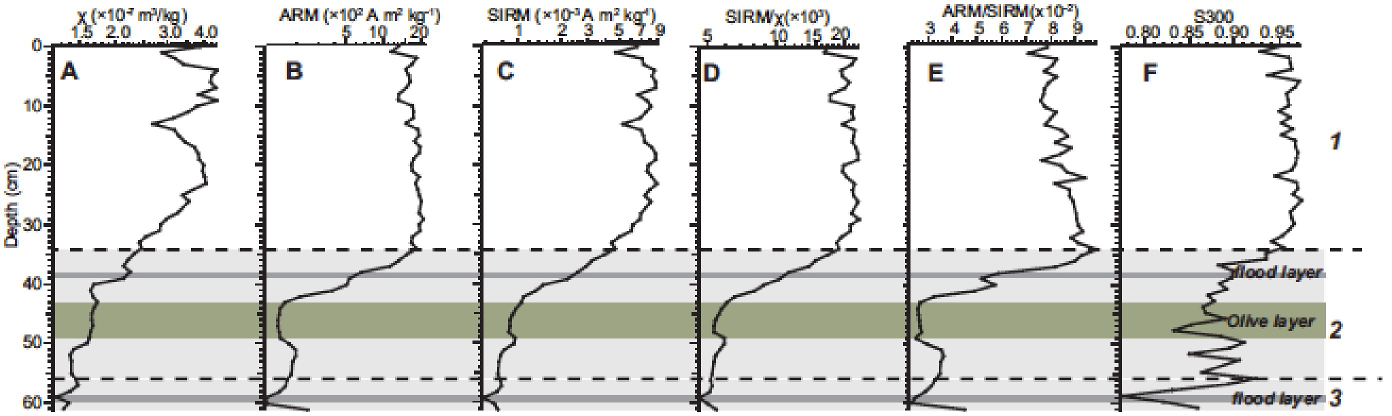

Figure 1. Downcore variability of bulk magnetic parameters. A. susceptibility χ; B. Anhysteretic remanent magnetization (ARM); C. Saturation isothermal remanent magnetization (SIRM); D. SIRM/ χ; E. ARM/SIRM; F. S300 ratio (S300= -IRM-300mT/SIRM).

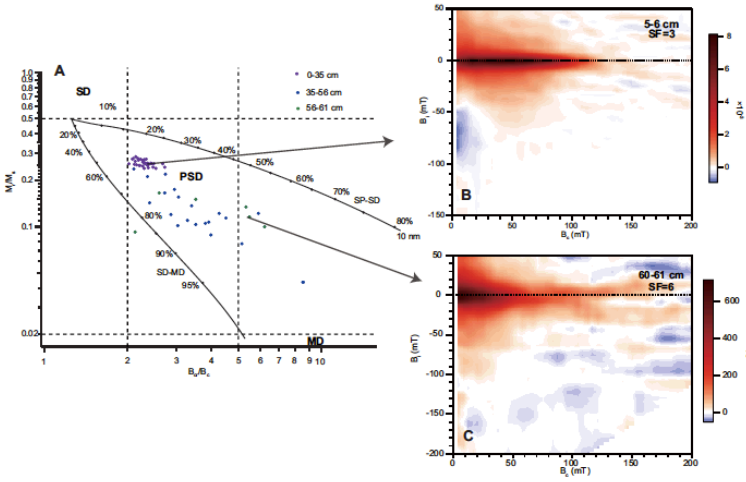

Figure 2. Day plot and selected FORC distributions. A. Day plot following Day et al. (1977) ; B and C. FORC distributions of 5-6 cm and 60-61 cm, respectively. Smoothing factors (SF) are shown in the figures.

(χ, ARM, SIRM), B_{cr}/B_{c} and M_r/M_s are distinguished by high values (Fig. 1), suggesting relatively high concentration of pseudo-single-domain (PSD) ferromagnetic minerals and possible contribution of superparamagnetic (SP) particles. FORC distributions also illustrate a mixture of PSD to multi-domain (MD) magnetic mineral assemblages and SD particles within this stratigraphic interval (Fig. 2B). The second zone (35-56 cm) features a major transition to much lower magnetic mineral concentrations and coarser magnetic grain sizes. A noticeable shift to higher values of B_{cr}/B_c but lower M_r/M_s is observed (Fig. 2A). Near the bottom of the core (56-61 cm), samples have the lowest concentrations of magnetic minerals with the highest proportion of high coercivity minerals with an average S-ratio of 0.85. FORC distribution further verified mineralogy shifts towards more contribution from high-coercivity Fe oxides (e.g. hematite), indicated by extended divergent contours to ~200 mT along the B_c axis (Fig. 2C). Additionally, the hysteresis parameters and the FORC diagrams indicate SP particle contribution that might be associated with later diagenetic processes, as evidenced by the positive region in negative quadrangle of B_i (Fig. 2C).

Low temperature measurements confirm existence of maghemite and magnetite mixture. A suppressed remanence decrease between ~100 K and ~120 K is observed across the Verwey transition (Tv) at ~120 K, suggesting the presence of magnetite (Fig. 3). RTSIRM cooling curves (Fig. 3) typically undergo a gradual increase first with a subsequent faster decrease and define hump-shaped curves that are matched with humped curves on warming, indicating maghemitization process (magnetite oxidation) throughout the core (Özdemir and Dunlop 2010). Furthermore, a downcore shift towards less oxidized inorganic magnetite is suggested by a transition from a double-peak signature across Tv to a bell-shaped suppressed peak (Chang et al. 2016). High-temperature measurements, however, have shown pyrite existence throughout the core, suggesting a highly reducing pore-water environment. Common appearance of magnetite in the core challenged the traditional view of magnetite reduction in anoxic environments and may provide a new insight into post-deposition diagenesis processes in marine sediments with other geochemical analyses.

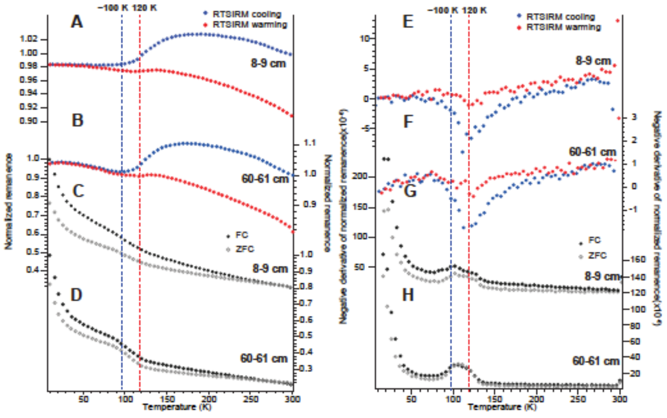

Figure 3. Low temperature measurements. A and B. Normalized remanence in RTSIRM cooling and warming curves for 8-9 cm and 60-61 cm (normalized over RTSIRM); C and D. Normalized remanence in FC and ZFC curves for 8-9 cm and 60-61 cm (normalized towards the first data point in each curve); E and F. Derivatives of RTSIRM cooling and warming curves of the two samples; G and H. Derivatives of FC and ZFC curves.

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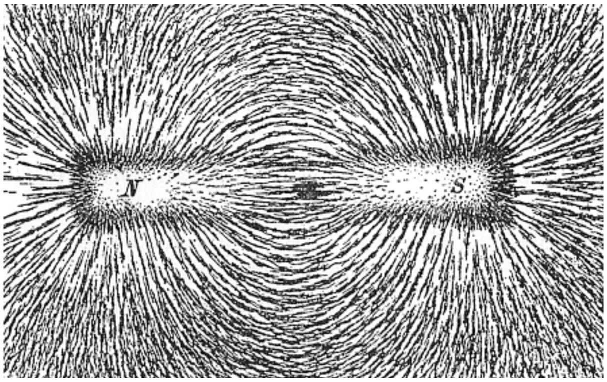

Current Articles

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.

Aeromagnetism, Magnetic Anomalies, and Surveying

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Special Issue for David Strangway

Call for submission of research papers in magnetism and electromagnetism to the Canadian Journal of Earth Sciences for publication in a special issue of tribute to Dr. David Strangway who died December 13, 2016.

David Strangway was born in Simcoe, Ontario, Canada, in 1934 and raised in Angola by missionary parents. He graduated in Physics and Geology in 1956 from the University of Toronto where he completed his MSc and PhD in magnetics research by 1960. After Assistant Professorships at the University of Colorado and Massachusetts Institute of Technology, he joined the National Aeronautics and Space Administration in 1970 as the head of the geophysics branch and leader of the "Moon rocks" research program. In 1973 Strangway returned to Toronto as Head of the Geology Department, and was later appointed Provost (1980) and President (1983) of the University of Toronto. In 1985 he began a successful twelve years as President of the rapidly growing University of British Columbia. In 1998, Strangway moved to Ottawa for six years as President of the government's new Canada Foundation for Innovation where he was responsible for dispensing $2.7 billion to Canadian universities for scientific research. Returning to British Columbia, Strangway founded Quest University, which opened in 2007. Today, this innovative liberal arts college has about 700 students. During his lifetime, Strangway held numerous important appointments and won many prestigious awards for his achievements. Above all, Dr. David Strangway was always a Renaissance man with broad-ranging interests and a great scientific curiosity.

This special issue of the Canadian Journal of Earth Sciences seeks to publish geophysical papers that report on any aspect of terrestrial and planetary magnetic or electromagnetic research. For magnetics, any of the categories listed in the "Current Articles" section of this issue of the IRM Quarterly will be suitable. The journal accepts papers from any country in English or French.

- Deadline for providing tentative paper title: June 30, 2017
- Deadline for submission of papers: March 30, 2018
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Please contact the Editorial Office of the Canadian Journal of Earth Sciences (cjes@nrcresearchpress.com) or Editor Ali Polat (polat@uwindsor.ca) to submit the tentative manuscript title.

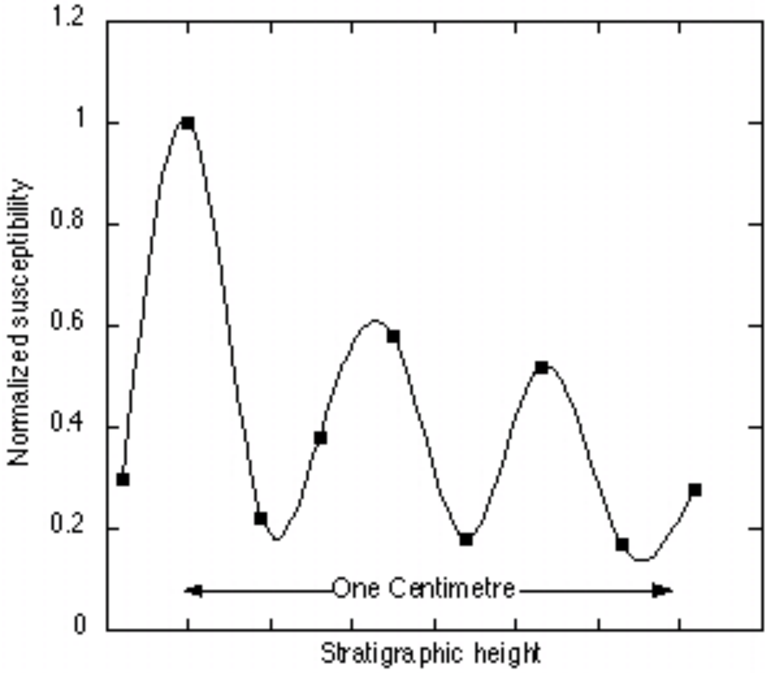
Thank you very much for your consideration, and we hope to hear from you soon.
Guest Editors David Symons (dsymons@uwindsor.ca), David Dunlop (dunlop@physics.utoronto.ca), and John Geissman (geissman@utdallas.edu)

cont'd. from pg. 1...

apparatus which was able to detect anisotropy, but even after incorporating several improvements (in 1927, and again in 1940), he was still unable to pin down the azimuth of maximum susceptibility. But instruments based on Ising's design eventually met with success, my favourite—naturally—being that built by Roy King himself in collaboration with Tony Rees (King and Rees, 1962).

Despite the fact that Ising never attained his goal as far as AMS was concerned, there are other reasons to remember his scientific work. In the 1943 paper (actually communicated on November 26th, 1941) he invented what we nowadays call environmental magnetism. He established a definite pattern of bulk magnetic susceptibility variations reflecting the annual nature of varves, with peaks due to increased input during spring floods. For these experiments, he increased spatial resolution to the point where he was using successive layers only 1.5 mm (yes, millimetres) thick. (He even proposed the idea that one could dispense with the tedious preparation of individual samples by simply "moving instead the whole collecting box through a registering apparatus", in other words, u-channels.) Broadening his investigations, he went on to observe annual patterns in fossil varves from the Carboniferous of Australia, using slices (he calls them ribbons) only 0.75 mm thick. I couldn't resist redrawing the corresponding plot (Figure 1). Going out on a limb, Ising finally asked if magnetic analysis combined with laboratory sedimentation experiments might lead to "quantitative data about the hydrographic conditions" prevailing during deposition.

Professor Ising's geophysical work is not much quoted now, but he has other claims to fame. The most outstanding of them being that he was the inventor of the particle accelerator. His initial paper on the subject (Ising, 1924) inspired Rolf Wideröe in Germany, whose 1928 paper was read in the spring of 1929 by Ernest Lawrence at Berkeley. Lawrence rushed to his laboratory—by 1931 he had a cyclotron, by 1939 he had a Nobel Prize. (Perhaps we can mentally award a little bit of it to Gustaf Ising.)



High-resolution magnetic susceptibility fluctuations in Carboniferous shale from Australia, interpreted by Gustaf Ising as annual varve layers. (Cubic spline fitted through data points hand-digitized from Fig.9 of Ising's 1943 paper.)

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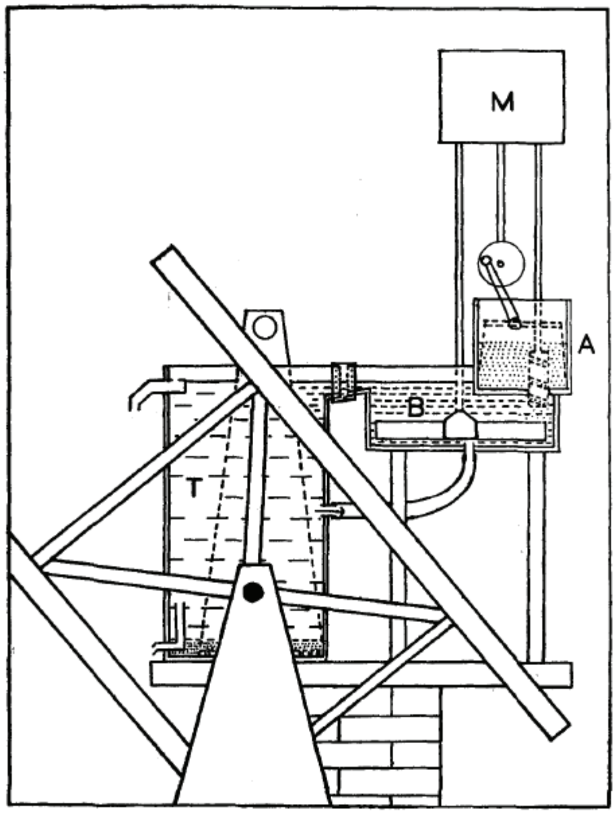

Original figure from King (1955) depicting the sedimentation apparatus used to investigate inclination shallowing.

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