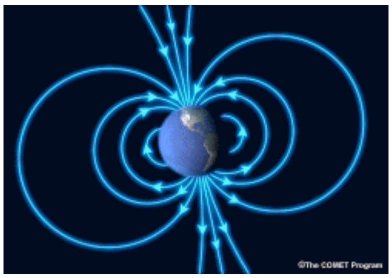
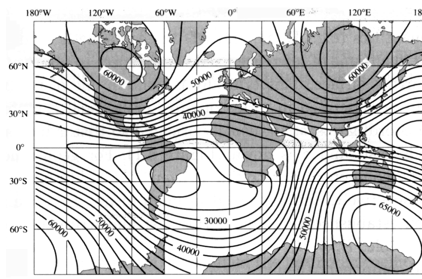
Workshop Volume





2011 MagIC Science & Database Workshop

Magnetics Information Consortium

Welcome to the 2011 MagIC Workshop in La Jolla

Thank you for making time to come to the **2011 MagIC Workshop**. We have made every effort to make this workshop successful by presenting a wide variety of scientific topics along with talks dealing specifically with the MagIC database and its online interface.

The **2011 MagIC Workshop** includes three keynotes, presentations on the MagIC database, software and the innovative online interface, a poster session, six short scientific talks, discussion of the new NSF Data Management Plans, and a hands-on data upload workshop. The keynotes and short talks will cover a range of topics within the paleomagnetic and rock magnetic sciences. Topics include magnetic stratigraphy, the early earth dynamo, cubic oxide exsolution, true polar wander, biogeomagnetism, Precambrian supercontinents, and the paleo-dipole. We also will discuss MagIC's goals, database functionality, its online interface, and a new community-driven review system. Because NSF grants now require a Data Management Plan, on Tuesday morning we therefore will discuss how MagIC initiative can be a part of the solution of this new NSF policy by providing guidance and assistance to the research community. Robin Reichlin from the NSF will be available to answer questions. On Wednesday, in a hands-on session, we will show you how to upload data to the MagIC database. You will have the opportunity to upload your own data in the afternoon. All poster presentations will be available for viewing and discussion on Monday afternoon and evening. Please feel free to view posters during lunch breaks and engage the poster presenters in discussions during breaks. They will be happy to talk to you about their work.

Thank you very much for your support !!!

Cathy Constable, Lisa Tauxe, and Anthony Koppers

The conveners of the **2011 MagIC Workshop**.

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Lunch Break 12:00 – 13:00		
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Welcome, What is MagIC? Science and Database Goals *Presenter* **Cathy Constable** **Update on MagIC's Archived Data, Search & Analysis Tools** *Presenters* **Anthony Koppers, Rupert Minnett** **Magnetic Stratigraphy Within Polarity Chrons** *Keynote* **Jim Channell** **Short Talk: First 2 GYR of Plate-Mantle-Dynamo Activity** *Presenter* **John Tarduno**	**Magnetic Properties under High Pressure: Insights to Planetary Magnetic Fields, Structure and Evolution** *Keynote* **Stuart Gilder** **Introduction Into Archiving in the MagIC Database** *Presenter* **Anthony Koppers** **Short Talk: Searching for the Dipole in Paleointensity Data** *Presenter* **Lisa Tauxe**	**Hands-on MagIC Data Upload Workshop, Part 2** **Uploading Your Data** *Presenters* **Nick Jarboe, Rupert Minnett, Anthony Koppers, Lisa Tauxe**
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15:30 – 16:30 Munk Lab	15:30 – 17:00 Munk Lab	15:30 – 17:00 Revelle Lab
Short Talk: Multi-Component Cubic Oxide Exsolution *Presenter* **Julie Bowles** **Short Talk: True Polar Wander and Life** *Presenter* **Joe Kirschvink**	**New Online Data Review System** *Presenters* **Rupert Minnett, Nick Jarboe, Anthony Koppers, Cathy Constable**	**Hands-on MagIC Data Upload Workshop, Part 3** **Wrap Up** *Presenters* **Anthony Koppers, Lisa Tauxe, Cathy Constable**
16:30 – 17:30 Munk Lab		
POSTER SESSION		
17:30 – 20:00 Munk Lab		
RECEPTION *continued poster session*		

MagIC Topics Presented During Workshop

1. MagIC Science and Database Goals (Monday Afternoon)

Lead: Constable
MagIC has created a fully searchable, on-line database open to the scientific community, migrating data from previous paleomagnetic databases and striving to update and include all relevant data with the help of the community. The MagIC database is intended to be used both as an archive of data and an active research tool. A brief outline will be provided of current and possible future scientific challenges addressable using the database.

2. Update on MagIC's Archived Data, Search and Analysis Tools (Monday Afternoon)

Lead: Koppers, Minnett
The MagIC database has a growing set of contributions that can be queried with a set of sophisticated search and analysis tools. This talk will explain what data have been archived so far, what will be archived in the future, and introduce the search and analysis interface.

3. NSF Data Management Plans and MagIC (Tuesday Morning)

Lead: NSF Program Managers, Constable
Increasing use of cyberinfrastructure in geosciences research presents parallel demands on researchers to provide detailed data management plans to NSF and other agencies in their grant proposals. Sharing of unpublished data may be also be necessary to facilitate collaboration in many projects. This session will discuss how MagIC could facilitate development of these data management plans and will include a long question and answer period.

4. Introduction Into Archiving in the MagIC Database (Tuesday Afternoon)

Lead: Koppers
The inclusion of all the possible measurements found in the geomagnetic, paleomagnetic and rock magnetic scientific disciplines requires a complicated data model. This talk will introduce the basics of the MagIC database model, the MagIC data policies, and how users should upload their published data sets into the MagIC database system.

5. New Online Data Review System (Tuesday Afternoon)

Lead: Minnett, Jarboe, Koppers, Constable
Each contribution to the MagIC database will be checked by a reviewer. This ensures that the data and metadata in MagIC conform to the database model and accurately reflect what has been published. An on-line review system has been created to help facilitate the reviewing

process. This session will show how the review system functions to help maintain the high quality of contributions to the MagIC database.

Special Hands-on MagIC Data Upload Workshop

6. Uploading Basic Data Sets (Wednesday Morning)

Lead: Jarboe, Minnett, Koppers, Tauxe
Many different types of data can be archived in the MagIC database. In this session we will take an example paper (Laj et al. 1997.) that has both paleomagnetic directions and intensities and compare it to its corresponding MagIC SmartBook that is used for the data uploading. We will then use the MagIC Console Software to work with and edit this SmartBook, prepare the data files for uploading, and finally upload this contribution in to the MagIC online database. Please bring your laptop and download the above files before the session.

7. Uploading Your Data (Wednesday Afternoon)

Lead: Jarboe, Minnett, Koppers, Tauxe
In this session we will help facilitate the uploading of your own data into the MagIC database. Bring your own data from past or current work and we will help you create your own Smart-Book and upload the data into the MagIC database. If time permits, we will also discuss the uploading of measurement data into the MagIC database.

Abstracts

Listing in alphabetical order

Multi-component cubic oxide exsolution in synthetic basalts: temperature dependence and implications for magnetic properties

Julie A. Bowles[1], Lisa Tatsumi-Petrochilos[2], Julia E. Hammer[2], and Stefanie A. Brachfeld[3]

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[2] Department of Geology and Geophysics, University of Hawaii
[3] Department of Earth & Environmental Studies, Montclair State University

Although the compositional unmixing of cubic-structured iron oxides has profound effects on the magnetic properties of rocks that contain them, a basic understanding of the kinetics and thermodynamics of this process has not been achieved in experimental studies due to sluggish reaction rates in binary oxide phases. Exploiting the fact that many natural Fe-oxides contain multiple additional cations, including Ti, Mg and Al, we perform novel "forward" laboratory experiments in which cubic-cubic phase exsolution proceeds from initially homogeneous multi-component oxides. A variety of Fe-Ti-Mg-Al cubic iron oxides were nucleated and grown in synthetic, multi-component basalt under different fO_2 environments, and annealed at temperatures ranging from 590 – 790°C for up to 88 days. Fine-scale lamellar intergrowths of Fe-Ti-Al-Mg oxides, interpreted to represent cubic phase exsolution, were observed in seven samples, one that was synthesized and annealed at approximately constant fO_2 (the quartz-fayalite-magnetite, or QFM, buffer) and six that were synthesized at very oxidizing conditions (~QFM + 6 log units) and then annealed at moderately oxidizing (~QFM) conditions. Results demonstrate that the consolute temperature of the multi-component system is significantly higher than anneal temperatures and Curie temperatures, suggesting that samples that undergo this type of exsolution can carry a total thermal remanent magnetization (TRM). Exsolved samples are characterized by a dramatic increase in magnetization and coercivity, and a shift in Curie temperature(s), confirming predictions that this type of exsolution exerts strong control on the strength and stability of magnetization.

Because Curie temperatures (T_c) of multi-component oxides are not linear combinations of end-member Curie temperatures, there is no simple numerical way to determine the T_c surface in a multi-component system. Database access to thermomagnetic data from well-characterized oxides of a variety of compositions would greatly enhance the feasibility of defining the relationship between the T_c and solvus surfaces. In turn, this would allow us to predict which exsolved oxide compositions should carry dominantly a TRM and which should carry dominantly a chemical remanent magnetization.

Improving Holocene global geomagnetic field reconstructions based on sedimentary data: implementation in GEOMAGIA50 database

Maxwell C. Brown[1,*], Monika Korte[1], Fabio Donadini[2], Ute Frank[1], Andreas Nilsson[3,4], Norbert Nowaczyk[1]

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Global geomagnetic field reconstructions for the Holocene can provide powerful information about the geodynamo process and can constrain geomagnetic shielding, important for our understanding of the interaction between the geomagnetic field and cosmogenic nuclide production. Coherent structure is evident in these reconstructions and this has significant implications for controls on the geodynamo. However, the resolution and reliability of current models require improvements and are limited by: 1) the restricted global coverage of sites, especially in the southern hemisphere; 2) the low precision of some magnetic data and independent dates; 3) an incomplete assessment of data quality. Improving these aspects for sedimentary records is particularly important as loosely constrained sedimentary data have a large influence on model output from spherical harmonic reconstructions of the Holocene geomagnetic field (e.g., CALS7k.2, CALS3k.3, CALS10k.1b and SED3k.1).

To improve global data coverage we have compiled a new library of Holocene sedimentary locations. The amount of data published for the Holocene greatly exceeds that included in the current CALS10k.1b model; however, a large number of data are poorly constrained in time and we expect a reduction in the size of the data set suitable for modeling after detailed assessment. Every record will be evaluated for its individual characteristics.

In previous model constructions all available sedimentary data were used, regardless of quality. This lead to unrobust field models when only sedimentary data were used: including data of questionable quality resulted in unreliable geomagnetic features. For certain locations there is a closer agreement between the output from models based on different subsets of data (e.g., SED3k.1 and ARCH3k.3) than between the models and the sedimentary data for that location. This indicates there is coherent structure between models based on non-overlapping data sources and hence within the sedimentary data, but also that there are significant differences between the models and some sedimentary data; a problem we are addressing through a more detailed assessment of records.

A further problem is the treatment of age data. As a result of the coeval evolution of radiocarbon and Holocene palaeomagnetic research a uniform approach to ^{14}C dating has not been applied across PSV studies. Revaluation of dates is therefore desirable. Applying a consistent approach to ^{14}C calibration and calculation of age-depth models could lead to more robust temporal constraints. This is possible where individual palaeomagnetic and ^{14}C core data are available. Multiple parameters, such as susceptibility, inclination, declination and rock magnetic properties can be correlated (using software designed at GFZ) and transferred onto a revised time-scale using a new age-depth model. We have initially used the Bayesian model, *Bacon*, of Blaauw and Christen (*in press*). We show application of this methodology to a UK lake and highlight differences with the previously modeled record and the model output for this location.

To improve the efficiency of data assessment we have designed a new database for global sedimentary data covering the last 10 ka (which in the future will be extended to 50 ka). This is implemented as part of the successful GEOMAGIA50 database, already constructed for palaeomagnetic data from archaeological and volcanic materials. Our aim is two-fold: 1) to transparently catalogue all available sedimentary data for the Holocene, so the broader scientific community can access a range of information related to specific cores (the current SECRV00 database lacks data from the most recent studies and a number

of older studies); 2) to design a database with the functionally to select palaeomagnetic data based upon parameters that reflect the fidelity of the data. To make accurate assessments of data quality it is necessary to determine palaeomagnetic, rock magnetic, mineralogical and chronological parameters that may influence the fidelity of the record. All available data will be catalogued based on these parameters. Measurements on the same specimen are tied to their age and/or depth, so it is possible to select data that satisfy specific quality criteria only. The new database allows retrieval of both core and stacked data, permitting assessment of individual sections of core data, consistency between core records and their relative influence on the stacked record. Our new assessment of published data is also included in the database structure. Compiling a broad range of queryable parameters for both core and stacked records will allow complete assessment of the fidelity of directional, relative palaeointensity and chronological data. High quality data can then be selected to optimize subsequent global modeling of the Holocene geomagnetic field and the influence of choosing specific data selection parameters on the output of these models can be assessed. Upload of particular parameters to the MagIC database is envisaged.

Magnetic stratigraphy within polarity chrons

J.E.T. Channell

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The marine sediment archive has become increasingly important for understanding the climate system because direct measurements of climatic parameters are woefully inadequate prior to ~100 yrs BP; and ice cores, although providing wonderful detail, are very restricted in distribution and duration. The European Project for Ice Coring in Antarctica (EPICA) has now obtained deuterium measurements (δD_{ice}), and a wealth of other climate data, back to ~800 ka (Fig. 1, Jouzel et al., 2007). Can marine "drift" sequences, with elevated mean sedimentation rates, provide climate/stratigraphic resolution to rival the EPICA ice core from globally distributed sites, and stretching further back in time? The study of rapid climate change, and the resolution of leads and lags in the system, requires global stratigraphic correlation at an appropriate resolution in marine sediments. In spite of the considerable progress made in the last 40 years, the quest for improved stratigraphic correlation remains one of the great challenges in paleoceanography. Benthic $\delta^{18}O$ is the hallmark of Quaternary marine stratigraphy, however, $\delta^{18}O$ changes in seawater are not globally synchronous on millennial timescales, and the rate of change of global ice volume (the basis for $\delta^{18}O$ stratigraphy) is gradual other than at Terminations, limiting the correlation potential of the records. There would be great advantage in coupling oxygen isotopes with an independent stratigraphic tool that is global in nature and devoid of environmental influences. The accumulation of sedimentary relative paleointensity (RPI) data in the last 15 years holds the promise of stratigraphic correlation within polarity chrons, possibly at millennial scale. Based on analysis of the recent geomagnetic field, it has been deduced that variations with time-constants exceeding one hundred years are largely governed by the main dipole (e.g. Valet et al., 2008), implying that millennial-scale RPI should be a global signal. Magnetic excursions are brief (millennial-scale) directional excursions that usually, when adequately recorded, are manifest as paired polarity reversals bracketing virtual geomagnetic poles (VGPs) that reach high latitudes in the opposite hemisphere, implying that excursions are attributable to the main dipole and therefore globally manifest. Excursions occupy minima in RPI records and RPI minima are more readily recorded than excursions because troughs in RPI records are longer lasting than directional excursions. There are ~6-8 magnetic excursions that are adequately recorded in the Brunhes Chron depending on the adequacy criteria (Fig. 1), and ~8 in the Matuyama Chron, and therefore, presumably, over 500 in the Cenozoic. The brief duration of excursions is such that they are rarely recorded except in sediments with accumulation rates exceeding 15 cm/kyr. New magnetic stratigraphies based on RPI and excursions are not only important for global stratigraphy at improved resolution, they are also important for testing numerical simulations of the geodynamo that can now mimic a wide range of geomagnetic field behavior depending on input parameters such as the geometry of core/mantle boundary heat flux.

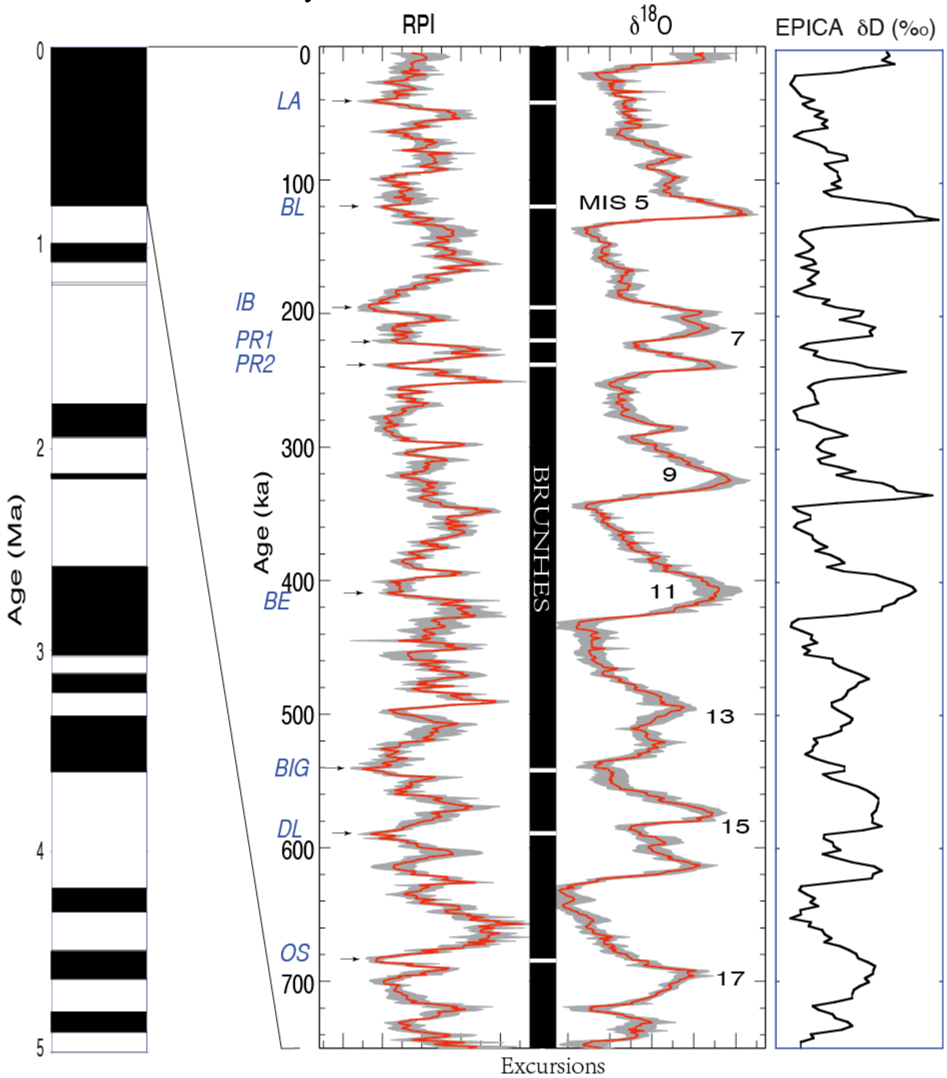

Figure 1: Left: Geomagnetic polarity record for the last 5 Myrs (black: normal polarity, white: reverse polarity). Right: Stack of relative paleointensity (RPI) and oxygen isotope data ($d^{18}O$) from deep-sea sediments with 2s error (Channell et al., 2009) for the last 750 kyr compared to the deuterium isotope data (dD) from the Dome C Antarctic ice-core (Jouzel et al., 2007). Arrows indicate documented magnetic excursions associated with RPI minima. Excursion Key: LA Laschamp, BL Blake, IB Iceland Basin, PR1 and PR2 Pringle Falls, BE Bermuda, BIG Big Lost, DL Delta, OS Osaka Bay. Marine isotope stages (MIS) are numbered.

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Neoarchean-Mesoproterozoic continental reconstructions

Evans, D.A.D.[1], Salminen, J.[1], Mitchell, R.N.[1], Kilian, T.M.[1], & Panzik, J.E.[1]

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Keywords: Neoarchean, Mesoproterozoic, supercontinents, paleomagnetism, tectonics, Nuna, Kenorland, Superia, Vaalbara, Sclavia

Both Archean-Paleoproterozoic and Paleoproterozoic-Mesoproterozoic transitions bore witness to fundamental changes across the entire Earth system (Reddy and Evans, 2009). A robust paleogeography is important for understanding processes of both the planetary interior and its surface environment. Several recent and ongoing studies have produced high-quality Precambrian paleomagnetic data, and a paleogeography is just beginning to take form for the interval of 2.7-1.5 Ga. Proposed hypothetical models of cratonic amalgamation at the end of the Archean include a complete supercontinent, named Kenorland, or alternatively several distinct supercratons in motion relative to one another, named Superia, Sclavia, and Vaalbara (Bleeker, 2003). Moreover, the Paleoproterozoic Era represented perhaps the first supercontinent cycle, beginning with the 1.9-1.8 Ga amalgamation of the supercontinent Nuna (a.k.a. Columbia, Hudsonland).

The Vaalbara craton, comprising Kaapvaal, Pilbara, and perhaps others, has a well constrained paleomagnetic apparent polar wander (APW) path for the intervals 2.8-2.7 Ga, and 2.2-1.8 Ga (De Kock et al., 2009). Here we report recently published and preliminary new paleomagnetic data constraining the configurations and motions of Superia, and Sclavia. Superia comprises the Superior craton plus its originally contiguous neighbors, which might have included Kola, Karelia, Wyoming, and Hearne, as indicated by the large igneous province (LIP) magmatic "barcode" record (Ernst and Bleeker, 2010). Superior craton itself has a well defined APW path from 2.2-1.8 Ga, plus high-quality data from the Matachewan dyke swarms at ca. 2.45 Ga (Buchan et al., 2007). In fact, the data are so well defined that eastern and western halves of the craton can be restored quantitatively to a precise original configuration prior to ca. 1.9 Ga deformation across the Kapuskasing zone (Evans and Halls, 2010); additionally, we are comparing directional variations among the Matachewan data to determine whether the Earth's geomagnetic field geometry was purely dipolar at 2.45 Ga. Paleomagnetic data from Kola and Karelia are more problematic. If one remanence component, rather rare in occurrence, from 2.45 Ga intrusions is preferred, then the barcode-inspired reconstruction is allowable (Bindeman et al., 2010). However, a much more common remanence component from the same intrusions would negate such a reconstruction (Salminen et al., 2010). We have also begun a systematic paleomagnetic sampling of mafic dykes (more than 100 sampled) across several basement-cored uplifts in the Wyoming craton, to test whether it was part of Superia. Our results will be integrated with U-Pb geochronology for robust APW path generation. Aside from Slave craton, it is not yet well known which other Archean blocks were originally included in Sclavia. The Paleoproterozoic APW path of Slave craton is beginning to take form (Buchan et al., 2009), including many new data from dyke swarms that we are currently studying, with ages broadly within ca. 2.2-1.9 Ga. A detailed evaluation of published Slave paleomagnetic data through 1.9-1.85 Ga

(Mitchell et al., 2010) indicates numerous rapid oscillations of motion, likely indicative of true polar wander during those times. Shortly thereafter, the Nuna supercontinent assembled into perhaps the first true supercontinent in Earth history.

Based on the temporal and compositional overlap between anorogenic magmatisms in west Baltica (East European craton) and in east Laurentia (North America and Greenland) and paleomagnetic data it has been proposed that those cratons were directly juxtaposed for more than 600 Ma (from ca. 1.8 to ca. 1.2 Ga), forming together with Siberia, and perhaps with some other continents, such as Amazonia and Australia, the core of the Nuna. However, a wide variety of configurations and lifecycles for Nuna have been presented. Earlier paleomagnetic data suggest a rather complex history between Baltica and Laurentia during the Mesoproterozoic (e.g. Buchan et al., 2000; Pesonen et al., 2003). Based on a tight cratonic fit, concordance with basement geology, and paleomagnetic pole matching we favor the long lasting configuration of Baltica and Laurentia named NENA (North Europe-North America) (e.g. Gower et al., 1990; Salminen and Pesonen, 2007; Evans and Pisarevsky, 2008; Evans and Mitchell, 2011). In order to further study this connection Mesoproterozoic (ca. 1580 Ma) 40 mafic dykes related to rapakivi magmatism have been sampled in Satakunta, west Finland, for paleomagnetic and U-Pb geochronology.
Except for Baltica and Laurentia, paleomagnetic data from several other continents for the Nuna time interval have been largely lacking. Recent high quality paleomagnetic data from Siberia allows reconstructions of Nuna core (Baltica-Laurentia-Siberia) on equatorial latitudes (Wingate et al., 2009; Evans and Mitchell, 2011). Furthermore we have sampled several Mesoproterozoic mafic formations in Bahia state, eastern Brazil, from the São Francisco craton in order to reconstruct São Francisco-Congo entity in Nuna. Preliminary data indicates intermediate latitudes for this entity, challenging its proposed Mesoproterozoic connection with the arctic Laurentian margin (Evans, 2009).
Quantitatively, the duration of Nuna can be tested by comparing the paleomagnetic APWPs of different continents, especially its core continents (Baltica, Laurentia, and Siberia). Baltica and Laurentia show convergent APWPs for ages younger than 1.8 Ga, and divergent APWPs for ages younger than 1265 Ma. However there is no precise estimate of the separation age; the oldest discrepant poles are ca. 1050 Ma (Salminen et al., 2009; Evans and Mitchell, 2011).

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Magnetic properties under high pressure: Insights to planetary magnetic fields, structure and evolution

Stuart A. Gilder

Ludwig Maximilians Universität, Munich, Germany

This presentation will give an overview on the effect of stress (pressure) on the magnetic properties of titanomagnetite, pyrrhotite and iron to better understand processes occurring in the crust, mantle and cores of the Earth and other planets. In general, pressure enhances the magnetic strength and magnetic coercivity of these materials, yet how magnetic species react to stress varies in relation to their domain state, oxidation level, and composition. The nature of the imposed stress (hydrostatic versus uniaxial) dictates the strain field and hence significantly influences the results. Moreover, polarization of the magnetic moment under load can bias the results from techniques such as alternating field susceptibility and Mössbauer spectroscopy . These subtleties will also be discussed.

Rock Magnetic Cyclo-stratigraphy: A New Chronostratigraphic Tool for Rock Magnetists

K.P. Kodama

Lehigh University

Rock magnetic cyclo-stratigraphy is a new technique that allows rock magnetic measurements to assign high-resolution time to a stratigraphic section of sedimentary rocks. In its simplest application anhysteretic remanent magnetization (ARM) measures magnetic mineral concentration variations in a magnetite-bearing sedimentary rock that record astronomically-driven global climate cycles (Milankovitch cycles). This allows time resolution at the precessional scale (~20 kyr), better than magnetostratigraphy even at times of high reversal rate (100 kyr resolution). Furthermore, many samples can be processed fairly rapidly because the samples do not need to be oriented. ARM or other remanence measurements (eg. Isothermal Remanent Magnetization-IRM) are preferred over magnetic susceptibility, since remanence measurements can be targeted at different sub-populations of ferromagnetic grains while susceptibility is a complicated signal that responds to diamagnetic, paramagnetic, and ferromagnetic mineral grain concentrations in a rock making the climate encoding difficult to interpret.

Three examples of rock magnetic cyclo-stratigraphy will be presented in the workshop poster: The first example is a rock magnetic cyclo-stratigraphic study of the Cretaceous Cupido Formation. ARM intensity variations (100 mT peak af field, 97 μT DC field) at two localities of the Cupido Formation platform carbonates in northeastern Mexico show that magnetite concentrations record short eccentricity (100 kyr), obliquity (40 kyr) and precession (20 kyr) orbitally forced global climate change (Latta et al., 2005). These cycles become particularly prominent when sequence stratigraphy boundaries are tied to the 405 kyr long eccentricity cycle. The magnetite is identified by additional rock magnetic measurements (IRM acquisition, Lowrie tests, low temperature IRM measurements). From its magnetic grain size and from SEM observations the magnetite is interpreted to be sourced from eolian dust (Figure 1).

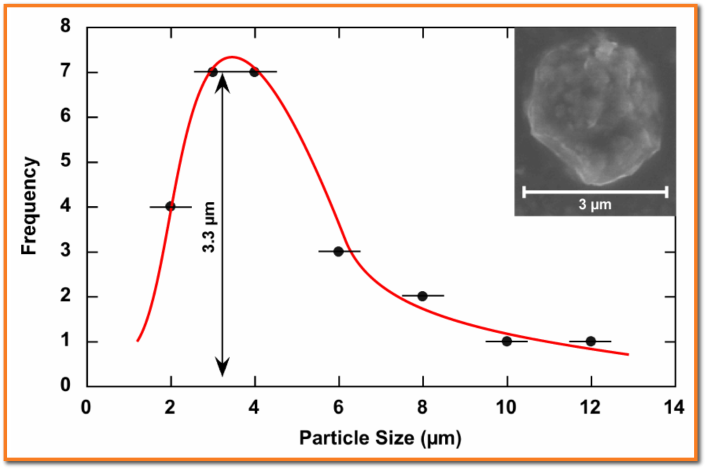

Figure 1: SEM and grain size of magnetite particles from the Cupido Formation.

The Eocene marine marls of the Arguis Formation from the Pyrenees in Spain is another example of the successful application of rock magnetic cyclo-stratigraphy (Kodama et al., 2010). In this study ARM variations record both short (100 kyr) and long (405 kyr) eccentricity as well as precession (20 kyr). The magnetic mineralogy of these rocks is depositional magnetite plus secondary iron sulfides, showing that a rock magnetic cyclo-stratigraphy is possible even if the depositional magnetic minerals have suffered from some reduction diagenesis. A standard magnetostratigraphy allowed a coarse assignment of absolute time. The identification of Milankovitch cycles in the rock magnetic cyclo-stratigraphy, and their refinement by tuning twice to short eccentricity, allowed higher time resolution at the precessional scale (20 kyr). Coherency analysis indicates that ARM maxima appear to be in phase with precessional insolation during the autumn indicating that ARM peaks during the fall rainy season. It appears then that the rock magnetics are encoding run off variations being driven by precession.

Finally, rock magnetic cyclo-stratigraphy has recently been pushed into the Precambrian by a study of the Neoproterozoic Johnnie Formation from Death Valley, CA. The Rainstorm Member of the Johnnie Formation is interpreted to record the oxidation of the early oceans by virtue of a negative ^{13}C isotopic anomaly in these shallow marine, carbonate-rich, silici-clastic red beds. Using a rock magnetic measure of the goethite:hematite ratio, a strong 5 m cycle is observed with a superimposed 0.75 m cycle. These cycles are interpreted to be short eccentricity and precession in the latest Precambrian (Kodama and Hillhouse, 2011). This interpretation is supported by a standard magnetostratigraphy that shows 4 polarity zones in the 45 m thick section we sampled. Average reversal rates of the geomagnetic field at about 1 Ga are estimated to average ~ 1.7/myr, but can be as short as 5-10/myr (Pavlov and Gallet, 2010). The duration of the ^{13}C isotopic anomaly is only 2-3 million years based on our rock magnetic cyclo-stratigraphy results, much shorter than the 50 million year duration estimated by thermal subsidence modeling of the same isotopic anomaly's duration in Oman (Figure 2).

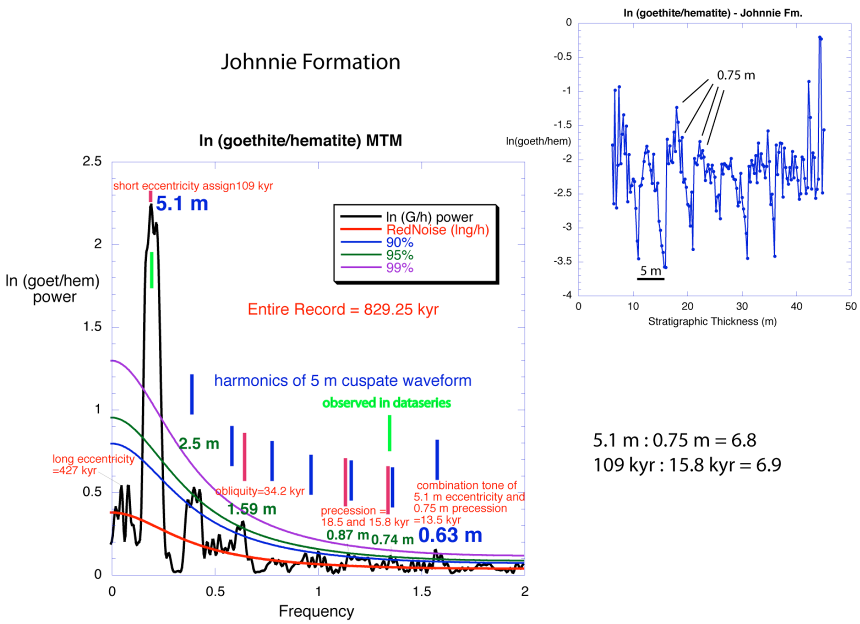

Figure 2: Magnetically-measured goethite/hematite ratio as a function of stratigraphic thickness and the corresponding power spectrum for the Neoproterozoic Johnnie Fm.

Rock magnetic cyclostratigraphy is a new tool for paleomagnetists and rock magnetists who want to contribute to chronostratigraphic studies important in all geologic research.

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Reconstructing the Global Geomagnetic Field from Archeo- and Paleomagnetic Data

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The past evolution of the global geomagnetic field is of interest in order to gain a better understanding of the geodynamo process in the Earth's core and to estimate the geomagnetic shielding against galactic cosmic rays. The amount of published archeomagnetic results and high resolution lake or marine paleomagnetic records over recent decades has become sufficient to attempt global modeling of magnetic field evolution on millennial time-scales (Ohno and Hamano, 1993, Hongre et al., 1998, Constable et al., 2000). Over recent years, a series of continuous models has been developed, attempting to give the highest possible spatial and temporal resolution for studying the geomagnetic field evolution at the core-mantle boundary and Earth's surface (Korte and Constable, 2003, Korte and Constable, 2005, Korte et al., 2009). The models are named *CALSxk*, **C**ontinuous models based on **A**rcheomagnetic and **L**ake **S**ediment data of the past **x** **k**yrs. The most recent model versions, *CALS3k.4* (Korte and Constable, 2011) and *CALS10k.1b* (Korte et al., subm. to EPSL), are an update of a previous 3kyr model and a lower resolution model covering the time interval 8000 BC to 1990 AD, respectively. The models can e.g. be used to estimate magnetic field strength and direction anywhere on Earth within their validity time span, to study geodynamo processes expressed by the field evolution at the core-mantle boundary, or to consider magnetic shielding for the production of cosmogenic nuclides.

The *CALSxk* models have improved substantially over time, due to improvements to the modelling technique, but mainly due to expansions of the global data compilation. Good repositories of available data are the most important prerequisite for global field reconstruction. Apart from the overall amount of data, the quality of the data is essential for the accuracy of the resulting global model. Metadata, providing information e.g. about laboratory techniques, material properties, and dating methods can help to obtain realistic uncertainty estimates for individual data. The MagIC Paleomagnetic database could become an ideal source of datasets for global modeling.

The present global compilation of archeomagnetic data goes back to the IAGA archeomagnetic directional database ARCHEO00 assembled by D. Tarling (http://www.ngdc.noaa/gov/geomag/paleo.shtml). Global intensity data have been compiled by Genevey et al. (2008) and Donadini et al. (2006). The latter database, GEOMAGIA (http://geomagia.ucsd.edu/), has since been improved to include all previously compiled and newly published archeomagnetic and lava directional and intensity data that became known to us (Donadini et al., 2009). All of this information has meanwhile been included in the MagIC Paleomagnetic database. The global distribution of data included in the GEOMAGIA database up to August 2009 and used for the most recent global models is shown in Fig. 1. It is obvious that most data come from low to mid latitudes in the northern hemisphere with the highest concentration in Europe. Data from high latitudes but also the southern hemisphere continents are clearly lacking for a good global coverage. The majority of these data come from the most recent 3 kyrs. Additional data, particularly from the southern hemisphere, are desirable to improve global models.

The present global compilation of sediment records started with records taken from the IAGA database SECVR00 (http://www.ngdc.noaa/gov/geomag/paleo.shtml), and we have consecutively added additional data that became known and available to us (Korte et al., 2005, Donadini et al., 2009, Korte and Constable, 2011). The global distribution of all records used in the construction of the latest global models is shown in Fig. 2. These data are not yet included in any proper database, but there is work in progress to achieve this aim. The temporal distribution of sedimentary data is better, but the southern hemisphere coverage is only slightly better than for archeomagnetic and lava data.

Archeo- and paleomagnetists are constantly producing new data and the growing understanding of magnetisation acquisition and suitable laboratory procedures leads to higher quality data. The value of these new data can be multiplied for purposes like e.g. global field modeling if they are not only published, but put into a proper database which allows to easily retrieve global datasets, and to obtain important metadata information.

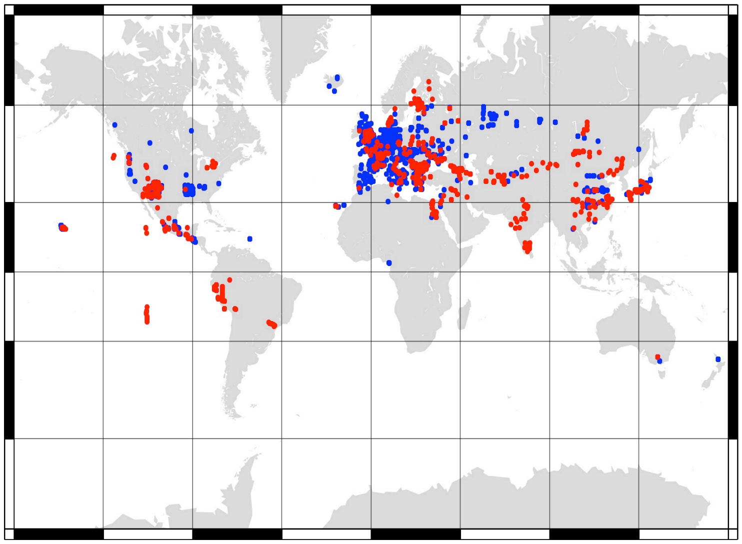

Figure 1: Global distribution of archeomagnetic directional (blue) and intensity data (red) included in the GEOMAGIA database by August 2009 and used for recent global models.

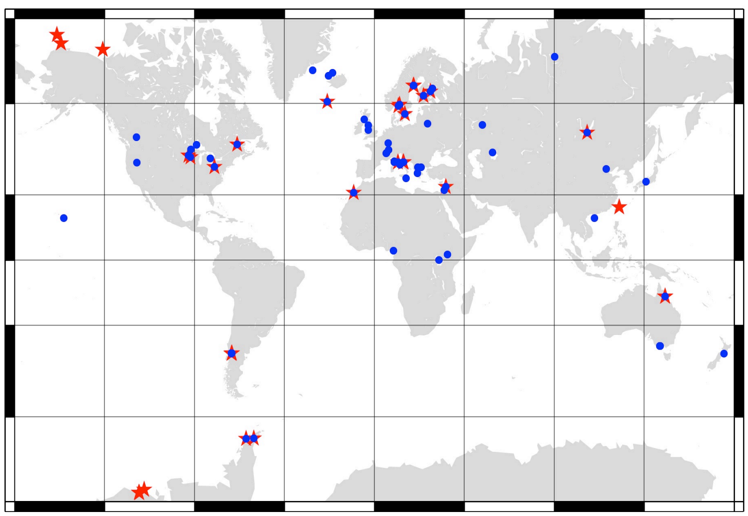

Figure 2: Sedimentary directional (blue) and relative intensity (red) records as compiled for the CALS10k.1b model.

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Toward a millennial-scale context for the South Atlantic Anomaly: Archeomagnetic studies of Iron Age southern Africa

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The current decay of the dipole geomagnetic field is well constrained for the last ~160 years due to global magnetic observatories and recent satellite observations. The decay appears to be related to the South Atlantic Anomaly and growth of a region of reversed-polarity flux at the core-mantle boundary below southern Africa [*Hulot*, 2002]. Our knowledge of field behavior before the widespread commissioning of observatories in the 1840's is based on an ever-growing database of paleomagnetic and archeomagnetic measurements. Current databases covering the last few millennia contain tens of thousands of results [*Donadini et al.*, 2009], but a continuing limitation is the paucity of Southern Hemisphere data. In particular, we are aware of no prior archeomagnetic data from southern Africa meeting modern laboratory standards.
The last 1800 years in southern Africa is known as the Iron Age. During this time, several migrations brought new Bantu-speaking peoples south from areas in the Nigeria-Cameroon-Congo region [*Huffman,* 2007]. Between 1000 and 1300 AD climatic conditions in southern Africa supported an agricultural society in the Limpopo Valley in southern Africa. This region, known today as the Mapungubwe landscape (Figure 1), borders present day South Africa, Botswana, and Zimbabwe.

Figure 1. The citadel of Mapungubwe (place of the jackals) located at the confluence of the Shashe and Limpopo rivers (northernmost South Africa).

In Iron Age southern Africa, farmers would often burn structures, specifically huts and grain bins, as a ritual of cleansing during prolonged periods of drought (*Huffman,* 2010). The remains of these structures (Figure 2) have been preserved at a number of sites and are the focus of our recent work [*Neukirch et al.,* 2011a].

Figue 2. (left) A modern Shona grain bin from Zimbabwe. (right) An Iron Age burnt grain bin floor prior to sampling.

Thellier-Coe [*Thellier and Thellier*, 1959; *Coe,* 1967] analyses of five burnt grain bins dating to 1200-1250 AD yield average paleointensity estimates (Figure 3) 15-30% below predictions from the ARCH3k and CALS3k models *Korte et al.,* [2009]. Site-mean directions also differ from model predictions by 10-20° (Figure 4).

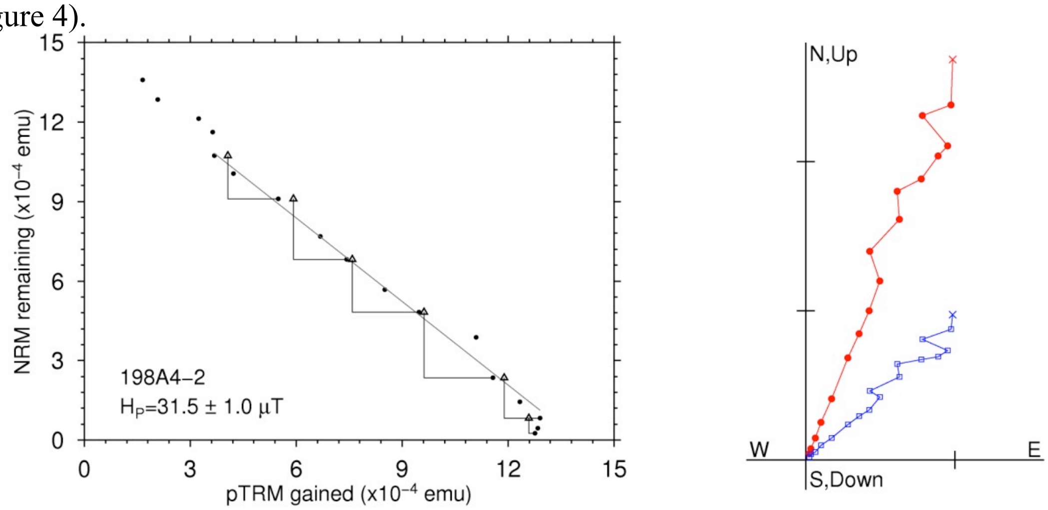

Figure 3. (left) An Arai plot [*Nagata et al.,* 1978] showing natural remanent magnetization (NRM) remaining versus partial thermal remanent magnetization (pTRM) gained during a Thellier-Coe experiment for a floor sample, and (right) an orthogonal vector plot showing the decay of the field-off steps (declination is red, inclination is blue). Figure adapted from *Neukirch et al*. [2011a].

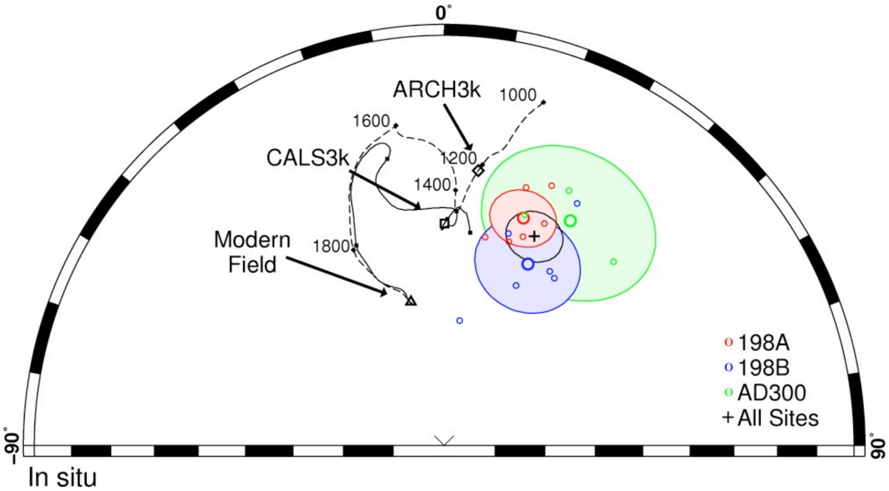

Figure 4. A comparison of site mean directions (colored circles) from 3 sites dated to 1200-1250 AD with model predictions following *Korte et al.,* [2009] (ARCH3k as black diamond and CALS3k as black square) Figure adapted from *Neukirch et al*. [2011a].

Currently we have sampled burnt hut and grain bin floors with ages ranging from 500 AD to 1600 AD, and have identified more to sample in subsequent field trips. These data will serve as tie points for our ongoing archeomagnetic studies of ceramics [*Neukirch et al.,* 2011b], vitrified kraals, and slag.

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Data analysis and visualization from a relational database

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The Institute for Rock Magnetism has maintained a comprehensive relational laboratory database since May of 2004. Currently nearly all data collected from instruments are uploaded, either directly via the instrument control software or manually via smart ferrets. This level of data aggregation has benefits that range from data management and retention to leading to new possibilities for data analysis, visualization and data mining. The inherent accessibility and portability of databases simplifies the task of preparing datasets from complex experiments for publication and upload to the MagIC database.

Once data is stored in a relational database it can be retrieved with little effort. Tools to evaluate data and explore relationships between current and historical experiments can be written in various programming and scripting languages. Visualization of data from different studies and sources becomes simplified. Software to evaluate complex multi-parameter datasets - such as magnetic susceptibility as a function of frequency, amplitude and temperature - and to compare to datasets from various instruments or projects becomes simplified.

In addition, having access to data collected over 7 years from the same instruments allows us to understand and visualize instrument characteristics and watch for possible long term drift or changes in the behavior of instruments such as gradual increase in instrument noise. The ability to do this for instruments across different laboratories could be useful in evaluating the state of instruments and help improve techniques.

How Accurate are Deep-Sea Sediments as Paleomagnetic Recorders?

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Deep-sea sediments, particularly those from the North Atlantic, have been instrumental in the development of modern paleomagnetic concepts. However, the accuracy of these sediments as geomagnetic recorders has never been explicitly tested. A critical missing component has been a lack of high-quality observational constraints to focus theoretical and empirical studies. Here we present u-channel paleomagnetic records from five high-resolution (~15-65 cm/kyr) deep-sea sediment cores taken from across the North Atlantic. Cores KN-158-04-2GC (43°29′N, 54°52′W, 3942 m) and KN-158-04-22GC (44°18′N, 46°15′W, 3959 m) were collected in the western North Atlantic from the New Foundland Margin and the New Foundland Basin, respectively. Cores KN-158-04-46GC (52°58′N, 19°49′W, 2758 m), KN-158-04-53GC (55°27′N, 14°42′W, 2184 m) and KN-158-04-57GC (58°39′N, 25°25′W, 2768 m) were taken from the eastern North Atlantic from the Rockall Trough, Feni Drift and Iceland Basin, respectively. Progressive alternating field demagnetization indicates that all cores preserve a strong, stable, low coercivity magnetization consistent with pseudo-single domain magnetite as the most probable remanence carrier. Well-resolved component directions as indicated by low MAD values (often <1), define a characteristic remanent magnetization (ChRM) with inclinations consistent with those expected for the sites latitudes. Declinations show variations consistent with paleomagnetic secular variation (PSV) records from the area. Normalized remanence records are consistent using different normalizers (e.g. ARM, IRM, *k*), and in general pass criteria (there is some variability between records) for reliable relative paleointensity (RPI) estimates. Each core is constrained by a high density of radiocarbon dates, providing strong independent chronologies. Recent radiocarbon dating [*Praetorius et al.,* 2008] allows the PSV and RPI records from Site 984 [*Channell,* 1999] to also be compared. These high quality Holocene deep-sea sediment paleomagnetic records are compared with paleo-geomagnetic estimates for the region derived from a series of ultra-high resolution, high quality and well dated PSV, RPI [*St-Onge et al.*, 2003; *Stoner et al.*, 2007] and archeomagnetic paleointensity [*Genevey et al.,* 2008] records. Comparisons indicate that the age of PSV features in all deep-sea sediment records are older than their equivalents in ultra-high resolution records. This age offset when multiplied by the sedimentation rate, is interpreted to reflect the depth of magnetic acquisition (lock-in depth). Holocene lock-in depths of 15 to <30 cm are observed at the site locations described above. These comparisons also show that PSV amplitude as measured by the variance about the mean of declination appears to be linearly related to sedimentation rate, suggesting that significant information is being lost even from high sedimentation rates. A post-depositional remanent magnetization (pDRM) model is being developed to explore these observations. The model convolves ultra high-resolution records with different filter shapes based on variable surface-mixed layer (M) and lock-in depths (L) to find values that best match each of the output records.

On the need for coincident paleodirectional and paleointensity data to evaluate the first 2 billion years of plate, mantle and dynamo activity

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Science Issues: Magnetic field strength, water and life on the early Earth

The evolution of Earth during the Hadean and Archean, and its relationship to the development of life, remains a frontier research area where the most advanced field and analytical techniques must be harnessed to glean details from the ancient geologic record. During this time, the early geomagnetic field shielded Earth from intense solar winds from the rapidly rotating young Sun. Therefore, the onset and strength of the earliest field are of prime interest for understanding evolution of the planet. Additional key questions related to early Earth history that can be addressed by paleomagnetic studies include the beginning of inner core growth and its effect (if any) on the geomagnetic field (Smirnov et al., 2011), and the start of plate tectonics and rates of early plate and mantle motions (the later defined by possible episodes of polar wander).

However, there are considerable obstacles preventing the easy retrieval of primary paleomagnetic information from the most ancient rocks. Even the best-preserved Paleoarchean rocks have seen low-grade metamorphism. The thermal and chemical effects render many, if not most, whole rocks unsuitable for analysis.

Our approach to these challenges is to focus on the study of single silicate crystals hosting minute magnetic inclusions (Tarduno, 2009). Recent investigations of Archean single silicate crystals from the Kaapvaal craton, using highly sensitive SQUID magnetometers and CO_2 laser demagnetization, have allowed definition of geomagnetic field intensities at 3.2 Ga (Tarduno et al., 2007), 3.4 Ga and 3.45 Ga (Tarduno et al., 2010).

In our current work, we extend this time line to 3.47 Ga through the study of single silicate crystals from granitic rocks that are subvolcanic feeders to the Duffer Formation of the Pilbara craton. Preliminary paleointensity data suggest that a protective magnetic field was present. Some of the first physical evidence for life has been reported in similarly aged rocks. However, the new measured field intensities are only ~25% of the modern value. These magnetic paleofield results suggest that the magnetopause was much closer to Earth during Paleoarchean times. The decreased standoff of the solar wind, together with the higher frequency of coronal mass ejections, would have promoted loss of volatiles and water from the atmosphere (Tarduno et al., 2010).

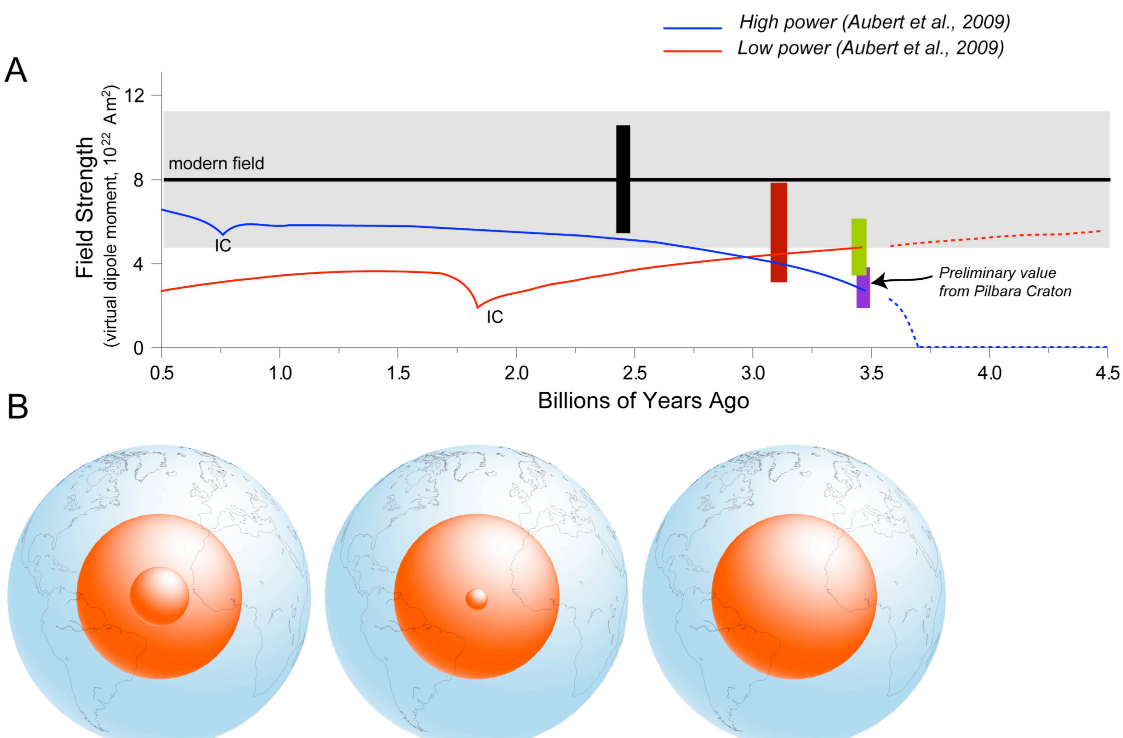

Figure 1. A. Field strength based on paleointensity analyses of single silicate crystals (Tarduno, 2009). Horizontal solid line and shaded area are modern field value and typical 0-5 Ma variation, respectively. Vertical lines are single silicate crystal paleointensity data (black, Smirnov et al., 2003; colored Tarduno et al., 2007; 2010). Preliminary value from Pilbara craton shown in purple. High and low power model results predict present-day core-mantle boundary heat flow rates of 11 TW and 3 TW, respectively (Aubert et al., 2010). IC marks time of inner core nucleation in each model. B. Inner core growth scenario following the model of Smirnov et al. (2011).

When the paleointensity values available from single silicate crystal analyses are compared with prediction from modeling (e.g. Aubert et al., 2010) an interesting picture emerges (Figure 1). *Sensu stricto*, the

2.5-3.45 Ga data might be compatible with either the low or high power models (which evoke present-day core-mantle boundary heat losses of 3 and 11 TW, respectively). However, the preliminary 3.47 Ga data appear to track the high power model better, and it should be noted that the low power model seriously underestimates paleointensity for the youngest time intervals. A model with greater power is also favored by recent geoneutrino measurements of the component of heat release contributed by decay of radiogenic isotopes (The KamLAND Collaboration, 2011).

Interestingly, the high power model of Aubert et al., (2010) suggests the absence of a magnetic field for times earlier than about 3.6 Ga. Thus, either there is some flaw in the modeling, or the atmospheric effects inferred in Tarduno et al. (2010) are very conservative and the Paleoarchean-Hadean Earth was a true deep ocean world.

The preliminary paleointensity estimate for 3.47 Ga we introduce above is based on the range of potential site paleolatitudes; in our opinion the paleolatitude of the Paleoarchean Pilbara is currently unconstrained. Nevertheless, paleolatitude values have been reported in prior works, and these values continue to be treated by some as primary remanences. This leads us to a discussion of databases below.

Database Issues: Evaluating ancient magnetizations

In a classic paper, McElhinny and Senanayake (1980) reported a positive fold test from extrusive volcanic Paleoarchean rocks of the Duffer Formation in the Pilbara. As discussed in Usui et al. (2009), however, the magnetic mineralogy of these rocks is inconsistent with a primary magnetization. In addition, folding was protracted, and possibly not complete until after 2.9 Ga.

We have recently conducted partial TRM experiments on some extrusive whole rock samples of the Duffer Formation. We imparted a partial TRM by heating samples at 350 degrees C (approximately equivalent to peak metamorphic heating) for 12 hours. To remove the magnetization imparted in the laboratory required heating to temperatures in excess of 580 degrees C. This behavior agrees with single domain theory and experimental results bearing on multidomain behavior: in whole rocks bearing such grains, we can expect low grade heating to contaminate the remanence to temperatures well exceeding the peak metamorphic temperature. In a more general sense, the application of pTRM experiments, analogous to those used in paleointensity investigations, could serve as a useful screening mechanism for those seeking paleodirections from Archean rocks. Coincident directional data with pTRM experiments would thus be preferred in the database; they might also serve useful for resolving controversial data for Proterozoic and younger time intervals. Our experiments further question the meaning of prior paleolatitude data reported for the Pilbara craton. A related question for discussion centers on how to handle field tests in databases that might be false positives.

Acknowledgments: This work was supported by NSF grants EAR1015269 and EAR1045651. We thank Levi Neukirch and Richard Bono for assistance during field studies.

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Arai Signature Ratio Correction Technique for Prevalent Multi-Domain Bias of Paleointensity

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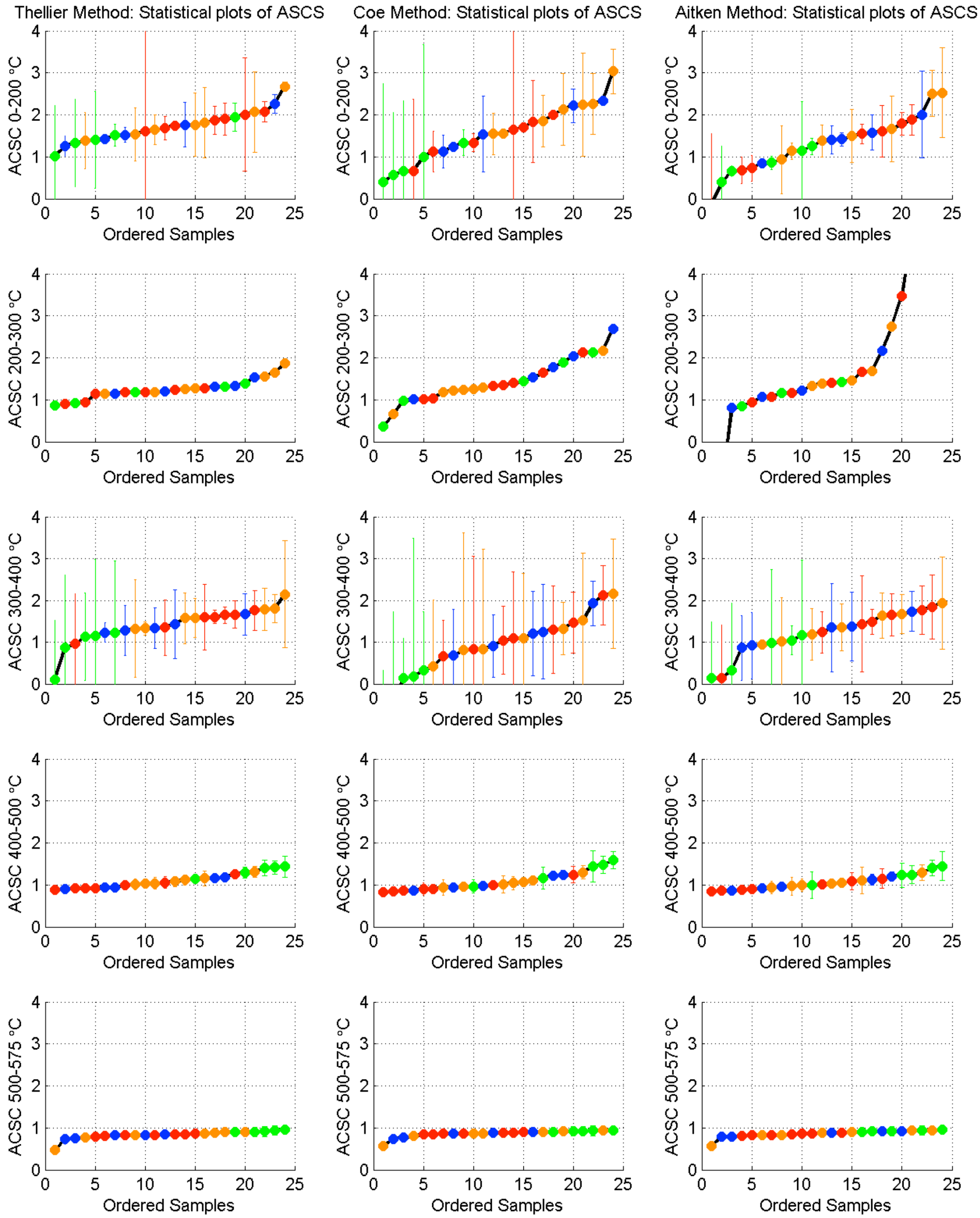
Although more than 10,000 site level estimations of absolute paleointensity from over 450 references have been included in the latest MagIC database [*Tauxe et al.*, 2011], most of the results fail to consider the concave-up shaped Arai diagram from multi-domain (MD) effects [*Levi*, 1977; *Xu and Dunlop*, 2004]. This usually overestimates the paleointensity due to the tendency of using lower temperature steps in the Thellier series experiments in order to avoid thermochemical alteration, which introduces a systematic bias to higher paleointensities in the database. We develop a technique for correcting this bias to determine unbiased paleointensities for a set of 24 basalt samples from sites GA78, 79, 84 and 85 from Floreana in the Galapagos Islands [*Kent et al.*, 2010; *Rochette et al.*, 1997] that have mutually consistent directions deviating ~40° from the reverse polarity time-averaged field. Rock magnetic experiments (loop, FORC and Js-T) show the main magnetization carriers are fine-grain low-titanium MD magnetite particles with grain size variations ($0.1 < Mr/Ms < 0.3$). Repeating of the loops and FORCs after thermal treatments to 600°C indicate the samples suffer very little from alteration. We used a comprehensive back-zero-forward (BZF) heating technique by adding an additional zero-field heating step in between the original Thellier two opposite in-field heating steps. This triple heating BZF experiment allows us to calculate natural remanence (NRM) loss and thermal remanence (TRM) gain in different ways, in order to estimate paleointensities with various protocols to provide internal self-consistency checks. Lab-applied field of 15 μT and 14 temperature steps up to 575°C were used. Partial TRM (pTRM) checks were inserted by adding forward-field heating steps to previous lower temperatures after the zero-field heating steps. After the first BZF experiment, we gave the samples total TRMs by cooling from 575°C in the same lab field. We then repeated the BZF described above, with the lab-applied total TRMs as synthetic NRMs, using the same lab field and target temperatures. Any systematic departures from linearity in the resulting synthetic Arai diagrams should therefore only represent the MD magnetization recording signatures of samples. From the first BZF, we estimate the uncorrected paleointensities by using the original NRM loss and pTRM gain ratios from a fixed temperature segment of 400°C to 500°C chosen to avoid viscous remanences (VRM) from lower temperatures and alterations from higher ones. From the repeated BZF, we calculate the synthetic NRM loss and pTRM gain ratios from the same temperature segment as the Arai signature ratio (ASR), which is the recording bias from the MD effects for each sample. The corrected paleointensity for each sample is then determined by dividing its original paleointensity by its ASR, which is expected to vary with MD content and temperature range. In these samples, values of ASR from room temperature to 400°C range from 1 to 2, from 400°C to 500°C between 0.9 to 1.5, and from 500°C to 575°C converge to between 0.8 to 1 (Fig. 1). Supported by internal self-consistence provided by the BZF, a high success rate (14/24), and good within-site agreements, the ASR correction technique provides what we believe is an accurate paleointensity for the collective site of 3.7±0.6 μT, a low value that is consistent with the excursional direction (D= 212.8°; I= -26.5°). Although many of the paleointensity results in the database are probably biased to higher values due to the concave-up Arai diagram, it is impractical for us to back-correct these results by using the ASR correction technique, due to the lack of comprehensive specimen level information and the unavailability of previous samples. The pilot paleointensity study on all sampled Galapagos lavas (>50 sites) [*Kent et al.*, 2010] has already suggested the previous average equatorial paleointensities of the geomagnetic field have been overestimated by a factor of 2 (see also [*Selkin and Tauxe*, 2000]). We will apply the BZF protocol and the Arai signature ratio correction technique from all of available Galapagos samples to determine what will hopefully be a more representative measure of the time-averaged equatorial paleointensity for the Plio-Pleistocene.

Figure 1:
Arai Signature Correction Slope (or ASCS, equivalent to ASR for that specific temperature segment) results calculated by using the Thellier (left column), Coe (middle column) and Aitken (right column) methods from temperature segments: 0 °C – 200 °C (1st row), 200 °C – 300 °C (2nd row), 300 °C – 400 °C (3rd row), 400 °C – 500 °C (4th row) and 500 °C – 575 °C (5th row). Color-codes for samples from site GA78 (blue), GA79 (orange), GA84 (green) and GA85 (red) are plotted with error bars.


Thellier Method: Statistical plots of ASCS
Coe Method: Statistical plots of ASCS
Aitken Method: Statistical plots of ASCS
ACSC 0-200 °C
ACSC 200-300 °C
ACSC 300-400 °C
ACSC 400-500 °C
ACSC 500-575 °C
Ordered Samples

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