The IRM
Quarterly
Winter 2018-19, Vol. 28 No.4

ISSN: 2152-1972

Inside...

Civilized magnetist's deadly sins

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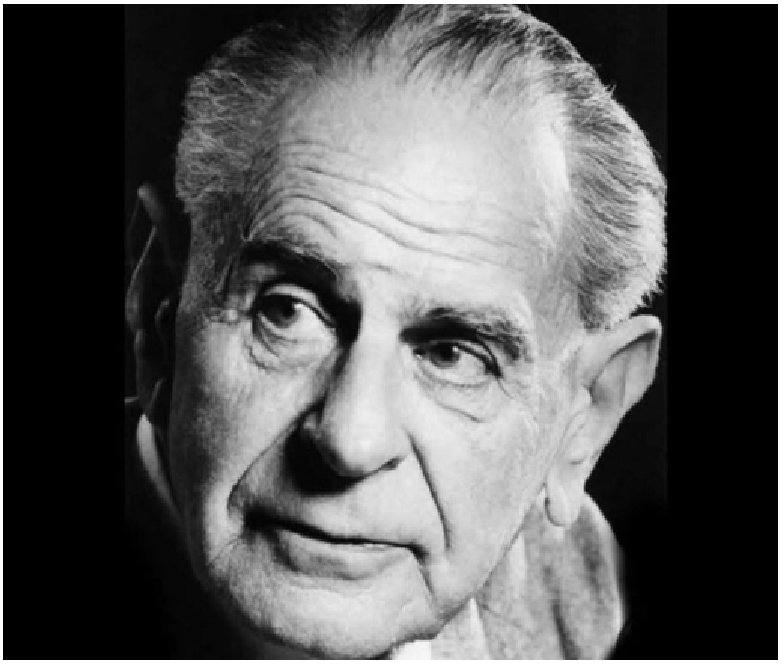
In 1973, Austrian ethologist and Nobel prize winner Konrad Lorenz (1903-1989) published a collection of essays titled "*Die acht Todsünden der zivilisierten Menschheit*", "Civilized man's eight deadly sins". In this short collection Lorenz describes eight human-caused processes that in his opinion were threatening to destroy our civilization and mankind as a species. These processes are: overpopulation, crimes against nature, the competitive rat-race, emotional atrophy, genetic decay, ruptured traditions, indoctrination, and nuclear weaponry.

Controversial as some of these might be, for better or worse they are certainly thought-provoking and make for a pleasurable read. Recent developments in the field of paleomagnetism as well as personal experiences have led me to consider whether as a research community, we too may be subjecting ourselves to practices that in the long term will turn out to be more harmful than good for our discipline. These practices will not necessarily lead to the demise of paleomagnetism but can definitely put a dampener on the proper advancement of science, leading to the existence of yet unresolved ~70 year-long controversies, for example. I do not have exactly eight sins in mind, and in fact as I write I am not even sure of what the final figure will turn out to be. I am sure, however, that these are based on personal experience and while collectively represent my views only, individually they are the result of ongoing discussions with many colleagues. While I am certainly not personally free from sin and do not wish to throw stones, I would love to start an open and honest discussion on the topic and I welcome replies and/or contributions to the IRM Quarterly. So here are my "civilized magnetist's deadly sins":

1. Catching up with fundamentals. All magnetic research disciplines in the Earth sciences are intrinsically tied to fundamental rock-magnetism. Even at the most basic "user-level", researchers in environmental magnetism or paleointensity, for example, are faced with challenges concerning magnetic mineralogy, granulometry, stability and alteration, to name a few. These challenges undermine the outcome of most experiments and their interpretation and have dictated the development of specific tests and measurement protocols which are more akin to the fundamentals of magnetic research, than the application itself. These developments have essentially driven the majority of the fundamental advances in these research areas.



"If we are uncritical we shall always find what we want: we shall look for, and find, confirmations, and we shall look away from, and not see, whatever might be dangerous to our pet theories."
Karl R. Popper

However, the same cannot be said for research in paleomagnetism, ironically one of the largest applications of rock-magnetism by publication numbers and researchers. The classical approach to paleomagnetism is in fact in stark contrast to other areas of research, and paleomagnetism is such an established field, and with its own set of traditions, that in fact it is barely even considered an application of rock magnetism. Of course, it is strongly dependent on the stability of magnetic grains and their ability to hold remanence through time based on Néel's relaxation theory. However, even when paleomagnetic textbooks abound in treatment of fundamental rock and mineral magnetism (e.g. Butler 1992, McElhinny & McFadden 1999, Tauxe et al. 2018), for most intents and purposes paleomagnetic research is almost exclusively based on the statistical evaluation of the

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Visiting Fellow Reports

Magnetic indicators of magma flow in the Columbia River large igneous province

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The ~17-6 Ma Columbia River Basalts large igneous province (LIP) (referred to herein as the Columbia River LIP) is the youngest known LIP on Earth, and an important test case for understanding the dynamics of LIP magmatism (e.g., Camp and Ross, 2004; Hales et al., 2005; Hooper et al., 2007). The voluminous lava outpourings associated with this event are roughly coincident with the initiation of the Yellowstone hotspot track (Hooper et al., 2007; Ellis et al., 2013). The Columbia River LIP is not only the largest known Cenozoic magmatic episode in the US, but its initiation represents a profound change in the geodynamical environment of the western US to the present day.

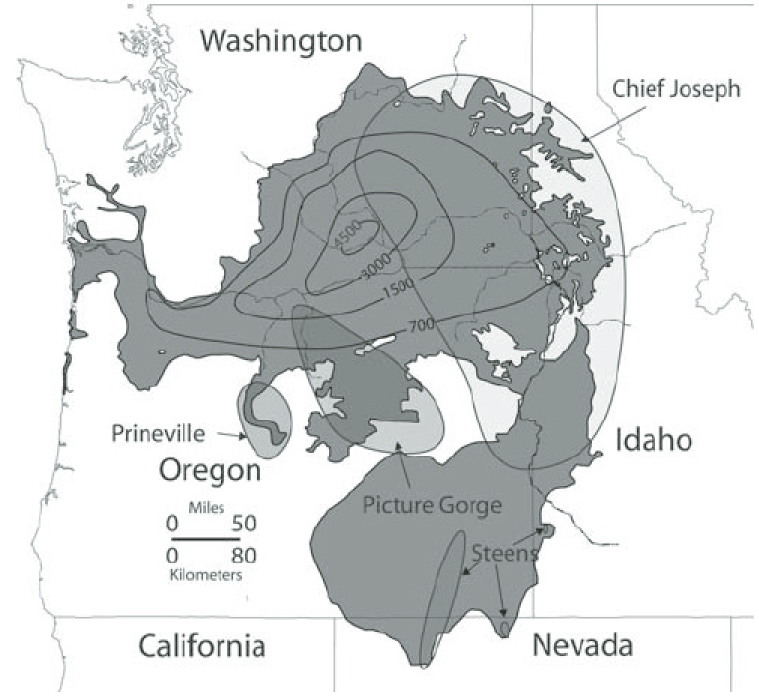

Figure 1: Simplified map from Reidel et al. (2013) of the Columbia River LIP showing the inferred distribution of lavas (grey) and exposed dike swarms (transparent polygons).

Despite the temporal association between the Yellowstone hot spot track and Columbia River LIP, their causal links are debated (e.g., see discussions Hooper et al., 2007). In all, the origin of Columbia River LIP magmas centers broadly, but not exclusively, on a few competing models. These include: (1) decompression melting of shallow mantle in a back-arc setting (Smith, 1992), (2) lithospheric delamination in the Wallowa Mountains region (Hales et al., 2005; Darold and Humphreys, 2013), and (3) impingement of the Yellowstone plume at base of the lithosphere near the Nevada-Oregon border (Hooper et al., 2007).

Given the excellent exposures and accessibility of dike swarms along the length of the Columbia River LIP, the dynamics of magma transport may be investigated through rock magnetic techniques, such as anisotropy of magnetic susceptibility (AMS) (e.g., Knight and Walker, 1988) and anisotropy of anhysteretic remanent magnetization (AARM) (Soriano et al., 2015). Numerous locations of melt generation and magma storage are proposed for the Columbia River LIP, and magnetic flow indicators are shown to be powerful tools for constraining melt sources associated with LIP magmatism (Ernst and Barager, 1992; Hastie et al., 2014). However, to date no study has applied rock magnetic techniques to examine magma flow within the Columbia River LIP dikes, and thus proposed models of long-distance magma transport have largely remained untested.

Rock magnetics of Columbia River Basalt dikes

Magma flow histories within intrusions can be interpreted through analyses of the directionality of the magnetic fabric, or anisotropy of magnetic susceptibility (AMS) (e.g., Knight and Walker, 1988). The basic principle of AMS is that many materials acquire more or less magnetization when a magnetic field is applied in different directions. This effect can be quantified as a three-dimensional ellipsoid with three principal axes oriented at 90° to one another and described by their relative magnitude and direction (Fig. 2). These axes are commonly referred to as the maximum (K1), intermediate (K2), and minimum (K3) susceptibility axes, where $K1 \geq K\ 2 \geq K3$.

For fast cooling magma, often near dike margins, magnetics grains are relatively small, and may be characterized by a single magnetic domain. For these magnetic minerals, spontaneous magnetization is fixed in the direction of the easy axis producing a null susceptibility along the long axis (Rochette et al., 1999). These minerals can produce inverse fabrics, requiring anisotropy of anhysteretic remanent magnetization (AARM) to determine the dominant shapes and orientations of ferromagnetic minerals. For these analyses, samples are demagnetized using alternating fields in the presence of a bias DC field, and their resulting magnetic remanence is measured. The sample is then demagnetized and the procedure is repeated, magnetizing the sample in a variety of directions to constrain the AARM ellipsoid, which, much like the AMS ellipsoid, can be used to infer the direction of magma flow.

We performed a pilot study on Columbia River LIP dikes, to test the applicability of rock magnetic analyses (AMS and AARM) to examine magma flow. Samples were collected from single sites on six individual dikes in 2016 and 2018. Two dikes sampled in 2016 were initially analyzed for AMS at Northern Arizona University.

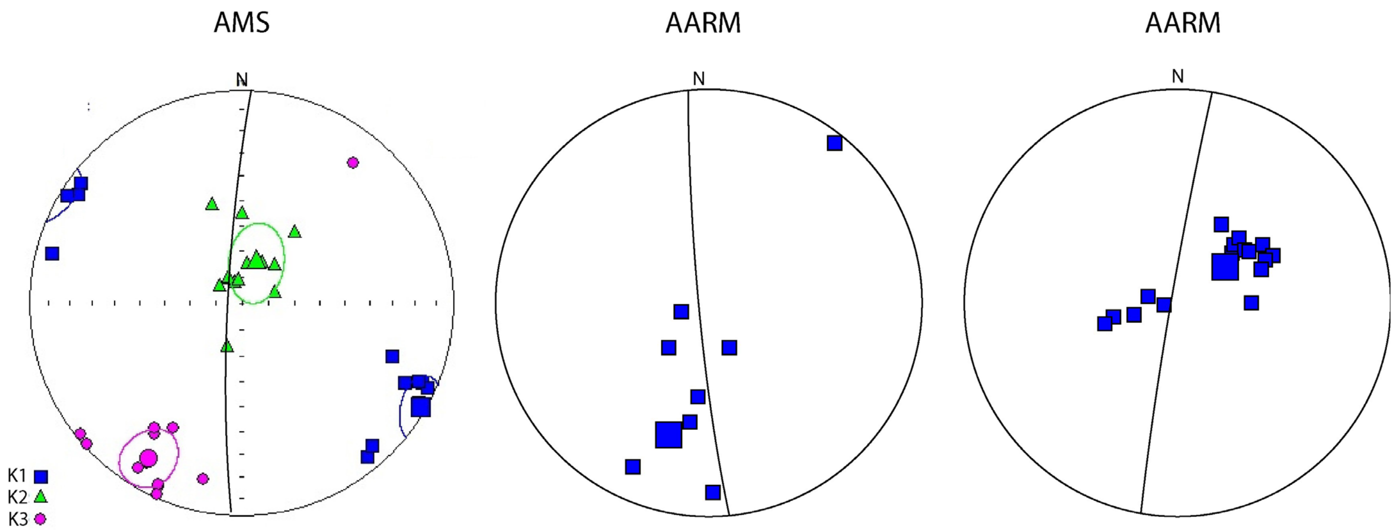

Figure 2. Examples of AMS and AARM data for select dikes of the Columbia River LIP projected on lower hemisphere stereonets. Dikes often exhibit anomalous AMS fabric (left), where K1 (blue squares) is normal or at a high angle to the dike plane (great circles). AARM analyses (two different dikes shown in the center and right) consistently produce K1 axes close to the dike plane (large blue squares represent mean K1 values). AARM analyses were performed at the Institute for Rock Magnetism, University of Minnesota.

Results reveal a strong magnetic susceptibility (values ranging 4.6-9.5 × 10-2 (SI)) with a moderate to high degree of anisotropy (Pj values ranging 1.03-1.26), suggesting that Columbia River LIP intrusions are ideally suited for magnetic fabric analyses. However, these initial results revealed anomalous AMS fabrics, where K1 was either normal or at a high-angle to the dike plane. The presence of anomalous fabrics motivated a study of AARM at the Institute of Rock Magnetism, University of Minnesota. In all, the AARM results reveal a relatively high degree of anisotropy, with mean Pj values of 1.12 and ranging from 1.02 to 1.65. The AARM ellipsoids range from prolate to oblate, and in all but one example the K1 axis occurs <30° of the dike plane, suggesting that the magnetic fabric is likely related to dike emplacement processes.

In all, these results support the utility of rock magnetic methods for investigating dike fabrics and magma flow processes in Columbia River LIP dikes. Future work will involve systematic across-strike sampling of dike intrusions at individual sites to test for multiple intrusive phases and constrain flow vectors, and sampling multiple sites along individual dikes to test the effects of localized flow processes.

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Visiting Fellowship Awardees

A list of Visiting Fellows and US Studend Fellows awarded, working backwards from the current bi yearly period.

Visitor Categories:
VF= Visiting Fellowship (10 days)
USVF= US Student Fellowship (5 days)

Previously awarded VFs are listed in parethesis.

2019a

Caderyn Owen Jones, USVF, Yale University
Jonathan Graham, USVF, UW-Madison
Wentao Huang, VF, U Rochester (2017a, 2016a)
Maryam Abdulkarim, VF, Imperial College
Marco Alban Albarran Santos, VF, UNAM
Joseph Biasi, VF, Caltech
Luigi Vigliotti, VF, U Bologna

2018b

Tania Mochales Lopez, VF, Spanish Geological Survey
Greig Paterson, VF, U Liverpool
Courtney Sprain, VF, U Liverpool (2014a)
Arlo Weil, VF, Bryn Mawr College
Jonathan Stine, VF, UT Dallas
Elham Hosseinzadehsabeti, USSF, Southern Illinois University
James Muirhead, VF, Syracuse University
Nicholas Swanson-Hysell, VF, UC Berkeley (2002b, 2010b)

2018a

Ioan Lascu, VF, Smithsonian Natural History Museum
Noah Vento, USSF, Texas A&M
Louise Hawkins, VF, U Liverpool
Thomas Berndt, VF, Peking University (2014b, 2016a)
Sarah Slotznick, VF, UC Berkeley (2015b)
Ben Gilbert, VF, Lawrence Berkeley National Laboratory
Huapei Wang, VF, U Geosciences Wuhan (2011b, 2012a)

2017b

IRM moves, no fellowships awarded

2017a

James Amato, USSF, UW-Milwaukee
Sope Badejo, VF, Imperial College (2016a)
Thomas Belgrano, VF, U Bern
Lauren Herbert, USSF, U of the Pacific
Wentao Huang, VF, U Arizona (2016a)
Ran Isshachar, VF, Tel-Aviv University (2015b)
Tom Mallett, VF, La Trobe University
Dominika Niezabitwska, VF, Polish Academy of Science
Sarah Slotznick, VF, UC Berkeley (2015b)

2016b

Lindsay Bollig, USSF, U St Thomas
Julie Bowles, VF UW-Milwaukee (2007a)
Caitlin Leslie, USSF, Baylor University
Suzanne McEnroe, VF, NTNU (1993b, 1997b, 2001b, 2004b, 2007b, 2009a)
Estefania Ortiz, USSF, Texas A&M
Steve Phillips, VF, U Texas
Courtney Wagner, VF, U Arizona
Yi Wang, VF, U Michigan

2016a

Charly Aubourg, VF, U Pau (2003a, 2006a, 2088b, 2009a, 2013a)
Michael Volk, VF, LMU-Munich
Valerio Funari, VF, U Bologna
Boris Resnick, VF, KIT
Thomas Berndt, VF, Imperial College London
Sope Badejo, VF, Imperial College London
Brendan Nash, USSF, Texas State University
Samantha Memkin, VF, U Michigan

2015b

Andrea Biedermann, VF, NTNU
James Byrne, VF, Tubingen University
Andrew Horst, VF, Oberlin College (2014a)
Ran Issachar, VF, Tel-Aviv University
Libby Ives, USSF, Iowa State University
Sophie Lappe, VF, UW-Milwaukee (2011a, 2014b)
Sarah Slotznick, USSF, Caltech

2015a

Matthew Dorsey, USSF, UW-Madison
Michael Schiltz, USSF, UW-Madison
Eric Ferre, VF, Southern Illinois University (2002a)
Josep Pares,VF, CENIEH
Tim van Peer, VF, U Southampton
Bin Wen, VF, Yale University

2014b

Sonia Tikoo, VF, UC Berkeley
Thomas Berndt, VF, Imperial College London
Agnes Kontny, VF, KIT
Natalia Bezaeva, VF, Moscow State University (2011b)
Sophie Lappe, VF, UW-Milwaukee (2011a)
Ian Moffat, VF, Flinders University
Geertje ter Maat, VF, Utrecht University
Casey Haack, USSF, Concordia College
Kelsey Seppelt, USSF, Concordia College
Abdallah Shubadeh, USSF, Concordia College

2014a

Courtney Sprain, VF, UC Berkely
Peter Lippert, VF, U Arizona (2013b)
Nathan Church, VF, NTNU (2007b, 2009b)
Tom Haerinck, VF, KU Leuven (2012a)
Lauren Hoyer, VF, U KwaZulu-Natal
Andrew Horst, VF, Oberlin College
Janine Roza, USSF, CSUB
Robert Coe, VF, UC Santa Cruz (1996b)
Sarah Friedman, USSF, Southern Illinois University (2010a)

2013b

Ellery Frahm, U Sheffield, VF
Katherine Knierim, VF, U Arkansas
Peter Lippert, VF, U Arizona
Robert Hatfield, VF, Oregon State University
Christoph Mang, VF, KIT (2011a)
Stefanie Brachfeld, VF, (2001b, 2011a)
Amy Chen, VF, Macquarie University (2008b, 2009b)

2013a

Charly Aubourg, VF, U Pau (2003a, 2006a, 2008b, 2009a)
Sara Guerrero Suárez, VF, U Computense Madrid
Xiangyu Zhao, VF, LMU-Munich
Kelsey Lowe, VF, U Queensland
Samer Hariri, VF, Wayne State University
Edivaldo Dos Santos, VF, Centro Brasileiro de Pesquisas Fisicas
Steven Skinner, USSF, Caltech
Alexander Michels, USSF, Michigan Technological University

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.

Environmental magnetism and Climate

Amalan, K., A. S. Ratnayake, N. P. Ratnayake, S. M. Weththasinghe, N. Dushyantha, N. Lakmali, and R. Premasiri (2018), Influence of nearshore sediment dynamics on the distribution of heavy mineral placer deposits in Sri Lanka, Environmental Earth Sciences, 77(21).

Ayoubi, S., and M. Karami (2019), Pedotransfer functions for predicting heavy metals in natural soils using magnetic measures and soil properties, Journal of Geochemical Exploration, 197, 212-219.

Barbosa, R. S., J. Marques, V. Barron, M. V. Martins, D. S. Siqueira, R. G. Peluco, L. A. Camargo, and L. S. Silva (2019), Prediction and mapping of erodibility factors (USLE and WEPP) by magnetic susceptibility in basalt-derived soils in northeastern SAo Paulo state, Brazil, Environmental Earth Sciences, 78(1).

Bessa, A. Z. E., G. Ngueutchoua, and P. D. Ndjigui (2018), Mineralogy and geochemistry of sediments from Simbock Lake, Yaounde area (southern Cameroon): provenance and environmental implications, Arabian Journal of Geosciences, 11(22).

Bonotto, D. M., and R. Garcia-Tenorio (2019), Investigating the migration of pollutants at Barreiro area, Minas Gerais State, Brazil, by the Pb-210 chronological method, Journal of Geochemical Exploration, 196, 219-234.

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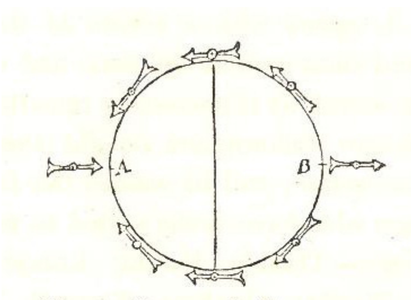

Fig. 1. GILBERT’S TERRELLA.

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characteristic remanent directions, from the goodness of the line-fits, since these were introduced by Kirschvink (1980), to their collective dispersion (typically assuming Fisherian distributions, though this assumption should not be taken for granted). Additionally, and only wherever possible, stability tests are performed to evaluate the relative timing of acquisition of the characteristic directions. However, a direct correlation between the directions isolated and the minerals in the specific grain sizes that carry those directions is not extensively investigated on a regular basis, and almost exclusively when controversial results are obtained, for example if remagnetizations are suspected or secondary, authigenic phases are involved.

At a minimum, if the remanence has been cleaned through thermal demagnetization, then the unblocking temperatures for the different components isolated provide invaluable, yet partial, information about the remanence-carrying mineralogy, but a targeted investigation of the grains that carry the ChRM is often lacking. To be clear, I am not necessarily referring to the magnetic characterization of the specimens, but instead the determination of which specific grains, and in which grain size/coercivity distribution, are responsible for the characteristic remanence and/or other remanence components. It has become increasingly more common to corroborate paleomagnetic observations with rock-magnetic evidence that pinpoints the remanence carrying minerals and their domain state. Since it was proposed by Day et al. (1977), the ”Day plot” has been widely employed to determine the domain state and thus stability of magnetites and titanomagnetites (and these phases only, though one may argue somewhat arbitrarily, e.g. Roberts et al., 2018) in rocks. FORC diagrams are becoming a staple in the rock-magnetic and paleomagnetic literature to map the coercivity distribution and interaction fields of specimens and discriminate the domain states of the minerals present. Unmixing of coercivity distributions from hysteresis loops, IRM/ARM acquisition curves, backfield demagnetization curves and FORC diagrams has also become very popular, and particularly for the remanence curves that can be acquired in most paleomagnetic laboratories.

Application and interpretation of these rock-magnetic tools, however, has sometimes remained somewhat simplistic. For instance, and regardless of the validity of the methods utilized, it is undeniable that the dominant minerals observed may not be the phases that carry the remanence of interest, oftentimes far from it. It is also undeniable that certain magnetic phases/grain sizes can dominate the bulk magnetic response owing to their intrinsic magnetic properties: for example, single domain grains will commonly dominate the remanence over the larger multi domain particles, because of their remanence ratio, but conversely MD grains will tend to dominate in-field measurements of magnetization (and susceptibility). Therefore, while every paleomagnetist wishes for stable SD particles, observing these in a specimen does not necessarily imply that these are responsible for the ChRM, nor that, if present, they are the most abundant. For example, complex magnetic histories have been documented in rocks with multiple component magnetizations. In one case study, the most stable high coercivity ChRM component, which would typically be interpreted as primary, is in fact carried by secondary magnetite. These grains formed during a thermochemical event that also led to the acquisition of a low coercivity thermoviscous overprint on the original titanomagnetite present. The secondary magnetite and the thermoviscous component thus carry the same orientation, while it was determined that the intermediate component isolated from the titanomagnetite records the primary remanence (Schmidt 1982).

Of particular significance may be the increasing recognition of the importance of MD grains to the remanence, somewhat shifting the paradigm of which grains are capable of holding stable remanences. In paleointensity, MD grains are responsible for the unwanted pTRM tails that are often observed and result in curved Arai plots, and are generally considered unstable carriers of ancient remanence. However, MD grains with high laboratory unblocking temperatures close to the Curie temperature have been observed and the phenomenon has been attributed to thermo-viscous processes, in some cases accompanied by chemical overprinting (Dunlop & Xu 1994, Xu & Dunlop 1994, Dunlop, Özdemir, et al. 1997, Dunlop, Schmidt, et al. 1997). MD remagnetization theory was very recently expanded by Berndt and Chang (2018) who effectively demonstrated why MD grains can contribute to the remanence up to high laboratory demagnetization temperatures, while their remanence is completely removed within the first few AF demagnetization steps. In any case, it is increasingly obvious that interpretations of complex magnetizations based on simplistic rock-magnetic observations are inadequate and may have resulted in erroneous interpretations of paleomagnetic records.

2. Data quality and the dipole assumption. Arguably the largest assumption of all and bearing tremendous implications for the validity of paleomagnetism, the dipolar field assumption states that on a millenial time-scale the Earth's magnetic field can be averaged to a dipole that is coincident with the Earth's rotation axis: the geocentric axial dipole hypothesis. While it does explain the larger part of the Earth's field (~80%) there are instances in which a pure dipole fit does not fully explain the observations. Features in the paleomagnetic record that may point to heightened non-dipole contributions are expressed as streaked (or elongated) VGP distributions, shallow paleomagnetic inclinations (particularly in igneous rocks, where inclination shallowing is not expected), asymmetries in dual-polarity data, and discordant pole positions obtained from rocks of the same age but situated at different geographical locations. Many such instances exist in the paleomagnetic record, and though the causes may not be unequivocal and can be attributed to a variety of processes (tectonics, shallowing of DRM inclinations, incorrect structural corrections, unremoved overprints, to name a few), the underlying data have often been overlooked or worse dismissed point-blank on the basis of being inconsistent. It is of paramount importance to make sense of the data at hand, and it is admissible to dismiss them only when it can be proven that they are in fact bad data. Fortunately, inconsistencies in the records have a way of resurfacing and old controversies are sometimes reignited.

As a community, we should look into these longstanding controversies deeply and without preconceptions, understanding that ultimately data are king and only by understanding these will we drive our science further. On this point it is interesting to read what Popper (1969) has to say about how some go about dealing with refutations. This he calls the method of auxiliary and *ad hoc* hypotheses. When conjectures and expectations meet contradictory evidence it is often observed that the hypothesis is altered in a manner to incorporate this new evidence. Popper (1969) uses the case of the orbit of Uranus as an example. Initially an *ad hoc* hypothesis was added that required the proximal location of another body. Later this body, Neptune, was discovered and the ad hoc hypothesis upgraded to an auxiliary hypothesis and the underlying Newtonian orbital mechanics was spectacularly confirmed.

Ad hoc hypotheses of this nature are reminiscent of 'TPW events' that plague paleomagnetism. TPW is often appealed to when aberrant paleomagnetic poles are encountered. While components of both APW and TPW almost certainly contribute to the totality of polar wander, no one today doubts that APW accounts for the majority of polar motion. Nevertheless, the apparent dispersion of palaeomagnetic poles from many geological periods (*s.l.*) has been proffered as evidence for TPW events, and even oscillations, at those times. Like Uranus' disturbing element, if similar TPW events could be observed on all continents/cratons, such hypotheses would be elevated to auxiliary hypotheses. In reality, while the discovery of Neptune in one fell swoop exonerated the conjecture of another orbiting body, providing corroborating evidence for TPW from one or more extra continents/cratons could be a Herculean task. The serious problems confronting upgrading *ad hoc* TPW hypotheses to auxiliary status comprises not just the existence of relevant well-dated stratigraphies/intrusives but also such sequences/igneous rocks being amenable to paleomagnetic analysis.

Are we at risk of being lumbered with a multitude of *ad hoc* hypotheses with little hope of ever corroborating or disproving them? One could also ask questions of the interminable quest to track supercontinents, with no regard to what is feasible given a) the increased sparsity of suitable rock sequences back in time, and b) the increased number of independent cratons back in time. Is paleomagnetism digging itself a hole that without a 'Neptune' it will not arise from?

3. Distributions and statistics. Spurious magnetizations, whether resulting from unremoved secondary overprints, poor magnetization acquisition, or anomalous geomag-

netic field behavior, to name a few possibilities, are the damnation and the largest challenge of most paleomagnetists. As mentioned above, paleomagnetic statistics are largely based on the assumption that the distributions of directions are circularly symmetric, or within the prediction of geomagnetic models, so that directions and VGPs are most commonly evaluated using the precision parameter and 95% confidence circle of Fisher (1953). Note, however, that in the case of paleomagnetic directions, paleosecular variation (PSV) will introduce scatter that makes Fisher statistics "inappropriate", since PSV will result in N-S elongations of the data that increase towards the equator. Spot readings of the geomagnetic field are immune from these elongations and Fisher statistics are applicable. Regardless, it is often "convenient" to report Fisher statistics for somewhat elongated data, and in fact it is done quite commonly, just as the uncertainty around a paleopole is increasingly more commonly reported as A_{95} rather than dm/ dp. A caveat, should be at a minimum to clearly state whether the distribution is circularly symmetric or not.

Somewhat relatedly, and although not common, one sometimes comes across a study where the Fisher α_{95} confidence circle is calculated using the approximation α'_{95}= 140/sqrt(kn), instead of the estimate formula α_{95}= $\cos^{-1}[1-(n-R)/R((1/P)^{(1/(n-1))}-1)]$, where P is taken as 0.05. As Tauxe et al. (1991) state: "There is no excuse for using α'_{95}, it is not difficult to compute the vastly more accurate approximation [... (α_{95})] and one can then obtain extremely reliable confidence regions if the distribution underlying the data is Fisherian." When reporting paleomagnetic statistics, however, it should become standard practice to also report the number of observations from which the means are derived, stating whether the average directions are calculated at the site-level (N) or from individual directions (n). Site-averaged directions should always be preferred for robustness.

Of even more fundamental importance, however, is the correction for magnetic declination. I recently encountered wrongly applied corrections, whereby negative (Westerly) declinations had been added back to the compass reading instead of being subtracted, or conversely positive (Easterly) declinations subtracted instead of added. Such mistakes are particularly treacherous because these corrections are never reported and lead to paleomagnetic directions being rotated twice the amount of the declination and possibly more if bedding tilt-adjustments are involved. The possibility of wrongly corrected azimuths "floating around" the literature is actually very daunting (even terrifying) and as geologists first, then paleomagnetists, we must ensure that we teach our students the appropriate use of a compass.

4. Resolution of demagnetization routines. Adding to the uncertainty surrounding the reliability of paleomagnetic directions is the detail of the demagnetization routine employed. Particularly for older studies, it is not uncommon to find coarse, widely spaced demagnetization steps. Moreover, in the case of alternating field demagnetization, the highest fields employed often do not completely demagnetize the samples. Worse, for studies published before the application of principal component analysis in paleomagnetism, one single "blanket" demagnetization step from the NRM to high temperatures or alternating currents is sometimes observed. Results obtained in this way should be treated with caution, as the fidelity of the ChRM directions obtained can be questionable owing to the possibility of overlapping components of magnetization that are not fully distinguished by the cleaning routine. Overlapping coercivity distributions and components of magnetizations highlight the importance of high-resolution demagnetization routines, particularly approaching the unblocking temperatures of the phases of interest and enabling to fully isolate those components of magnetization. As the sensitivity and precision of magnetic instruments increases, so does the "possibility window" and it is worthwhile, or even imperative, to take advantage of this.

It is worth mentioning that for AF demagnetizations, effective protocols that minimize gyroremanent magnetization (GRM) effects have been proposed (see Finn & Coe 2016) and it is recommended that these are utilized whenever GRMs are detected, if not as standard practice.

5. Secondary magnetizations have been at the fulcrum of long lasting disputes, for example regarding the mechanisms of remanence acquisition in red beds, whether DRMs, CRMs or both. More recently, detailed rock-magnetic investigations of remagnetizations in carbonate rocks have been undertaken in search of diagnostic features that allow characterizing their remanence. In paleomagnetism, diagnostic features for overlapping/ unremoved components of magnetization are expressed as curvatures in the Zijderveld diagrams and sometimes lead to failed or undetermined stability tests. Curved components on Zijderveld diagrams often translate into great circle paths on a stereonet (note, however, that apparently curved components on Zijderved diagrams could also arise from poorly resolved demagnetization of a two-component magnetization, which will not result in a great circle path), and intersections of great circle paths from different specimens are interpreted as the common direction of magnetization. Great circle analysis has been improved to incorporate set points (those directions isolated through PCA on linear Zijderveld segments) and sector constraints to estimate the arc of the great circle where the ChRM direction is expected (see McFadden & McElhinny 1988). The technique, however, still requires that stepwise cleaning of the remanence progressively uncovers the primary remanent direction. Uncovering of a primary ChRM, however, should not be taken for granted, and the same applies to set points determined from specimens that demagnetize linearly. A secondary magnetization may in fact be coercive enough to result in linear PCA segments on certain (softer) specimens but curved paths in others (harder). In other words, the assumption for the great circle method to work is that the primary ChRM (which should have similar orientation -small dispersion- among specimens) is harder than the secondary magnetization. It should also be noted that the secondary magnetizations recovered should also bear similar orientation/distribution if these were acquired during the same event and during a relatively finite period, leading to subparallel circles and associated uncertainties. Note however, that complex magnetizations acquired during deformation (e.g. prefolding primary magnetizations and syn- or post-folding secondary magnetization) will invalidate this statement because the two components should be evaluated in different coordinate systems.

In the simplest scenario, the great circles should be somewhat subparallel and converge towards the primary direction (Fig. 1a). Importantly, smaller incident angles among the great circles increase the uncertainty around their intersections (Schmidt 1985) and warrant the use of sector constraints (McFadden & McElhinny 1988). If the opposite is the case, though, and the softer primary magnetization is completely lost, then the great circles will converge towards the secondary magnetization direction. The soft nature of the primary magnetization implies that the NRM mean direction will have a disperse distribution. In this case the angle of incidence of the great circles should be larger and the mean intersection have higher precision, however the direction obtained will be secondary (Fig. 1b). A complex magnetization history, particularly for older rocks, will enhance this effect. One could say that the more dispersed the NRM and the orientation of the great circles, the less likely the great circles will be to intersect at a primary direction. It is not uncommon, in fact, to observe great circles that are not subparallel and converge towards a direction that is not reasonably primary, indicating that the assumptions for the method do not always hold. These statements are corroborated by the understanding that magnetization directions with too low dispersion may be the result of remagnetizations (e.g. Deenen et al. 2011). Great circle-derived paleomagnetic directions should always be viewed with caution and with an open mind.

A natural question then is: what is the expected dispersion for remagnetized data? There isn't a straight answer to this question. From the above it is clear that if great circles converge towards the primary direction, then dispersion of remagnetized data can be larger than that of primary ChRMs. However, in the case of hard remagnetizations, it could be significantly lower (i.e. higher ChRM precision indicates remagnetizations). The question of what amount of dispersion reflects paleosecular variation (PSV) was valiantly addressed by Deenen et al. (2011) who attempted to determine guideline and N-dependent confidence intervals for VGPs, above or below which one may want to question the data. These guidelines however do not distinguish between rock-types, igneous or sedimentary, which are subject to fundamentally different magnetic acquisition processes. Moreover, they can comprise different ranges of magnetic mineralogies in different grain size ranges, and implicitly should yield different dispersion whether they average PSV or not. Furthermore, due to their different properties (e.g. porosity) they will also likely be affected differently by the variety of possible secondary magnetization processes (CRM, IRM, VRM… and in the case of sediments by syn- and post-depositional compaction), lending ambiguity to the interpretation of Deenen et al.'s (2011) α_{95} min-max guidelines.

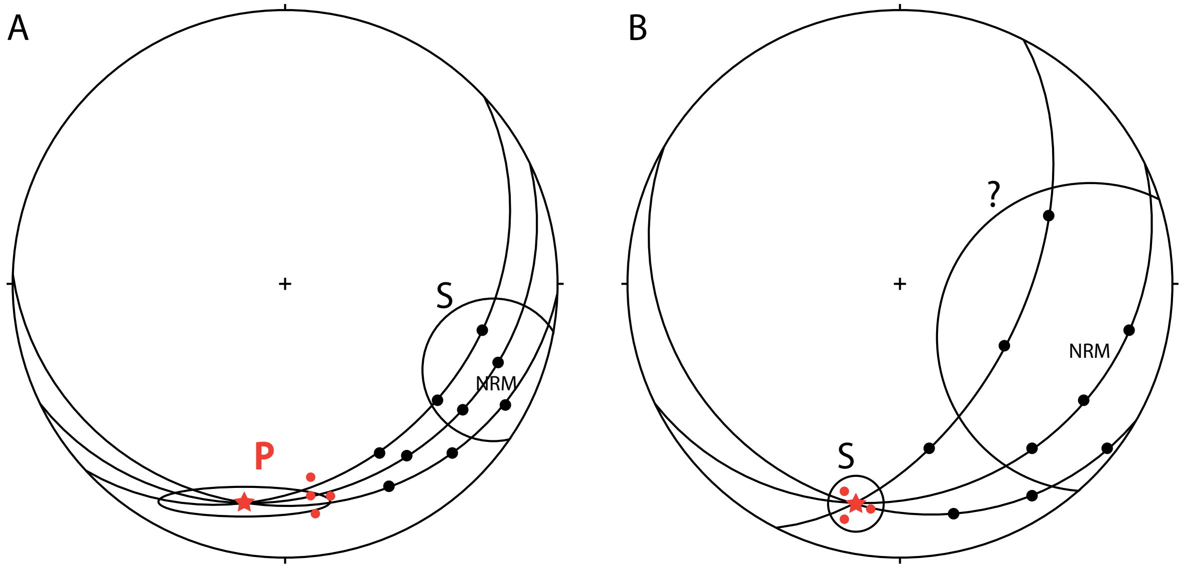

Figure 1. Great circle analysis of demagnetization data. A) a primary, hard, direction of magnetization (P) is obtained from the intersection of great circles fitted through progressive demagnetization (black dots) of a secondary, softer remagnetization of the NRM (S), and a few set-points obtained from linear fits (red dots). If the overprint is common among the specimens, the great circles should be subparallel to each other, resulting in greater uncertainty around the common direction, and in the intersection of the great circles (red star, bound by a narrow ellipse) not to coincide with the expected mean of the set-points; B) intersection of demagnetization great circles for a coercive secondary overprint (S) affecting a softer/weaker NRM of unknown origin (?). The higher dispersion of the NRM directions relative to the secondary magnetization is highlighted by the higher angle of incidence of the great circles at S than in (A). Note that in this case any set-points measured are more likely to agree with the intersection of the great circles and reflect secondary magnetizations.

6. To cut or not to cut? Related to the discussion on dispersion is the use of cut-off angles, whether in the form of variable Vandamme (1994) or fixed cut-off angles, typically set between 45° and 40° (e.g. Wilson et al. 1972, Watkins 1973, McElhinny & Merrill 1975), but sometimes as small as 35°. Use of cut-off angles was introduced in the study of PSV to eliminate outliers, resulting from transitional data obtained on volcanic rocks cooled during a reversal, for example, or excursions of the geomagnetic field. This makes sense, but can also introduce bias to the data, rendering elongated data-sets more circular, where the elongations actually represent real underlying geological processes (tectonics) or complex magnetization histories. In such cases attempting to estimate PSV may be futile in the first place and applying cut-off angles will still lead to erroneous estimates. Whatever the case may be, it appears that the experience of the paleomagnetist in identifying outliers through careful scrutiny of the directions from the site to the formation level must come before the blind application of any cut-off angle. The internal consistency of the data-set, and on comparison to coeval data derived from the same craton, can then be critically evaluated.

To make my case I bring forward a “blind” real example (there is a fitting Italian expression: “name the sin but not the sinner”) of what I consider to be an over-application of the cut-off technique. A paleomagnetic study was conducted on two stratigraphic sections (I and II) within the same basin, and the authors isolated a large number of dual polarity characteristic directions that do not define a consistent distribution, though they do define an area of highest clustering of VGPs in the southwestern quadrant of the stereonet. To make sense of these data, two previously published paleopoles obtained from the same basin and that had been determined to be primary were plotted, with 45° cut-off angles drawn around the mean poles. All VGPs that fall within the two 45° circles were accepted as deriving from primary magnetizations, whereas all other poles were rejected as being subjected to remagnetizations. In support of the latter interpretation, the authors speculate that the excluded paleopoles that define non-Fisherian distributions are the expression of the APW of the craton during the time the rocks were deposited, superposed by PSV and directional scatter due to other effects such as lightning strikes.

One may see why the authors would have utilized such approach (which also passed peer-review), but in truth the study adds nothing to the understanding of which directions are primary and/or secondary, and to the fidelity of paleomagnetic recording of those rocks in general. In fact, the “new paleopole” obtained is not a new pole at all, but essentially an "average" of the two previously published paleopoles, based on data that cannot be fully evaluated, and thus with precision and confidence intervals that are rather meaningless. Moreover, the study leaves the reader with the obligation to trust the arguments for primary magnetizations presented in the older studies without reporting any detail. The cut-off angles thus become a means to minimize the extent of controversial data, rather than to eliminate outliers that do not reflect PSV. The fallacy of this approach brings us back to the need for more detailed rock-magnetic investigations and/or better stability tests to help assess the fidelity of paleomagnetic records, the mineralogies that carry those records, and their coercivity distributions, providing insight (and hopefully a solution) into the processes that generated the observed dispersions of directions.

7. The quick-fix. I had mentioned paleomagnetic statistics earlier in this article, and the examples shown above make a valid case for utilizing site-statistics to help identify outliers. Statistics are the bread and butter of paleomagnetists and ideally uncertainties should be propagated from the sample (MAD) to the formation level, passing through the site-means. In practice this is almost never done: sample directions may be discarded based on the MADs, and equally weighted site-mean directions are typically averaged to determine the Formation mean and its uncertainty. This is acceptable, and I refer to the book by Irving (1964) for a better discussion on the propagation of errors. When no statistical treatment is presented, however, it becomes impossible to determine whether outliers are true outliers (in disagreement with directions from the same site), or whether they are discordant (in agreement with other directions from the same site but in disagreement with other site-means or poles). Following this terminology, outliers can be easily explained as misoriented specimens and eliminating these point-blank is legitimate. Eliminating discordant data, however, needs justifying. In truth, such discordant data should never be eliminated point-blank but rather discussed, as they may provide the key to understanding an underlying process (e.g. Bilardello et al. 2018).

Techniques have been used for the purpose of minimizing the effect of controversial data, that instead of cleaning the data of outliers or unwanted effects, attempt to provide a correction. Blanket corrections of the data, however, may have the unwanted effect of confounding the paleomagnetic record instead of identifying the underlying roots of the problem. One such technique was described in a previous IRM Quarterly article (26-3, "The do’s and don'ts of inclination shallowing corrections") and is the (mal)practice of applying blanket inclination corrections based on average shallowing factors.

Bazhenov and Shatsillo (2010) proposed an ingeniously simple method for correcting data from inclination shallowing and non-dipole effects, that is somewhat akin to calculating mean pole positions from oceanic data (e.g. McElhinny & McFadden 1999). The technique involves connecting sampling-site locations and respective paleopoles using great circles, and determining corrected mean pole positions based on the intersection of great circles of multiple site-pole pairs for same-aged rocks. The more spread out the sites are in latitude and longitude, the smaller the uncertainties associated with the technique itself become, owing to the angles at which the great circles intersect (Schmidt 1985). Uncertainties around the mean intersection of any great circles can then be evaluated by bootstrapping the data obtained at each study site and generating multiple great circle fits. If the poles are indeed same-aged and reliable, then the point cloud of the intersections of great circles should then define an ellipse, and a confidence region can be drawn that incorporates 95% of the point cloud (Fig. 2).

Bazhenov and Shatsillo (2010) investigated Late Permian poles, but did not perform a bootstrap analysis to evaluate the uncertainty. Instead, they tested the dataset by fitting non-dipole (G2 and G3) terms to the difference in observed paleomagnetic inclination for a site (relative to the expected dipole inclination) versus the dipole inclination. Data from a collection of sites lie on the same fit if the source of uncertainty is common. They found that for their study on Northern Eurasian data most data could be fitted by common non-dipole components, validating the technique and providing evidence for primary and coeval magnetizations. Other data from South France, however could not be fitted with the same G2 and G3 components, and were thus likely affected by other processes which they attributed to tectonic rotations or less-likely to Early Triassic remagnetizations.

Recently, the same technique was applied to global data by utilizing the bootstrap method to evaluate uncertainties, however without testing the contribution of the non-dipole component fits to the data. In this study (Fig. 3) the bootstrap point clouds (red dots in the figure) appear to only somewhat resemble ellipses where the great circles are strongly subparallel to each other (see Schmidt 1985). Overall, however, the uncertainties do not define ellipses and the confidence envelopes drawn are irregular, indicating that these data are likely affected by multiple processes. Because neither inclination shallowing or non-dipole contributions would affect the orientation of the great circles and hence their intersections, tectonic rotations and/or remagnetizations are left as alternate possibilities to explain the observations.

Underlying published data should always be tested for consistency before being applied to particular techniques and appropriately cited for verification. Speaking of "Big Data" in paleomagnetism is out of proportion, but undoubtedly mistakes occur in publications and in database entries, and these can be easily propagated. Particular caution should be exercised when utilizing published datasets. In particular, databases are sometimes offline and it can be difficult to match a reference number to a publication, therefore the datasets used should be appropriately cited, possibly not as database entries.

A technique that utilizes the intersections of small circles (SCI) to analyze the remanent direction of synfolding magnetizations was proposed by Shipunov (1997). The technique was subsequently modified somewhat by other researchers (e.g. Henry, Rouvier, et al. 2004, Waldhör & Appel 2006, Villalaín et al. 2016, Calvín et al. 2017) notably to incorporate a dispersion analysis of the corrected directions. However, care must be taken when interpreting the uncertainty around the mean direction. When the intersections of the SCI method are evaluated, these will suffer from a similar distribution of uncertainty discussed by Schmidt (1985) for great circle analysis, with the confidence ellipse becoming progressively more elongated with decreasing incident angles among the small circles (Fig. 4). The uncertainty therefore closely follows the distribution of the traces of the magnetizations along the small circles, and hence the bedding attitude.

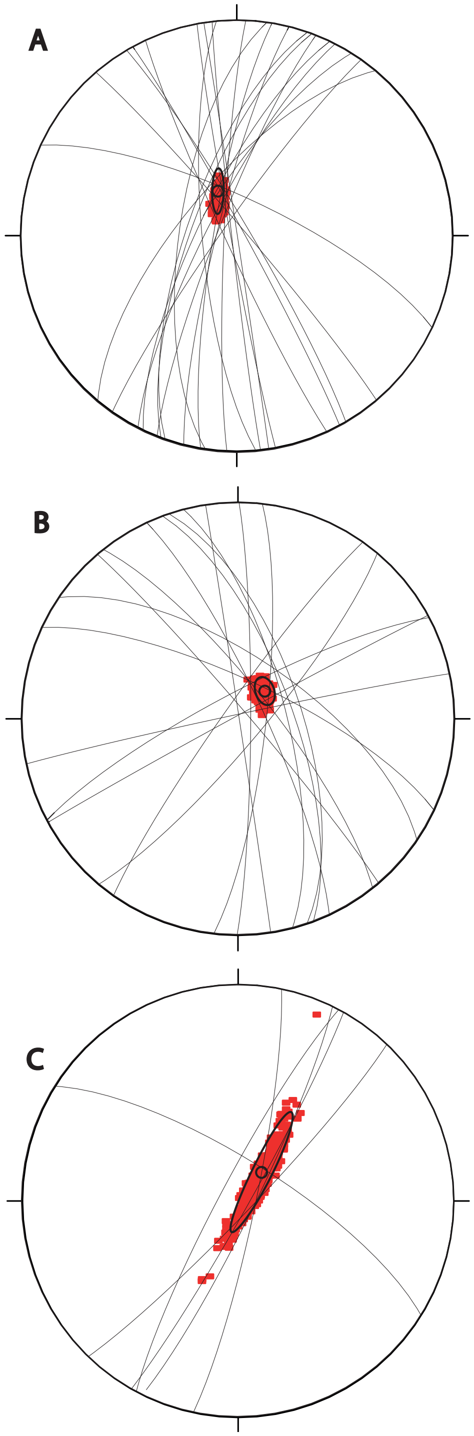

Figure. 2. Bootstrap analysis of intersection of great circles from Bilardello et al. (2018) for rock formations of different ages. View is centered on the South Pole with Greenwich at the top: the bootstrapped point cloud (red squares) distributions of intersections of great circle-fits to VGP distributions have an elliptical shape and can be fitted with a 95% confidence ellipse around the mean, indicating a common (re)magnetization event.

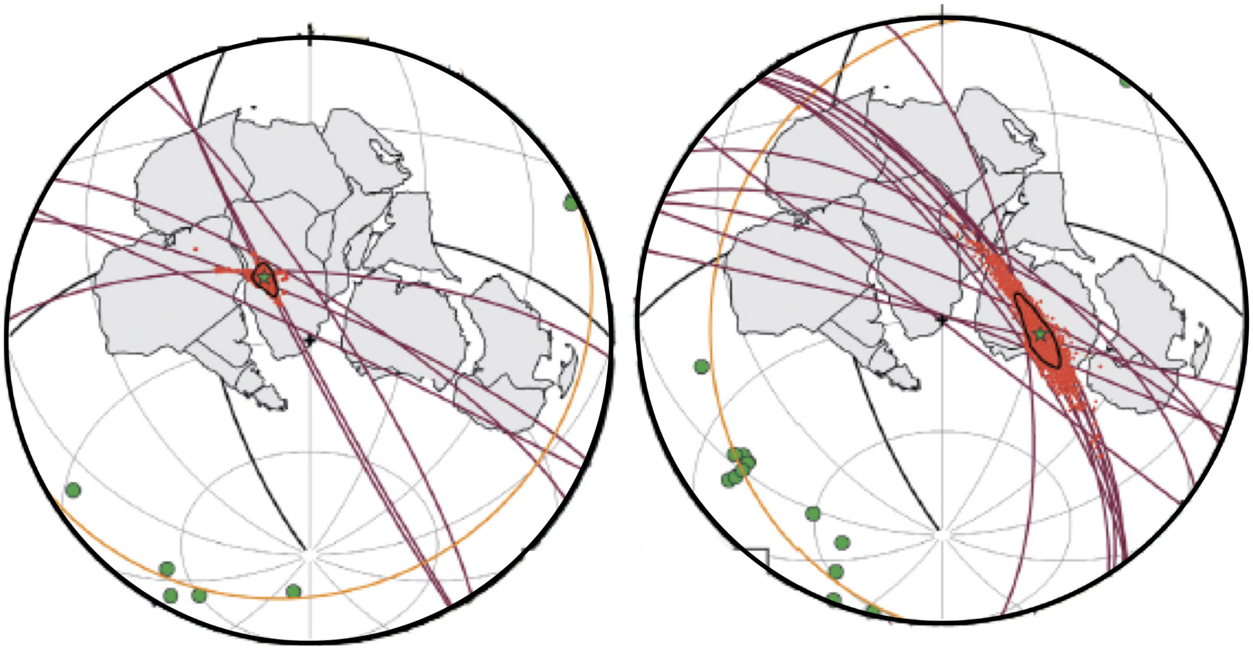

Figure 3. Intersection of site-pole great circles (SP, red) applied to global data of two supposedly distinct age of magnetizations, modified after Gallo et al. (2017). Green dots are the poles to the individual SP circles, which are fitted with a great circle (yellow) whose pole, in turn, defines the mean intersection of the SP circles (green star). Red dots are the bootstrapped intersections of SP circles defining irregular confidence regions.

The technique is known for working well on elongated distributions of magnetizations, however these are only elongated in *in-situ* or tilt-corrected coordinates. Implicit assumption of the techniques is that the strength of the distribution (affecting both girdles and clusters, *sensu* Woodcock (1977)) is maximized after the optimum "differential untilting" and thus the original elongation will also be minimized. The uncertainty of the distribution will be elongated along the small circles, and the maximum strength of the "corrected" distribution of directions will be obtained when the directions are artificially elongated perpendicular to that (Fig. 4b3. The less concentric the great circles are (the higher the incident angles), the more symmetrical (clustered) the distribution of best-fitted directions and uncertainty ellipse (Fig. 4b1). The elongation of the corrected directions is therefore meaningless and only reflects the variability of bedding attitude. The true elongation of the corrected directions is unknown and cannot ever be determined from the correction itself. Application of the technique is thus questionable for "truly" elongated data, i.e. magnetizations that are acquired over an extended period of time, such as secondary chemical magnetizations, before, during, or after folding. Use of the technique further implies that the remanence is acquired homogeneously through time, so that, at best, it will only return a mean direction acquired at a "mean" synfolding age.

Moreover, Calvin et al. (2017) discuss the uncertainty

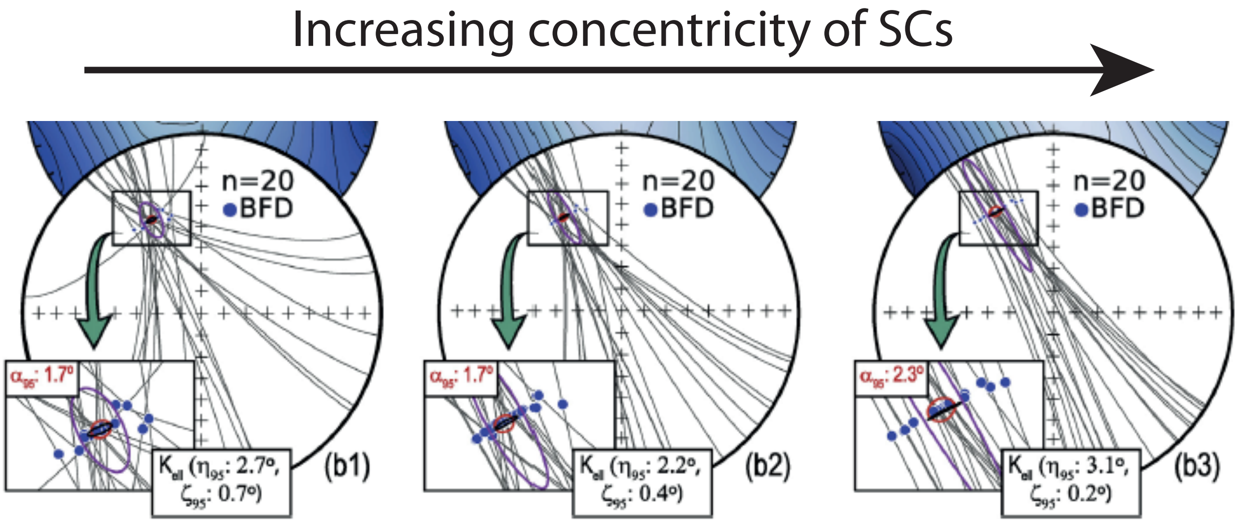

Figure 4. SCI technique for increasing concentricity of the small circles (panels b1, 2 and 3), modified after Calvin et al. (2017). The mean direction and 95% uncertainty of the technique (purple ellipse) are plotted over the distributions of small circles. The blue dots are the best fit directions (BFDs) obtained from the technique. Inset shows an enlargement of the best fit directions together with the Fisher (1953) α_{95} circle in red and a Kent (1982) 95% confidence ellipse in black. Note that the strong elongation of the best fit directions is an artifact of the technique.

around the bedding correction that yields the best-fit corrected direction. If this bedding attitude is to be used to restore magnetic fabrics in the "optimum synfolding coordinates", as has been done, then the non-negligible uncertainty around the bedding attitudes needs to be propagated through the Jelinek (1981) or bootstrap confidence ellipses around the eigenvectors. These uncertainties will otherwise be severely under-determined.

8. Ego-driven science. Finally, it is my feeling that oftentimes paleomagnetists feel proprietary about the magnetizations measured. Let me explain.

Many rock-magnetic experiments, stability tests and error analyses performed appear to be aimed at demonstrating that data collected are primary, instead of investigating whether they are primary: e.g. presence of SD grains is taken to demonstrate that the remanence is stable regardless of whether it is specifically attributed to those grains; positive fold tests are often taken as proof of primary magnetizations instead of the mere indication that the remanence was likely acquired prior to the deformation event. Similar assertions can be made regarding other stability tests like the conglomerate or reversal tests, for example, even though their validities have been questioned (Henry, Merabet, et al. 2004, Henry et al. 2017, Heslop & Roberts 2018a, b).

Science is hypothesis-driven, and the attachment to a successful outcome of our research is understandable. We ultimately desire for our research to pan out, to answer the specific questions we had set out to investigate, to demonstrate that we are worthy of funding, and to fulfill our egos. This predicament is exacerbated by the availability of funding and the academic pressure in general (the competitive rat-race of Lorenz (1973)), and is particularly felt by today's young upcoming paleomagnetists. However, whether the magnetizations investigated are primary or secondary is out of our control, and over-rationalizing the data collected to force a fit to a preconceived model (or an *ad hoc* hypothesis) has the long-lasting effect of inconsistent data "contaminating" the records. The effects of these contaminations are actually more profound than one immediately imagines. Not only do they confound the paleomagnetic record, but they also considerably slow down the proper advancement of science, owing to the intrinsic human quality of finding comfort in the *status quo*. It is important to remind ourselves that as scientists we are not responsible for the magnetizations carried by rocks and for what story these magnetizations may be telling us. In fact, it is more important that the data are rigorously processed, tested, and interpreted correctly, and build towards a common scientific good. With that comes the paramount responsibility of peer-reviewers and particularly of journal editors as "gatekeepers" of science, to ensure that sins are kept to a minimum.

Over the past few years I have grown increasingly disconcerted by some new trends in paleomagnetism and I know my frustrations are shared by many. I sincerely hope this article may serve as stimulus for a fruitful discussion.

Up scientists to labs, *engagez-vous*!

Acknowledgements

Many thanks to Mike Jackson and Phil Schmidt for the ongoing discussions, valuable comments and suggestions.

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Sponsored by the Institute for Rock Magnetism, with anticipated funding by NSF

Iron minerals in the Earth's crust and sedimentary cover contain fossilized records of ancient geomagnetic field activity, and in their physical and chemical characteristics they hold evidence of geological processes and events that have affected them. This conference will explore the state of the art in magnetic studies of natural materials, examine methods for extracting paleomagnetic and paleoenvironmental information through magnetic analysis, and assess what such studies are telling us about the history and workings of our planet and its surroundings.

The Santa Fe Conference format is designed to be interactive and in-depth, allowing extended periods of open discussion following invited lead talks on selected topics. For this meeting, we are planning sessions focusing on: 1) the Highs and Lows of Short-term Geomagnetic Field Behavior; 2) Enviromagnetism and Biogeomagnetism; 3) Processing Procedures and Protocols: Pitfalls, Progress and Promise; and 4) Fundamental Rock Magnetism, Micromagnetic Modeling and Imaging. These will be complemented by two keynote sessions: 1) The influence of short-term (decadal to millennial) geomagnetic field variations on cosmogenic nuclide production; and 2) Advances in magnetic microscopy: mapping fields at the nanoscale, inverting for magnetization distribution, and integrating with other spatially-resolved characterization methods. Finally, we plan to have an optional full-day workshop on micromagnetic modeling on Sunday June 9, led by Wyn Williams (Edinburgh).

Contingent on NSF funding, on-campus accommodation costs (room and meals) will be covered by a conference-support grant, and there will be no registration fee for the conference. Participation is open to students, post-docs and faculty researchers, and will be limited to a maximum total of fifty participants. Session descriptions, schedule and more information will be posted as details are finalized at www.irm.umn.edu.

We are also planning an optional pre-conference field trip (Thursday June 6), to be led by Mike Petronis (New Mexico Highlands University) and John Geissman (UT-Dallas). There will be a registration fee of approximately $40 for the field trip, and for those who wish, Wednesday night accommodations at St John's (including 3 meals) will be available for approximately $90. There will also be a registration fee of about $50 for the micromagnetic workshop, and Sunday night accommodations at St. John's will be available for approximately $90.

We expect a limited number of student travel grants ($300-$500) to be available thanks to anticipated funding from NSF.

The Institute for Rock Magnetism is seeking a Facility Manager to begin in the Fall of 2019 or early 2020.

Position responsibilities include:

- administering the visiting researcher programs;
- managing the facility financial operations;
- working with visiting scientists and assisting with training in instrument usage, specimen preparation, experimental design, data analysis and interpretation;
- helping to maintain the hardware and software resources of the facility;
- participating with IRM faculty and staff in the planning, management and supervision of facility operations and in preparing extramural funding proposals;
- carrying out independent research.

More detailed information on the breakdown of essential functions of the position can be found on the job posting in the University's employment system.

Required qualifications: PhD in geology, geophysics or physics (exceptional candidates with MS degrees and significant experience will also be considered); expertise in fine-particle magnetism and magnetic characterization; collaborative aptitude.
Preferred qualifications: Managerial and organizational skills; proficiency with laboratory instruments, software, programming and data analysis.

To apply:

- go to http://humanresources.umn.edu/jobs
- search for Job Posting ID Number: 328647
- submit CV/Resume and a Cover Letter
- provide names and e-mail addresses of three references
- Recommended but not required: a Statement of Research Interests.

Please contact Bruce Moskowitz (bmosk@umn.edu), Josh Feinberg (feinberg@umn.edu), or Mike Jackson (irm@umn.edu) for questions.

The IRM welcomes new RAC members

Julie Bowles (University of Wisconsin-Milwaukee)
Sonia Tikoo (Rutgers University)
Karl Fabian (Geological Survey of Norway)

Replacing Laurie Brown (U Massachusetts), Richard Harrison (Cambridge University), and France Lagroix (IPGP, Paris).

We thank Laurie, Rich and France for their service and commitment to the mission of the IRM!

The IRM Quarterly

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 Sølheid** and **Dario Bilardello**, Staff Scientists.

Funding for the *IRM* is provided by the **National Science Foundation**, the **W. M. Keck Foundation**, and the **University of Minnesota**.

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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