Brunhes Geomagnetic and Rock Magnetic Variations Recorded in Eight Holes Cored at ODP Site 1062 on the Bahama Outer Ridge

Gary D. Acton Ocean Drilling Program, Texas A&M University, 1000 Discovery Drive, College Station, TX 77845; ph. 979-845-2520; email: acton@odpemail.tamu.edu); Bradford M. Clement (NSF, 4201 Wilson Blvd. Arlington, VA 22230; email: bclement@nsf.gov); Steven P. Lund (Dept of Earth Sciences, University of Southern California, University Park, Los Angeles, CA 90089; email: slund@usc.edu); Makoto Okada (Dept. of Environmental Sci., Ibaraki University, Bunkyo 2-1-1, Mito, 310-8512, Japan; email: okada@mito.ipc.ibaraki.ac.jp); Trevor Williams, Borehole Research Group, Lamont-Doherty Earth Observatory, Palisades, NY 10964; trevor@ldeo.columbia.edu

During Ocean Drilling Program (ODP) Leg 172, we cored eight holes at Site 1062 on the Bahama Outer Ridge (4770 m water depth), providing redundant recovery of Pleistocene and Holocene sediments. The holes transect a mudwave, where sedimentation rates have been rapid, averaging over 10 cm/k.y. and ranging from 3 to 33 cm/k.y. Altogether, 1 km of core was recovered from the eight holes, of which 590 m are piston cores through Brunhes-age sediments. The larger than average number of holes provides an unprecedented opportunity to examine repeatability of the paleomagnetic record at a site, to estimate statistical properties of the signal, and investigate biases related to coring, sampling, and measurement methods. Fine-scale adjustment to the meters composite depth (mcd) gives an indication of between-hole, decimeter-scale sedimentation rate variations across the mudwave and/or core expansion and related drilling deformation. Millennial scale changes in direction and intensity correlate well between holes for nearly all of the past 800,000 yrs, indicating a robust record of secular variation has been obtained. The mean record provides a good standard for regional and possibly global correlation. Site 1062 also contains records of more than ten excursions that can be correlated between two or more holes. We will discuss the lithostratigraphic position, age, directional change/VGP paths, and rock magnetic characteristics of several of these excursions along with multiple records of the Brunhes/Matuyama transition.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3a. Gary D. Acton; Ocean Drilling Program, Texas A&M University, 1000 Discovery Drive, College Station, TX 7784 3b. 979-845-2520 3c. 979-845-2520 3d. acton@odpemail.tamu.edu 4. No

Paleomagnetic Intensity Data as a Time Series: Opening a Window Into Dynamics of Earth's Fluid Core?

Ross E Baker Graduate Program in Physics and Astronomy, York University, Toronto, Canada, M3J 1P3; ph. 416-736-5245; fax 416-736-5817; email: rossb@yorku.ca); K D Aldridge (Department of Earth and Atmospheric Science, York University, Toronto, Canada, M3J 1P3; ph. 416-736-2100 ext. 77705; fax 416-736-5817; email: keith@yorku.ca)

We consider paleomagnetic intensity data obtained from sedimentary cores as a time series related to fluctuations of the fluid velocity in Earth's core. Although this is a gross oversimplification of the relationship between these two vector fields, some aspects of their possible interaction might be obtained through inversion of paleomagnetic intensity data. In particular, the onset and development of turbulence as seen in laboratory experiments on fluid instabilities may be contained in a paleointensity time series. Just as in these laboratory experiments, changes in flow regimes of Earth's fluid core and the effects of irregularities on the development of bifurcations should be traceable in relative paleomagnetic intensity data. For example, growth of the inner core would alter the geometry determining instability properties that are detectable in the observed growth and decay of paleointensity. Limiting this interpretation are factors such as errors in timing and in measured relative paleointensity.

Non-linear inversion of records from the ODP983 dataset of paleomagnetic intensities will be presented. Growth and decay with time of paleomagnetic amplitudes are modelled as exponential and two harmonics. This simple model accounts for most of the paleomagnetic amplitude signal, thus providing a first step in modelling the dynamical processes producing the magnetic field.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) R E Baker Graduate Program in Physics and Astronomy York University Toronto, Canada M3J 1P3 (b) 417-736-5245 (c) 416-736-5817 (d) rossb@yorku.ca 4. Yes

Paleomagnetic survey of Late Permian series in Morocco: implications for Pangea reconstruction and GAD Hypothesis.

J. Besse Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05, France, ., O. Oufi, , Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05, France

The configuration of Pangea is one of the strongest debates on recent times large scale reconstructions. Various conflicting configurations have been proposed, and discussed using a large amount of suggestion including misleading ages, remagnetizations, unsufficient demagnetization process, error in magnetization recording for sediments, odd Earth magnetic field during certain periods, etc... Recent paleovertebrates d ata indicates that the basal part of the Argana formation (Morocco) is Tatarian (Upper Permian), this serie being thus one of the most well dated clastic serie of Africa. A new paleomagnetic surve y allowed us to sample 15 sites (90 samples). The sites directions are well grouped after tilt correction and the mean direction is deduced, using Fisher's statistic, as Ds = 313.4 , Is = 8.5 , K = 50.9, A95 = 5.6. A fold test is positive at 95%, and so is the inversion test. These results suggest that the HT component is effectively a primary direction. The presence of mixed polarities, suggests that T1 and T2 formations post date the Kiaman period , the end of which is estimated at approximately 265Ma.A comparison of these data with 38 available worldwide paleomagnetic data suggests a A Pangea configuration.(roughly the Atlantic pre- opening configuration). We discuss the occurrence of lithospheric deformation inducing important rotations at various scale, particularly in future rifts or mountain zones (Colorado, South of France, South American cordilleras, east of Australia etc) or even the quality of fits. Using these rotations, most of worldwide poles can be reconciled using a rough GAD hypothesis during the 250-275 Ma period. Occurrence of Octupole components or flattening are also discussed for the Permo-Triassic period.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. [* J. Besse*] Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05. 4. No

Long term variations in geomagnetic intensity: Links to mantle and crustal processes

A J Biggin Centro de Geociencias, UNAM Campus Juriquilla, Queretaro, QRO 76020, Mexico; ph. +55 442 238 1104 ext. 124; fax. +55 442 238 1100; email: andy@geociencias.unam.mx); D N Thomas (School of Earth Science and Geography, Kingston University, Penrhyn Road, Kingston-upon-Thames, Surrey, KT1 2EE, UK; ph.+44 20 8547 2000 ext. 2403; fax. +44 20 8547 7497; email: n.thomas@kingston.ac.uk

From the results of a rigorous statistical analysis, time correlations are evident between significant transitions in the dipole moment record for the period 10 - 400 Ma and first-order plate tectonic events. A qualitative first-order theory relating large-scale crustal behavior to changes in mean geomagnetic poloidal field intensity will be presented. This theory assumes that the passage of subducted material into the lower mantle produces an instantaneous increase in the mean heat flux across the core-mantle boundary through a process known as induced convection. The potential of this simple model for explaining the observed synchroneities between mean geomagnetic intensity and large-scale plate tectonic behaviour will be demonstrated.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3a. A J Biggin (Centro de Geociencias, UNAM Campus Juriquilla, Queretaro, QRO 76020, Mexico; (b) +55 442 238 1104 ext. 124 (c) fax. +55 442 238 1100 (d) andy@geociencias.unam.mx); 4. No

Paleosecular variation in Mexico during Tertiary and Quaternary

H Böhnel Centro de Geociencias, UNAM-Campus Juriquilla, Queretaro 79230, Mexico; ph. 52-442-2381106, ext. 109; fax 52-442-23801105; e-mail: hboehnel@geociencias.unam.mx); R S Molina Garza (Centro de Geociencias, UNAM-Campus Juriquilla, Queretaro 79230, Mexico; ph. 52-442-2381106, ext. 126; fax 52-442-23801105; e-mail: rmolina@geociencias.unam.mx

Volcanism as a consequence of prolonged subduction of oceanic plates in the Pacific Basin is ubiquitous in Central Mexico. More than 100 paleomagnetic site-mean directions are available for the last 10 Ma. These data were pre-selected according to geological-tectonic reliability criteria and most also comply with modern quality standards as number of samples, demagnetization treatment, within-site dispersion. We analyzed the VGP dispersion using different time-windows, to obtain the angular standard deviation (ASD) and revised its time variability. The ASD values vary largely when different cut-off limits or outlier criteria are used to eliminate sites with intermediate VGP positions. Therefore, the analysis method is critical in establishing comparable ASD values, which may then be used as observational data for paleosecular variation models.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) H Böhnel Centro de Geociencias UNAM Campus Juriquilla Queretaro, 76230 (b) 52-442-2381106 ext. 109 (c) 52-442-2381105 (d) hboehnel@geociencias.unam.mx 4. No

Solar-Terrestrial Interaction During a Varying Dipole Moment

S E Boralv Swedish Institute of Space Physics, Box 537, 751 21 Uppsala, Sweden; ph. +46184715930; fax +46184715905; email eb@irfu.se); H J Opgenoorth (Swedish Institute of Space Physics, Box 537, 751 21 Uppsala, Sweden; ph. +46184715912; fax +46184715905; email opg@irfu.se); S C Buchert (Swedish Institute of Space Physics, Box 537, 751 21 Uppsala, Sweden; ph. +46184715928; fax +46184715905; email scb@irfu.se

The magnetic dipole field of the Earth has decreased by roughly a factor of two during the last 2000 years. We will discuss the effects in the magnetosphere due to a decreasing dipole moment, in terms of magnetospheric size and the current systems therein. Expected signatures in solar terrestrial interaction should include a shrinking of the magnetosphere as the protective magnetopause moves closer to Earth. A more effective coupling between the Solar wind and Earth's magnetic field should furthermore result in a strengthening of the current systems in the magnetosphere. The resulting widening of the auroral oval will move the region affected by auroral activity further equatorward, i.e. above more densly populated regions. The Earth's protection against the solar wind will be strongly influenced (decreased) as the dipole moment varies.

Recent observations also indicate that the magnetic flux of the sun in increasing, which is another important factor regarding the interaction betwen the solar wind and the Earth's magnetosphere. We will point out the implications of the combined effect of the Sun's and the Earth's time-varying magnetic fields for near-Earth space plasma physics. An inproved understanding of space weather phenomena, in particular in a variable environment is important for future technology both in space and on ground. As the solar-terrestrial interaction enhances, space weather events will more effectively interfere with technology in near-Earth space as well on ground, as ground-induced currents are produced during magnetospheric storms and substorms above more populated regions.

1. Chapman conference on Timescales of the Geomagnetic Field 2. Contributed 3a. S E Boralv, Swedish Institute of Space Physics, Box 537, 751 21 Uppsala, Sweden 3b. +46184715930 3c. +46184715905 3d. eb@irfu.se 4. student

Carnian - Norian biomagnetostratigraphy at Silická Brezová (Slovakia): correlation to other Tethyan sections and to the Newark Basin

J.E.T. Channell [*J.E.T. Channell*] (Department of Geological Sciences, University of Florida, Gainesville, FL 32611; ph. 352-392-3658; fax 352-392-9294; e-mail: jetc@ufl.edu); H.W. Kozur (Rézsü u. 83, H-1029. Budapest, Hungary); T. Sievers (Dept. Geological Sciences, University of Florida, Gainesville, FL 32611-2120); R. Mock, R. Aubrecht, M. Sykora (Dept. Geology and Paleontology, Comenius University, 84215 Bratislava, Slovakia)

Correlations of Upper Triassic magnetic stratigraphies from Tethyan sections have been hampered by difficulties with conodont biostratigraphy and taxonomy, and discontinuous sedimentation, particularly in the "Hallstatt Limestones" of Turkey and Austria. The magnetic stratigraphy and conodont biostratigraphy from the upper Carnian to upper Norian limestones exposed at Silická Brezová (Slovakia) can be correlated to other Tethyan sections and to the continental succession in the Newark Basin. The resulting correlations help to resolve some of the apparent discrepancies in existing conodont zonations, and result in a revised correlation to North American terrestrial vertebrate and palynologicial zones. The correlations imply that the Norian-Rhaetian boundary lies within Newark polarity zone E17r at ~207 Ma. The Carnian-Norian boundary lies close to the base of Newark polarity zone E7r at ~226 Ma. This implies durations for the Norian and Rhaetian stages of 19 Myr and 7 Myr, respectively.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3a. J.E.T. Channell, Dept. Geological Sciences, POB 112120, University of Florida, Gainesville, FL 32611 3b. 352 392-3658 3c. 352-392-9294 3d. jetc@ufl.edu 4. No -- Jim Channell Dept. Geological Sciences University of Florida 241 Williamson Hall PO Box 112120 Gainesville, FL 32611, USA

Comparison of U-channel and Discrete Sample Data Recording Polarity Reversals and Excursions: Examples From the North Atlantic

J.E.T. Channell Department of Geological Sciences, University of Florida, Gainesville, FL 32611; ph. 352-392-3658; fax 352-392-9294; e-mail: jetc@ufl.edu

Back-to-back 1-cm cubic discrete samples have been collected alongside u-channel samples spanning polarity reversals and excursions at ODP Leg 162 sites from the Iceland Basin (Sites 980/981, 983, 984) and from ODP Site 919 off east Greenland. The Iceland Basin Basin Event at ~190 ka is recorded at Sites 980, 983 and 984. The Laschamp Event at ~40 ka, and an event postdating the Laschamp, possibly correlative to the Mono Lake Event, are manifest at Site 919. Comparison between u-channel and 1-cm discrete sample data, and deconvolved u-channel data, indicate both types of samples have disadvantages related to measurement smoothing (for u-channels) and deformation and handling (for 1-cm discrete samples). Virtual geomagnetic poles (VGPs) derived from 1-cm discrete samples collected across the Matuyama-Brunhes and Jaramillo polarity reversals at Sites 983/984 are arranged in clusters over the Americas and NE Asia. The clusters are similar to those observed from u-channel data (Channell and Lehman, 1997), indicating that the VGP clusters are not an artifact of the u-channel measurement procedure.

1. Chapman Conference on Timescales of the Geomagnetic Field
2. Contributed 3a. J.E.T. Channell, Dept. Geological Sciences, POB 112120, University of Florida, Gainesville, FL 32611 3b. 352 392-3658 3c. 352-392-9294 3d. jetc@ufl.edu 4. No

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1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3a. J.E.T. Channell, Dept. Geological Sciences, POB 112120, University of Florida, Gainesville, FL 32611 3b. 352 392-3658 3c. 352-392-9294 3d. jetc@ufl.edu 4. No

How long does it take for Earth's magnetic field to reverse polarity?

Bradford M. Clement Divsion of Ocean Sciences, National Science Foundation, 4201 Wilson Blvd., Arlington, VA, 22207, bclement@nsf.gov, and
Dept. of Earth Sciences, Florida International University, Miami, FL, 33199).

The past several years have witnessed a proliferation of numercial models of the geodynamo that exhibit "earth-like" magnetic field behavior, most notably secular variation and polarity reversals. Each of these models, however, use parameters that are far from earth-like. Paleomagnetic records provide constraints on these models and may provide guidance in how to produce a more realistic geodynamo model. By far the most important constraint on geodynamo models was the discovery of polarity reversals.

Opdyke's pioneering work in deep-sea sediment records also provided some of the earliest estimates of the duration of polarity transitions. Theses estimates effectively ruled out the possibility that free decay and subsequent growth of the field could account for reversals. Instead, an active process is required for polarity reversal.

The durations of reversals and the rates at which the field changes, remains one of the most important contributions that paleomagnetism can provide to dynamo theory. In this paper I present an initial summary of the durations of polarity transitions from sediments that have been published to date. Each transition zone is defined as the stratigraphic interval that is bounded by the level at which the paleomagnetic directions exceed the circular standard deviation of the lower polarity chronozone and the level at which the directions fall within the circular standard deviation of the upper polarity chronozone. Estimates of the durations are then calculated using the best estimate of sedimentation rates for each section. Comparison of the durations with 1) reversal, 2)the site distribution, 3) sedimentation rates, and 4) full polarity secular variation in each record, provide insights into the remanence acquisition processes as well as providing an average estimate of polarity transition duration.

1. Chapman Conference on Timescales of the Geomagnetic Field
2. Contributed
3. (a) B M Clement, Division of Ocean Sciences, National Science Foundation,
4201 Wilson Blvd., Arlington, VA, 22230 (b) 703-292-8581, (c) 703-292-9085,
(d) bclement@nsf.gov
4. no

Short-Term Changes in the Geomagnetic Field: High-Resolution Records and the Relation to Geodynamo Simulations

R S Coe (Department of Earth Sciences, University of California, Santa Cruz, CA 95064; ph. 831-459-2393; fax 831-459-3074; email: rcoe@es.ucsc.edu); J M G Glen (U S Geological Survey, 345 Middlefield Rd, Menlo Park, CA 94025; email: jglen@usgs.gov)

Rapid changes of the geomagnetic field challenge the resolution of the best natural recorders. Volcanic records are literally shot full of holes with gaps of unknown length between each cooling unit. Sedimentary recordings are smoothed to an unknown degree by poorly understood remanence lock-in and diagenetic magnetization processes. Moreover, hiatuses may be common, especially in environments of rapid deposition, and they are usually difficult to identify. Thus paleomagnetic records are always incomplete and give only lower bounds on how fast and complex the field changes actually were. Geodynamo simulations provide a complementary approach to this problem, but limitations in computer power have prevented them from operating near the parameter regime appropriate for the core, with concomitant loss of spatial and temporal resolution. Nonetheless, they can provide insight into what kinds of field behavior may occur.

To make progress in the face of such difficulties we need to bear these shortcomings in mind while pushing forward on all fronts. In this paper we explore the possibility that at least some reversals and excursions are much more complex than typically portrayed, with episodes of oscillatory and very rapid field change.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) R S Coe, Department of Earth Sciences, University of California, Santa Cruz, CA 95064 (b) 831-459-2393 (c) 831-459-3074 (d) rcoe@es.ucsc.edu 4. No

The Spectrum of Geomagnetic Temporal Variations

Catherine G. Constable (Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0225; ph: (858) 534-3183; fax: (858) 534-8090; email; cconstable@ucsd.edu); Catherine L. Johnson (Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0225; ph: (858) 822-4077; fax: (858) 534-5332; email; cljohnson@ucsd.edu)

In the course of Neil Opdyke's career new uses for paleomagnetic data have evolved that make increasingly stringent demands on data quality and on temporal resolution in age constraints. Determinations of polarity and paleoinclination were sufficient for traditional magnetostratigraphic studies and for evaluation of the geocentric axial dipole (GAD) hypothesis. Today, paleomagnetic data are used to analyze geomagnetic field variations on time scales ranging from hundreds to billions of years. For example, researchers strive to make inter-hemispheric comparisons of marine sediment records with sub-millennial scale accuracy. Details of field behavior, such as deviations from GAD, run the risk of being interpreted in terms of specific temporal and spatial variations in core-mantle boundary conditions. Expectations are evolving that we may detect departures from GAD of the average magnetic field direction that are as small as 1 or 2 degrees. Yet there remains much that is poorly documented about geomagnetic field variations, including the nature of the geomagnetic spectrum. Still unanswered is the basic question of how long one needs to average the geomagnetic field in order to uncover a "stable time-averaged field", always assuming that such a thing exists. Knowledge of the spectrum could help resolve this issue.

We construct a power spectrum of geomagnetic paleointensity variations that spans the period range from 10 to 10 million years. The spectrum has the most power at long periods, reflecting the overwhelming influence of geomagnetic reversals, and in general the power decreases with increasing frequency (decreasing period). Empirical estimates of the spectrum are derived from the magnetostratigraphic time scale, from marine and lake sediment relative intensity records, and from historical observations. Existing spectral estimates do not indicate any distinctive behavior that allows separation of excursional and transitional field behavior from what might be called normal secular variation. However, there does appear to be a characteristic spectral signature associated with the recurrence time of cryptochrons during the Oligocene. A number of researchers have suggested the occasional presence of quasi-periodic field variations corresponding to changes in Earth's orbital parameters and

1. MEETING: Chapman Conference on Timescales of the Geomagnetic Field 2. CONTRIBUTED 3a. Catherine G. Constable, Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0225 3b. ph: (858) 534 3183 3c. fax: (858) 534-8090 3d. email; cconstable@ucsd.edu) 4. NOT a student**************

by extension associated with long term climate modulation.

In the absence of reliable measurements of very long (greater than a few million years) period paleointensity variations, we use the magnetostratigraphic timescale and a simplistic statistical model which supposes that field intensity is constant except during finite intervals when the field is reversing. During a reversal, the intensity is diminished, but also constant. Under this model the time required to acquire a reliable average for the field intensity, and the average value itself, depend on the reversal rate and the typical reversal duration. For a fixed reversal rate the spectrum is essentially constant at low frequency. The spectrum falls off as approximately the inverse square of the frequency above a critical value determined by the characteristic reversal transition length. The actual geomagnetic spectrum differs from this predicted spectrum because of changes in reversal rate, fluctuations in paleointensity, and lack of uniformity in the time taken for individual reversals. We assess the limitations of the model and show how it can be extended to include more realistic field behavior based on empirical spectra derived from paleomagnetic records. The resulting spectrum is used to examine how long is needed to obtain a reliable estimate of paleosecular variation (PSV) and the time-averaged field (TAF).

Spectral estimates for intensity variations can pave the way to extend existing statistical models for PSV to include temporal covariance. Most recent statistical PSV models assume temporally independent or uncorrelated samples of the field except in the axial dipole. To include a general temporal covariance in our current PSV model, known as CJ98, we need to determine whether and how the characteristic time scales for variations change with the spatial scale and/or non-zonal nature of the field. For example, there are indications in historical field models that small scale and/or non-zonal parts of the field may change more rapidly than others. In CJ98 the axial dipole has a special status, and because of this CJ98 predicts that at any single location temporal changes in the X and Z components of the geomagnetic field should be coherent for axial dipole field variations, with no coherence between X and Y or between Y and Z. By analyzing a relative intensity record with associated directional information it could be possible to identify the time scales characterizing variations in the axial dipole part of the field. This coherence between X and Z combined with a lack thereof among other components appears to exist at long periods for the record we have examined so far.

Such analyses indicate the importance of jointly estimating directional and intensity variations for the geomagnetic field. Unlike the usual estimates of coherence from separate cores, the single-core estimates described above are not afflicted by the relative uncertainties in dating. Standard techniques for identifying dipole variations from relative paleointensity records involve stacking records from multiple locations after using tie point and associated age estimates to put the records on a common time scale. The sampling process combined with correlating ages between cores with even slight variations in sedimentation rates can easily lead to incoherence at periods that are of considerable interest in the geomagnetic spectrum. We seek methods that will avoid such complications, or at least enable the evaluation of the resolution attainable with the available age information.

Apparent and True Polar Wander and the Geometry of the Geomagnetic Field in the Last 200 Million Years

VINCENT COURTILLOT JEAN BESSE AND [*VINCENT COURTILLOT*] (Laboratoire de Paléomagnétisme, Institut de Physique du Globe de Paris).

We have constructed new synthetic Apparent Polar Wander Paths (APWPs) for the African, Antarctic, Australian, European, Greenland, Indian, and North and South American plates over the last 200 Ma. We have used a selection of 19 paleomagnetic data from DSDP sites, 2 poles computed from skewness of marine magnetic anomaly profiles in the Indian Ocean and 221 cratonic paleomagnetic poles. A total number of 242 independent data has been retained, with a good distribution of site longitudes (ranging from 120 W to 155 E). Updated kinematic models allowed us to relate the paleomagnetic data of all plates over the entire period of interest and to construct a master synthetic APWP, using the data of all plates transferred onto a single one and averaging them within 10 and 20 Ma sliding windows. Moderately far-sided poles are consistent with a persistent quadrupole moment (on the order of 3% of the dipole over the last 200 Ma), but its amplitude can be neglected for most applications and in that sense the geocentric axial dipole (GAD) hypothesis is confirmed on the time scales of interest to our study. The successions of tracks, standstills, loops, and directional changes for all APWPs are discussed. The overall shape of the Eurasian and North American APWPs between 150 and 50 Ma confirms the existence of a loop, though somewhat smaller and more complex than previously recognized. The timing of the so-called Cretaceous standstill appears to

be slightly later than previously thought: 60-120 Ma rather than 70-130 Ma, and a cusp occurs near 140 Ma. Paleomagnetic and (Indo-Atlantic) hotspot APW are then compared, and a new determination of "true polar wander" (TPW) is derived, with both 10 and 20 Ma time window averaging. Under the (debatable but reasonable) hypothesis of fixed Atlantic and Indian hotspots, we confirm earlier findings that true polar wander appears to be episodic in nature, with periods of (quasi-) standstill (Jurassic, Late Cretaceous/Tertiary) alternating with periods of faster TPW (in the Cretaceous and most convincingly in the last 10, or even 3 Ma). The typical duration of these periods is on the order of a few tens of millions of years (50 Ma) with wander rates during fast tracks on the order of 30 to 50 km/Ma. A total TPW of some 30 is suggested for the last 200 Ma, but data and hypotheses prior to 130Ma are less robust than since then. We find no convincing evidence for episodes of superfast TPW such as proposed recently by a number of authors. We use our master synthetic APWP to predict the latitude evolution of test points in North America, South Africa and India, and compare those with estimates derived in the hotspot and TPW reference frames. We show that these three "latitude estimates"are mutually consistent. Comparison over the last 130 Ma of TPW deduced from hotspot tracks and paleomagnetic data in the Indo-Atlantic hemisphere with an independent (and methodologically distinct) determination for the Pacific plate supports the idea that, to first order TPW is a truly global feature of Earth dynamics. Comparison with numerical modelling estimates of TPW shows that all current models still fail to some extent to account for the observed values of TPW velocity, and for the succession of standstills and tracks which is observed.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. INVITED 3 (a) Vincent Courtillot Institut de Physique du Globe Place Jussieu 75005 Paris France (b) phone 33 1 44 27 24 34 or 39 08 (c) fax 33 1 44 27 74 63 (d) mail: courtil@ipgp.jussieu.fr 4. No ---- Jim Channell Dept. Geological Sciences University of Florida 241 Williamson Hall PO Box 112120 Gainesville, FL 32611, USA

Intensity of the Geomagnetic Field During Precambrian Time

D J Dunlop [*D J Dunlop*] (Department of Physics, University of Toronto, Toronto, ON L5L 1C6, Canada; ph. 905-828-3968; fax 905-828-5425; e-mail: dunlop@physics.utoronto.ca); Y J Yu (same address)

There are only 16 published Thellier-type paleointensity estimates for Precambrian rocks. Because of the episodic nature of orogenesis, these cluster in a few time intervals: 4 between 1240 and 850 Ma, 3 between 2170 and 1850 Ma, 8 between 2750 and 2450 Ma, and a single earlier Archean result (3500 Ma). Most of the late Archean-early Proterozoic results are from dikes but primary TRM was not demonstrated by baked contact tests, nor were successful paleointensity results obtained from the contact rocks. Two results are from very large intrusions with multiple phases and a long intrusion and cooling history. Late Precambrian results from the very slowly uplifted Grenville Province have an even longer cooling history but the partial TRMs can be dated fairly accurately by Ar/Ar geochronology. The geographic distribution is extremely biased, with almost all results from North America, Greenland and Baltica, and only one study each from Africa and Australia. The African result (Komati, S. Africa) is believed to be from primary TRM but the Australian result (Hamersley, W. Australia) is recognized to be a remagnetization. Numbers of acceptable results are often small and standard deviations large. Despite these limitations, the VADMs for all but three studies lie within a range 0.5-1.5 times the average Phanerozoic field, excluding the last 0.3 Ma, and only two results are conspicuously high (>10 E23

Am2). There is no obvious record of onset and growth of a dynamo field in the Archean or early Proterozoic.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited (by J. E. T. Channell) 3. (a) Dr. D. J. Dunlop, Department of Physics, University of Toronto at Mississauga, 3359 Mississauga Road North, Mississauga, ON L5L 1C6, Canada (b) 905-828-3968 (c) 905-828-5425 (d) dunlop@physics.utoronto.ca 4. No

Can a Persistently Non-uniformitarian Neoproterozoic-Cambrian Geomagnetic Field Explain Rapid and Oscillatory APW Motions?

David A D Evans Dept of Geology & Geophysics, Yale University, New Haven CT 06520-8109; ph. 203-432-3127; fax 203-432-3134; email: dai.evans@yale.edu); T D Raub (Dept of Geology & Geophysics, Yale University, New Haven CT 06520-8109; ph. 203-432-3114; fax 203-432-3134; email: timothy.raub@yale.edu

Unusually rapid apparent polar wander (APW) motions, oscillating about great circles, appear to characterize continental motions in late Neoproterozoic to Cambrian time. One explanation invokes a series of true polar wander (TPW) events about a minimum inertial axis of mantle upwelling that was inherited from the breakup of the early Neoproterozoic supercontinent Rodinia (Evans, 1998 and in press). Here we investigate alternative explanations, exploring geomagnetic field configurations necessary to account for all available data without appealing to unprecedented rates of TPW. Abandoning the geocentric axial dipole (GAD) hypothesis can quickly lead to untestable complexities, therefore we consider only the simplest classes of models as null hypotheses for robust paleomagnetic and paleoclimatic tests. The paleomagnetic dataset demands, in particular, that Laurentian inclinations swing rapidly between vertical and horizontal several times between 615 and 500 Ma. Inclinations from Australia, Siberia, and South China are always near-horizontal but declinations appear to swing wildly during the same interval of time. A reasonable paleogeography arises if all APW paths are forced to be

coincident, as in the TPW model.

A conceptually simple perturbation from the GAD model which explains these data involves a field that was geocentric and dipolar, but not persistently aligned with the Earth*s spin axis. To account for the paleomagnetic data, the symmetry axis of such a geomagnetic dipole field would need to oscillate (or somersault) about arc lengths of a great circle. The great circle could have any orientation in rotational space, but a preferred pair of longitudes would be most analogous to TPW kinematics and would also bear resemblance to some aspects of Neogene polarity transitions. In contrast to the TPW model, a tumbling geocentric dipole would produce no sealevel variations and would predict more static paleoclimatic regimes for each craton. Assumption of polar rotational latitudes for glacial deposits, a commonly employed test of the GAD hypothesis in Phanerozoic times, is compromised in the late Neoproterozoic by possible Snowball Earth events, which are supported by several independent lines of geological evidence.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) D A D Evans, Dept of Geology & Geophysics, Yale University, PO Box 208109, New Haven CT 06520-8109 (b) 203-432-3127 (c) 203-432-3134 (d) dai.evans@yale.edu 4. No

A second possible perturbation from the GAD hypothesis introduces a field that was geocentric and spin-axial, but substantially (or even primarily) non-dipolar. If multiple nodes of zonal harmonics yielded several rotational latitude bands with vertical inclination, then a single, slow, latitudinal drift of Laurentia during the opening of the Iapetus Ocean would experience rapid and large-magnitude oscillations of magnetic inclination, as observed. This model is challenged by the highly variable record of declinations from other cratons; any geocentric-axial field produces declinations of 0 or 180 degrees uniformly over the globe, depending on polarity. A corollary is necessary to explain the variable declinations. One possibility is that, in the absence of a dominantly dipole component, the residual non-dipole field could have been very weak relative to typical Cenozoic intensities. Intriguingly, the Laurentian paleomagnetic record of variable inclination arises primarily from igneous rocks, while the Australian, Siberian, and South Chinese records of variable declination come mostly from studies of sedimentary rocks. We appeal to the precedent of Neogene polarity transitions and postulate that persistently weak geomagnetic intensities could have imparted a low-inclination bias to DRM/pDRM processes in these rocks; and further, we wonder whether any local consistencies in declination could be due to other sources of particle alignment such as sedimentary paleocurrents. This geocentric, spin-axial but non-dipolar hypothesis for the Neoproterozoic-Cambrian geomagnetic field can be tested by paleointensity measurements of igneous rocks and by comparison between observed paleomagnetic declinations and inferred paleocurrent directions in sedimentary rocks.

Preliminary Magnetostratigraphic Results From ODP Leg 198- Shatsky Rise

H F Evans (Department of Geological Sciences, University of Florida, Gainesville, FL 32611; ph. 352-392-3298; e-mail: geohelen@ufl.edu); J E T Channell (Department of Geological Sciences, University of Florida, Gainesville, FL 32605; ph. 352-392-3658; e-mail: jetc@ufl.edu)

Shatsky Rise is medium-sized large igneous province located in the North-central Pacific Ocean and was the target of ODP Leg 198. Sediments of Paleogene and Cretaceous age are buried at relatively shallow depths on three topographic highs that make up the Rise. A total of eight sites were drilled on the leg, five of which (1207, 1208, 1210, 1211 and 1212) have produced good magnetic stratigraphies for sediments ranging in age from Late Cretaceous to Recent. Shipboard magnetic data measured on the half-core provided high quality data for sediments from Miocene to Recent. These data have been ground-truthed using discrete sample cubes. However, shipboard data from Paleogene and older sediments were uninterpretable due to the unconsolidated nature of the sediments. Discrete samples have been used to provide a magnetic stratigraphy for these sediments. Biostratigraphic results were used to aid in the interpretation of the magnetic stratigraphy in the Paleogene and Cretaceous. Orthogonal projections from discrete samples show a significant drilling related overprint in most of the sediments but this can be removed at peak fields of 15mT. Magnetostratigraphic results from these sediments will provide critical information regarding the timing of climatic and paleoceanographic events in the Paleogene and

Cretaceous.Two sites (1207 and 1208) provided outstanding Neogene age sections with relatively high sedimentation rates. At site 1208 sedimentation rates calculated from shipboard magnetostratigraphic results are 4.5-5.5 cm/kyr for the Brunhes and Matuyama chrons.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) H F Evans, Department of Geological Sciences, University of Florida, Gainesville, FL 32611 (b) 352-392-3298 (c) 352-392-9294 (d) geohelen@ufl.edu 4. Yes

Third Superchron During the Early Paleozoic ?

Y. Gallet Laboratoire de Paléomagnétisme, Institut de Physique du Globe de Paris, France) ; V. Pavlov (Dept. of Geomagnetism and Paleomagnetism, Institute of Physics of the Earth, Moscow, Russia

Since the 1960's, research on geomagnetic reversal chronology has established the existence of two superchrons, one during the Cretaceous and the other (Kiaman) during the Late Paleozoic. The occurrence of superchrons has been linked to major events in the Earth's history such as plumes, flushing events or true polar wander episodes. Over the past few years, we have performed several magnetostratigraphic studies on Early Paleozoic (Cambrian and Ordovician) sedimentary sequences from Siberia. Our results show high magnetic reversal frequencies during the Middle and Early Cambrian. In contrast, several records suggest the occurrence of a ~20 Myr long, reversed polarity interval in the Lower (Arenig) and Middle (Llanvirn and lower half of the Llandeilo) Ordovician, suggesting the presence of a new superchron Given our present state of knowledge, we propose that the reversal behavior during the Early Paleozoic was similar to the one which prevailed during the Cretaceous, marked by a drastic decrease in magnetic reversal frequency between the Lower-Middle Cambrian and the Lower Ordovician leading up to a superchron. We further propose to give the name of " Moyero " to this probable third superchron. This name is attributed to the Siberian section which yields a complete record of this reversed polarity interval.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) Y. Gallet, Laboratoire de Paléomagnétisme, IPG Paris, 4 Place Jussieu, 75252 Paris cedex 05 France (b) 33 1 44 27 24 32 (c) 33 1 44 27 74 63 (d) gallet@ipgp.jussieu.fr 4. No

Multiphase Modeling of Contact Metamorphic Systems and Application to a Miocene Transitional Geomagnetic Field Record, Paiute Ridge, Nevada

J W Geissman (Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131-1116; ph. 505-277-3433; fax 505-277-8843; e-mail: jgeiss@unm.edu); G N Keating (Environmental Dynamics and Spatial Analysis, EES-10, Los Alamos National Laboratory, Los Alamos, NM 87545; ph. 505-667-5902; fax 505-667-1628; e-mail: gkea@lanl.gov)

We present a numerical model that improves our capability to simulate multiphase, nonisothermal flow in variably saturated porous and fractured media, in this case poorly welded to partially fused ash flow tuff, at magmatic temperatures and shallow crustal pressures to better understand the cooling and hence magnetization acquisition history of these rocks. Simulations of heat and fluid flow in variably saturated host rock near a magmatic intrusion provide insight into processes of dryout, condensation, and resaturation effects and implications for host-rock alteration and the rate at which the host rock cools, and thus magnetizations are recorded in it, following contact metamorphism.We developed a numerical model capable of simulating multiphase flow of heat, water and air in variably saturated porous / fractured media near a magmatic intrusion. The numerical code solves nonlinear conservation equations for mass and energy, using thermodynamic properties of water and air in the ranges 10ºC £ T £ 1500 C, 0.00123 £ P £ 1000 MPa and 10ºC £ T £ 1500ºC, 0.00123 £ P £ 22 MPa, respectively. The study area is located at Paiute Ridge, eastern

Nevada Test Site, Nevada, USA, where hypabyssal mafic intrusions were emplaced at about 8.5 to 8.6 Ma (Ar/Ar age estimate) and cooled during a geomagnetic field reversal, inferred from paleomagnetic data from over 100 sites in intrusions and remagnetized host ash-flow tuffs. A radial model of heat flow and multiphase pore fluid flow adjacent to a 1200ºC intrusion characterizes the thermal evolution of the contact metamorphic system. For likely initial pore saturations of 0.4 to 0.6, Aan expanding dryout zone near the intrusion and a condensation zone of enhanced saturation ($S < 0.8$) extends 150 to 400 m from the intrusion. Pore water in the condensation zone drains steadily so that host-rock pore saturation never exceeds 0.8. Host rock temperatures reach 800ºC near the contact and cool below 100ºC within 1000 to 2000 years after emplacement for moderate initial pore saturations (0.4 to 0.6), 2 to 4 times faster than predicted by a simple conduction model. The thermal history of the system is very sensitive to initial saturation. The multiphase thermal model allows bounds to be placed on the rate of change of the transitional part of the geomagnetic field during the field reversal recorded at Paiute Ridge. hypothesize

1. Chapman Conference on Timescales of the Geomagnetic Field
2. Poster 3. (a) J W Geissman Department of Earth and Planetary Sciences University of New Mexico Albuquerque NM 87131-1116 (b) 505-277-3433 (c) 505-277-8843 (d) jgeiss@unm.edu 4. No

Magnetization acquisition is interpreted to have taken place during the life of the thermal system that developed in the intrusions and contact rocks and that the paleomagnetic data provide a quasi-continuous record of the transitional part of the reversal. Sites in intrusions and thermally annealed ash-flow tuffs reveal subtle yet systematic variations in paleomagnetic directions. We combine the directional data with robust thermal (temperature/time) models to estimate the rate of change of the geomagnetic field. At site 98_42, intensely fused tuff below the sub-vertical contact of the main lopolith of the complex reveals a systematic change in direction of at least 16º from less than a meter from the contact to over two meters away. At site 94_43, moderately fused tuff of the upper country rock to this same lopolith reveals a progressive change in direction from about 220 /+17 to about 270 /+10 between about 440 and 580ºC, respectively, in thermal demagnetization. Modeled times of between 140 and 290 years (site 98_42) and between 215 and 440 years (site 94_43) for the duration of magnetization acquisition at two different sites correspond to estimated rates of change of 0.13 to 0.06 degrees/year for the field during the transitional part of the reversal recorded at Paiute Ridge.

Low Secular Variation in the Pacific

D Gubbins D Gubbins (School of Earth Sciences, University of Leeds, Leeds LS2 9JT, UK; ph +44 113 343 5255; e-mail gubbins@earth.leeds.ac.uk)

There are many hints that the temperature of the lower mantle affects core convection and the geomagnetic field. One of these is the lack of secular variation throughout the Pacific sector of the core-mantle boundary during the last 500 years of direct observation. It is difficult to explain permanent blocking of secular change from this hemisphere using lateral variations of core-mantle boundary temperature inferred from seismic velocities in the mantle because the latter are roughly symmetrical about the Pacific rim, with a fast ring beneath the subduction zones and slow regions in the central Pacific and from Africa through the Atlantic. Such a geometry could lock the core flow or produce symmetrical thermal winds, but would not be expected to permanently eliminate secular variation from just one of the two hemispheres. Thermal wind calculations confirm this view, as does a recent geodynamo simulation that produces a time average resembling the paleomagnetic time average but never a snapshot of the field that looks like the present geomagnetic field. However, simple convection calculations do show rolls that drift through the Atlantic region but are suppressed in the Pacific. This is because the lower mantle seismic velocity pattern is not perfectly symmetric: the Pacific slow anomaly is extended longitudinally more than the one in the Atlantic and is capable of completely suppressing convection in the upper layers of the core.

Data from C14-dated lava flows on

Hawaii show that low secular variation has persisted there for at least 5 kyr and probably 10 kyr. An excursion was recorded at 20 ka, but in the last 5000 years the magnetic direction has changed by significantly less, and much more slowly, than it has throughout most of the Atlantic region in the last 200 years. This suggests Hawaiian secular variation may reflect a different physical process from that in the Atlantic - a process with a longer inherent time scale. For example, the Atlantic may be dominated by MAC waves or westward drift of small scale magnetic features, while the Pacific may see drift of convection rolls or dynamo waves. In this talk I shall review the available data and examine possible sources for the weak Hawaiian secular variation, including whether it can be explained entirely by magnetic changes outside the "Pacific" sector of the core-mantle boundary.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) D Gubbins School of Earth Sciences, University of Leeds Leeds LS2 9JT, UK (b) +44 113 343 5255 (c) +44 113 343 5259 (d) gubbins@earth.leeds.ac.uk 4. No

A Source Model for the Geomagnetic Field

C G A Harrison (Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami Fl 33149, ph 305-361-4610; fax 305-361-4632; e-mail: charrison@rsmas.miami.edu)

A new model has been developed for the geomagnetic field observed over the past few million years. It consists of an axial dipole which is allowed to vary about a mean value, and a number of off centered vertical dipoles whose strength is chosen from a zero-mean Gaussian distribution with a certain standard deviation. The depth of the off centered dipoles is chosen so as to duplicate the slope of the Lowes-Mauersberger function which is a property of the Earth's magnetic field that does not vary significantly over the past 300 years, in contrast to other properties that vary considerably. The off centered dipoles are randomly located longitudinally, but are concentrated towards the poles, using a Fisher distribution, so as to give the correct distribution of Virtual Geomagnetic Pole scatter as a function of observation latitude. This requires the off centered dipoles to be statistically concentrated so that their polar concentration is ten times as large as their equatorial distribution. The number of dipoles and their variance is chosen so as to give the best fit to the latitudinal distribution of VGPs from Icelandic paleomagnetic data. No low latitude cutoff was employed. The variance of the central dipole was also allowed to vary but the best results were obtained when the variation was small. The model was checked using (a) latitudinal and longitudinal variation of magnetization of Icelandic lava flows, and (b) paleofield intensity measurements made on Icelandic lava

flows using Thellier-Thellier or similar methods. The fits are very good. Since the central dipole does not vary in intensity very much, the off centered dipoles can partially cancel the central dipole's contribution to the first degree Gauss coefficients if they align statistically in the opposite direction to the central dipole.

1. Chapman Conference on Timescales of the Geomagnetic Field
2. INVITED? 3.(a) C. G. A. Harrison, Rosenstiel School of Marine and Atmospheric Science, University of Miami, 4600 Rickenbacker Causeway, Miami, Fl 33149. 3.(b) 305 361 4610 3.(c) 305 361 4632 3.(d) charrison@rsmas.miami.edu 4. No

Geomagnetic Field During a Reversal

J R Heirtzler Laboratory for Terrestrial Physics, NASAGoddard Space Flight Center, Greenbelt, MD 20771; ph. 301-614-6019; fax 301-614-6015; email: jamesh@ltpmail.gsfc.nasa.gov

It has frequently been suggested that only the geomagnetic dipole, rather than higher order poles, reverse during a geomagnetic field reversal. Under this assumption the geomagnetic field strength has been calculated for the surface of the .Earth for various steps of the reversal process.

Even without an eminent “reversal” of the field, extrapolation of the present secular change (although problematic) shows that the field strength may become zero in some geographic areas within a few hundred years.

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Contributed (a) J R Heirtzler Laboratory for Terrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771 (b) 301-614-6019 (c) 301-614-6015 (d) jamesh@ltpmail.gsfc.nasa.gov No

Paleomagnetism, Paleosecular Variation, Successive Reversals and Absolute Paleointensities Recorded in the Ko'olau and Wai'anae Volcanoes, O'ahu, Hawai'I

E. Herrero-Bervera SOEST-HIGP University of Hawaii at Manoa, Honolulu, HI, 96822; ph. 808-956-6192; fax 808-956-3188; e-mail: herrero@soest.hawaii.edu); J-P Valet (IPGP 4 place Jussieu, 75252 Paris, France; ph. 33-1-44-27-74-63; fax 33-1-44-27-33-73; e-mail: valet@ipgp.jussie.fr

The island of Oahu is the third largest island in the Hawaiian group. It consists of primarily of two coalesced shield volcanoes, the Wai'anae and Ko'olau, each now deeply eroded. The Ko'olau volcano is the younger of the two and was active after the Wai'anae volcano had ceased to erupt. Both volcanoes have suffered mass wasting events that have shaped the two volcanoes leaving a highly dissected morphology with superbly exposed lavas suitable for paleomagnetic research. The offshore expression of the slid blocks from the Ko'olau volcano is an extensive rubbly field of debris extending approximately 230 km from the island across the Hawaiian Deep onto the Hawaiian Arch. We have studied the lavas of the Ko'oalu Volcano as well as the deep-sea sediments on top of the detached blocks by means of magnetostratigraphy to investigate the volcanic evolution and the timing of the catastrophic events that denudated the volcano. Magnetostratigraphic results of the subaerial part of the Ko'olau complex indicate that at least on the normal Reunion Subchrons (ca. Reunion II 2.15+/-0.04 to 2.11+/-0.04 Ma) had been registered at two different locations. Deep-sea cores have recorded several reversals. The oldest one is the top of the Olduvai Subchron (ca. 1.78 Ma). The land and

deep-sea paleomagnetic studies indicate that the timing of the main collapse of the Ko'olau Volcano that originated the detachment of the blocks had to occur between 21.to 1.78 million years ago based on the magnetostratigraphic evidence. Paleosecular variation studies conducted on 19 dated sites with ages between 33 and 700 ka from the Honolulu Volcanic Series (HVS) exposed on SE Oahu and 10 lava flows belonging to the Ko'olau Volcanic Series (KVS) ranging in age from 1.8 to 2.6 Ma yielded successful mean paleomagnetic directions. The average value of the site mean declinations is 359.6^{o} while the mean inclination of 34.5^{o} is 3.5^{o} lower than the value of the geocentric dipole at the site for the HVS. The mean declination obtained for the KVS is 177.7^{o} and the mean inclination is 34.9^{o} (alpha95<5^{o}). The mean direction of magnetization obtained after correcting the site localities of the Matuyama KVS is perfectly antipodal to the mean directions of the Brunhes HVS. This agreement suggests that the time-averaged directions obtained for these two periods are reasonably representative

1. Chapman Conference on Tiemscales of the Geomagnetic Field 2. CONTRIBUTED (oral presentation) 3a. Emilio Herrero-Bervera, SOEST-HIGP University of Hawaii, 1680 East West Rd. Honolulu, Hawaii 96822 3b. 808-956-6192 3c. 808-956-3188 3d. herrero@soest.hawaii.edu 4. No.

of the mean geomagnetic field. The value of dispersion is consistent with the typical value of PSV at the site latitude. The declination does not significantly deviate from the N-S axis but there is a persistent offset by almost 4 degrees in inclination with respect to the expected value of GAD at the site latitude.The Waianae volcano lavas (3.8-2.4 Ma) located on the west part of the island of Oahu, Hawaii has provided a unique opportunity to document the geomagnetic field behavior over a relatively long period of time. This has been an ideal location to investigate the Earths magnetic field because extensive and superbly well-exposed lava flows make up sequences that include at least three back-to-back reversals of the geomagnetic field (Gilbert-Gauss 3.57 Ma through the Upper Mammoth 3.22 Ma). Five thick sections appropriate for paleomagnetic sampling have been successfully studied. The geomagnetic results include the pre- and post-transitional directions with determinations of absolute paleointensity from the three successive reversal volcanic sequences. The dominant pattern of the directional changes is the presence of large inclination paleosecular changes with increasing amplitude and steep values during transitional periods. Our results indicate that there is no evidence for preferred longitudinal sectors or for clusters of directions that would be related to periods of standstill during reversals. In contrast, the presence of parallel records has demonstrated that clusters of directions are not reproducible between parallel sections and thus related to local eruption rates. Some recurring features could reflect characteristics inferred from studies of the secular variation in the Pacific. Absolute paleointensity experiments of 240 lava flows have been conducted on one sample per lava flow using a modified version of the Thellier-Coe technique. We obtained a 23 percent success rate for the paleointensity determinations of at least 4 samples per lava flow and indicate that there is a range between 3.5 and 88 uT. The paleofield was reduced to at least one tenth of the present-day value during transitions characterized by a mean paleointensity of 15 uT, whereas the field recovery depicts a mean paleointensity of 40 uT (normal polarity intervals) with severe paleointensity highs during the recovery periods.

Geomagnetic Field Inclinations and Absolute Paleointensities for a 350 kyr Time gap From the 350 m Core of the Kalihi Scientific Drilling Project Recovered From the Ko'olau Volcano, O'ahu, Hawai'i.

E. Herrero-Bervera SOEST-HIGP, University of Hawaii at Manoa, Honolulu, HI 96822, ph:808-956-6192; fax 808-956-6138; e-mail: herrero@soest.hawaii.edu), J-P Valet (IPGP, 4 place Jussieu, B89 Tour 24, Paris,75252, France, ph. 33-1-44-27-74-63, fax 33-1-44-27-33-73, e-mail: valet@ipgp.jussieu.fr), M.O Garcia (SOEST-Dept. Geology and Geophysics, University of Hawaii at Manoa, Honolulu, HI 96822, ph. 808-956-6641, fax 808-956-5512, e-mail: garcia@soest.hawaii.edu

In order to investigate the volcanic evolution of the Ko'olau Volcano, O'ahu, Hawai'i and the geomagnetic field behavior recorded by the lavas, a paleomagnetic and rock magnetic study was conducted on a 350 m thick sequence of flows from the Kalihi Scientific Drilling Project. This drill core records geomagnetic field inclination for the period approximately between 2.75 to 3.1 Ma. The core extends deeper stratigraphically any surface exposures of the volcano and the rocks obtained have experienced less tropical weathering than surface rocks. Previous published work on Ko'olau has indicated that the volcano was formed during the Matuyama Chron (Doell and Dalrymple, 1973, GSA Bull, 84, 127-42). We drilled multiple one-inch long samples from each of the 103 flows in the drill core section. The paleomagnetic results of all the specimens were stepwise demagnetized by alternating fields from 5-100mT. Companion specimens from the same core were demagnetized at 15 temperature steps. In both cases the demagnetization

diagrams obtained with each technique showed a stable and unambiguous characteristic direction of remanence (ChRM). The ChRM calculated using principal component analysis for the demagnetization diagrams with a well-defined component trending towards the origin. No bias or systematic departure from the origin was accepted and in all cases the ChRM relies on a minimum of seven successive directions isolated during demagnetization. In addition, low-field susceptibility versus temperature (k-T) and SIRM experiments were performed on a dozen or so flows at different different levels of the core. As a result of such tests, we were able to identify magnetite and in few instances a low-temperature mineral phase (300-400 degrees C), reflecting the presence of titanomagnetite with low Ti content as suggested by its large susceptibility. We used the modified Thellier-Coe double heating method to determine paleointinsities. pTRM checks were performed systematically one temperature step down the last pTRM acquisition in order to document magnetomineralogical changes during heating. We were able to obtain paleointensity determination for 25 lavas (out of 103 flows) which

1. Chapman Conference on Timescales of the Geomagnetic Field 2. POSTER 3. (a) E. Herrero-Bervera, SOEST-HIGP, University of Hawaii at Manoa, University of Hawaii at Manoa, HI 96822 (b) 808-956-6192 (c) 808-956-3188 (d) herrero@soest.hawaii.edu 4. No

represent about 25 percent success rate. The analysis reveals two instances of near-zero and two instances of low negative inclination (reversed polarity, 7.5 uT of low paleointensity) within an otherwise normal polarity. In particular, flow units 34-50 record a horizontal inclination and may be associated with the top of the Kaena Subchron. This interpretation is supported also by two Ar-Ar age determinations for flow 14 (2.89+/-0.12 Ma), and flow 66 (3.06+/-0.15 Ma old), and subaerial lavas at several localities where the Reunion II Subchron (ca. 2.11 to 2.15 Ma) is recorded and which previous results were reported by Herrero-Bervera et al (2002, PEPI, 129, 83-98). Our findings lead us to conclude that the growth of the Ko'olau volcano was concomitant with respect to the youngest exposed lavas of the Wai'anae Volcano and both were forming during the Kaena Subchron.

Geomagnetic Directional and Absolute Paleointensity Variations Over 350 kyr From Lava Sequences Recorded in O'ahu, Hawai'i.

E. Herrero-Bervera (SOEST-Hawaii Institute of Geophysics and Planetology, 1680 East West Rd., Honolulu, HI 96822; ph. 808-956-6192; fax 808-956-3188; e-mail: herrero@soest.hawaii.edu); J-P Valet, Institut de Physique du Globe de Paris, 4 Place Jussieu, Paris, 75252, France, ph. 33-1-44-27-74-63; fax 33-1-44-27-33-73; e-mail: valet@ipgp.jussieu.fr)

Five thick sections of Hawaiian lavas in the Wai'anae volcano on O'ahu have recorded the transitional behavior of the paleofield during the Gauss-Gilbert (3.6. Ma), Lower and Upper Mammoth polarity transitions. Stepwise a.f. demagnetization was applied to a minimum of 7 samples per lava flow. At least one specimen per lava flow was thermally demagnetized. Rock magnetic studies (e.g. k-T, SIRM and grain size analyses) indicate that the magnetization is carried mainly by Ti-poor magnetite. Demagnetization experiments have identifed at least 22 trasitional lavas out of 245 lavas studied. The dominant pattern of the directional changes, such as the presence of large inclination variations with increased amplitude and steep values during transitional periods were observed in three sections that recorded the Lower Mammoth polarity transition, whereas the Gauss-Gilbert and Upper Mammoth reversals did not record such paleosecular variation changes. In addition of the directional analyses, we have obtained absolute paleointensity determinations from the 5 sequences. We used the modified Thellier-Coe double heating method to determine paleointensities on at least 4 samples per lava flow

studied. pTRM checks were performed systematically one temperature step down the last pTRM acquisition in order to document magnetomineralogical changes during heating. The protocol involved demagnetization of the NRM between room temperature (To) and the heating step (Ti) followed by pTRM acquisition (in presence of a field ranging from 35.6-42.5 uT depending upon sample position along the holder) for the same interval temperature. The pTRM check was obtained after demagnetization in zero field between To and Ti-1. The temperature was incremented by steps of 50^{o}C between room temperature and 500^{o}C, and every 25-30^{o}C at high temperatures. The specimens have been processed within a Pyrox oven in the shielded rooms of the HIGP and IPGP laboratories both in air and in an Ar atmosphere. The paleointensity determinations were obtained from the slope of the Arai diagrams. Special care was taken to interpret the Arai diagrams within the same range of temperatures lower than 300^{o}C unless a clear and unique slope would be present. We were able to obtain paleointensity determinations for 34 lavas (out of 240 flows) which represent approximately 15 percent success rate.
The 1. Chapman Conference on Timescales of the Geomagnetic Field 2. POSTER 3. (a) E. Herrero-Bervera, SOEST-Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, Honolulu, HI 96822 (b) 808-956-6192 (c) 808-956-3188 (d) herrero@soest.hawaii.edu 4. No

28 independent estimates of paleofield range between 3.5 and 88 uT. The field intensity was reduced to at least one tenth of the present-day value during the transitions. In some cases the lava flows preceding the polarity changes is characterized by a mean paleointensity of 15uT (reversed polarity) whereas the field recovery depicts a mean paleointensity of 40uT (normal polarity) with severe paleointensity highs during the recovery periods.

Regionally Recurring Transitional Field Structures: Further Evidence of Mantle Control Over the Geodynamo

K A Hoffman Physics Department, Cal Poly State University, San Luis Obispo, CA 93407; ph. 805-756-1357; fax 805-756-2435; e-mail: khoffman@calpoly.edu

The question of whether mantle influence over the reversing geodynamo is observable has been hotly debated over the past several years. Paleomagnetic database studies of late Cenozoic transition records have been inconclusive. Yet, certain recurrent features of reversing fields continue to be reported. Our findings indicate that the apparent inconsistency can be explained through regional rather than global investigations of available data. For example, some Matuyama-Brunhes reversal records contain the common feature of grouped sequential VGPs near and within western Australia. Those that do often are from sites that roughly ring Australasia. Yet detailed Matuyama-Brunhes records from the North Atlantic, for example, do not.

Five reasonably detailed transitional field records from lavas erupted at the Society Island hotspot spanning the past 3 Ma--a Pliocene event (from Huahine), and the Punaruu Event, termination of the Jaramillo, Matuyama-Brunhes, and Big Lost Event (from Tahiti)--all contain some degree of VGP clustering off the western Australian coast. Interestingly, VGPs associated with the modern-day field after removal of the axial dipole term determined for sites that surround Australasia (spanning 90 of longitude and 60 of latitude) are found to cluster about western Australia. Such is also the case for the modern-day non-dipole field. These findings suggest that bundles of concentrated magnetic flux presently emerging from the fluid core beneath Australasia have been held essentially stationary by the mantle over the past several millions of years, and that they regionally dominate the surface field at those times when the axial dipole is weak or non-existent.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) K A Hoffman Physics Department Cal Poly State University San Luis Obispo, CA 93407 (b) 805-756-1357 (c) 805-756-2435 (d) khoffman@calpoly.edu 4. No

Contributions to the study of the Origin and Distribution of Magnolias from Paleomagnetism

E. Irving Pacific Geoscience Centre, PO Box 6000, North Saanich, BC, Canada, V8L 4B2: ph 250 656 9645: e-mail tirving@pgc-gsc.nrcan.gc.ca): R.Hebda (Royal British Columbian Museum, Victoria, BC, Canada, V8V 1X4:
e-mail rhebda@royalbcmuseum.bc.ca

The modern genus Magnolia is a classic biogeographic disjunct, occurring in southeast Asia and the Americas mainly from Virginia to Colombia but nowhere in-between. This disjunct has now been documented in detail by DNA studies. Magnolias are temperate to warm temperate plants. Species diversity is highest in low latitude at moderate to high altitudes. Fossils that can be securely related to the genus occur in Tertiary rocks of western and eastern North America, northern Europe and southern Siberia and in the Quaternary of Japan. Fossils localities are strung out across Europe and central Asia between these two areas of modern occurrence. Late Cretaceous probable ancestors of modern magnolias occur in western North America. Including these, the fossil ages are systemmatically older in the west than in the east. Paleolatitudes determined paleomagnetically of the Late Cretaceous and Paleogene fossil localities are about 60 N, much higher than at present; warm temperate conditions extended to high latitude attributable to greenhouse Earth. Paleolatitudes of Neogene fossil localities are lower typically 40 to 50 N. We attribute this to global cooling in the Oligocene. Using geophysically derived paleogeographies we propose the following. (1) Magnolias originated in westen North America and migrated eastward to Europe via the Thulean land bridge during the early Paleogene and from there into eastern Asia at some time not yet ascertained. (2) Following Late Neogene uplift of mountains in SE Asia and Mesoamerica and creation of the Panama land bridge, they migrated south into these areas where they rapidly speciated. (3) During Quaternary glaciation they were eliminated from northern and western North America, Europe and southern Siberia, creating the present disjunct pattern. Based on the fossil record and paleogeographic considerations, neither of the current centres of highest diversity appear to be a centre of origin of the genus.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a)
E.Irving Pacific Geoscience Centre, PO Box 6000, North Saanich, BC, Canada, V8L 4B2: ph 250 656 9645: e-mail tirving@pgc-gsc.nrcan.gc.ca 4. No
Edward (Ted) Irving Pacific Geoscience Centre Subdivision GSC - Pacific 9860 W. Saanich Rd., Sidney, BC V8L 4B2 Phone: (250) 363-6509 Fax: (250) 363-6739

Testing the GAD Hypothesis: Lava Flow Records from 0-5Ma.

Catherine L. Johnson (Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0225; ph: (858) 822-4077; fax: (858) 534-5332; email; cljohnson@ucsd.edu); Catherine G. Constable (Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0225; ph: (858) 534-3182; fax: (858) 534-5332; email; cconstable@ucsd.edu)

The GAD hypothesis is one of the enduring foundations of paleomagnetic work. In 1969, Opdyke and Henry used inclination records from 52 deep-sea sediment cores to demonstrate that, on average over the past 700 kyr, the geomagnetic field has closely approximated that of a geocentric axial dipole (GAD). Opdyke and Henry also recognized small deviations from the GAD-predicted inclinations although they could not ascertain their origin (measurement error, secular variation, persistent non-GAD contributions to the field). Deviations of the time-averaged field from GAD were first noticed by Wilson and Ade-Hall [1970] and confirmed by Wilson [1971, 1972]. The non-GAD component of the field was observed as "far-sided" pole positions, and is usually represented via an axial quadrupole term in spherical harmonic expansions. Opdyke [1972] also noted that "it would be useful to know how much time is necessary to sample" to estimate the average field.

Three decades later we are still seeking a satisfactory answer to this question, along with estimates of any persistent departures from GAD. Although it has become possible to obtain high quality paleofield directional data from both lava flows and sediments, it is increasingly clear that full vector records of field behavior are necessary to quantify non-GAD contributions to the time-averaged field, and to estimate paleosecular variation (PSV). For example, investigations of persistent non-zonal and high latitude field structure are greatly aided by absolute declination and intensity measurements respectively. It is also well known now that estimates of the time-averaged field (TAF) direction derived solely from unit vectors will have small but systematic biases. As larger regional datasets become available it should prove possible to discriminate between the effects of this bias and actual departures from GAD.

The issue of how long a temporal sample is required is difficult to address using lava flow records, for which it is often difficult to acquire accurate ages or even relative stratigraphy in some cases. Only a decade ago 10 sites and 10kyr were considered a reasonable rule of thumb. Simulations from recent statistical models for PSV suggest that 1. MEETING: Chapman Conference on Timescales of the Geomagnetic Field 2. CONTRIBUTED 3a. Catherine L. Johnson, Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, 9500 Gilman Drive, La Jolla, CA 92093-0225 3b. ph: (858) 822-4077 3c. fax: (858) 534-5332 3d. email; cljohnson@ucsd.edu) 4. NOT a student ************** hundreds of sites are necessary. The time interval needed to estimate the average field is perhaps best addressed by considering sedimentary records and the associated spectrum of paleofield variations, and we address this in an associated paper.

Here, we review the current status in modeling of the global time-averaged field (TAF) and paleosecular variation (PSV). We present results from a multi-institutional project to characterize 0-5 Ma field behavior using lava flow data. Neil Opdyke has played a pivotal role in these investigations, collecting new data from South, Central and North America, and Australia.

Motions of Mantle Hotspots With Respect to the Spin Axis

Dennis V. Kent [*Dennis V. Kent*] (Department of Geological Sciences, Rutgers University, Piscataway, NJ 08854 & Lamont-Doherty Earth Observatory, Palisades, NY 10964, U.S.A., email: dvk@ldeo.columbia.edu); David A. Schneider (American Scientist, Research Triangle Park, NC 27709, U.S.A.)

Assessments of the coherence of the global (Pacific and Indo-Atlantic) hotspot reference frame typically require determining a plate circuit through the Southern Ocean and between East and West Antarctica, where plate tectonic configurations and histories are poorly constrained. For this reason, we examined the hotspot reference frame and the possibility of true polar wander using a novel approach - one that is largely independent of the motion of lithospheric plates. If a hotspot has remained fixed with respect to Earth's spin axis, any volcanic edifice created over it must have formed at the present-day latitude of the hotspot and should give the same mean paleomagnetic inclination irrespective of subsequent plate motion. After converting mean paleomagnetic inclination to paleocolatitude according to a field model (usually taken to be that of a geocentric axial dipole), it is thus possible to make a simple test of hotspot fixity. If a hotspot has remained stationary since the formation of the volcanic edifice under examination, the paleocolatitude small circle derived from it will pass through the present-day geographic pole. Accordingly, paleocolatitude small circles for separate hotspots should intersect at the present geographic pole if all these hotspots have remained stationary. If, however, these hotspots have moved

in unison, the common intersection of their paleocolatitude small circles will be displaced, marking the position of the spin axis with respect to the sub-lithosphere mantle or mesosphere at that time. Any departure from a common intersection for the paleocolatitude small circles for all hotspot edifices of similar age would imply that there has been appreciable relative motion among the causative hotspots and, to a corresponding degree, indicates the lack of a coherent hot spot reference frame from which to judge true polar wander.

With the exception of the Ontong Java Plateau, whose connection to the Louisville hotspot is problematical, paleocolatitude circles for 7 of the 8 oldest (Early Cretaceous, ~125 Ma) edifices from the Indo-Atlantic and Pacific have a common intersection indicating a net offset of about 18 degrees. Given the involvement of hotspots from all the major ocean basins, this polar offset may document true polar wander, a net rotation of the mantle mesosphere with respect to the spin axis that accumulated over some time since 125 Ma. Late Cretaceous (65 - 81 Ma) edifices for the Hawaii hotspot do not give reasonable paleocolatitude small circle intersections with coeval edifices from other hotspots, indicating that the Hawaii hotspot was not part of the same coherent global reference frame.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) D V Kent, Lamont-Doherty Earth Observatory, Palisades, NY 10964, U.S.A. (b) 845.365.8544 (c) 845.365.8158 (d) dvk@ldeo.columbia.edu 4. No

On the paleoposition of North America in mid-Vendian through Cambrian time: A Restudy of the Sept Îles and Pointe du Criarde Intrusive Suites, Quebec, Canada

J L Kirschvink (Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA; ph 626-395-6187, e-mail: kirschvink@caltech.edu); M Higgins (Dept. Sciences de la Terre, Universite du Quebec a Chicoutimi, 555 blvd de l'universite, Chicoutimi, Quebec, G7H 2B1, CANADA, e-mail: mhiggins@uqac.ca); D A D Evans (Dept. of Geology & GeophysicsYale University, P.O. Box 208109, New Haven CT 06520-8109; e-mail: dai.evans@yale.edu); T D Raub (Dept. of Geology & GeophysicsYale University, P.O. Box 208109, New Haven CT 06520-8109; e-mail: timothy.raub@yale.edu); K Farley (Division of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA 91125, USA; e-mail: farley@gps.caltech.edu)

Suggestions that Earth experienced large episodes of true polar wander during Vendian and early Cambrian time hinge both on the reliability of the underlying paleomagnetic data and the validity of the axial geocentric dipole hypothesis. In an attempt to assess the reliability of one of the critical middle Vendian directions for North America, that reported by Tanczyk et al. (1987), we conducted an intensive paleomagnetic re-sampling of the Sept Îles and Pointe du Criarde intrusive suites along the northern shore of the Gulf of St. Lawrence, near the town of Sept Îles, Québec. Tanczyk et al. identified a two-polarity, low-latitude component (termed 'A') from the Sept Îles intrusive suite, and a steeply-inclined two polarity direction (termed 'B')

from it and from a newly recognized but younger intrusive complex now called the Pointe du Criarde intrusion. A subsequent radiometric U/Pb date indicates that the older intrusion was emplaced ~ 564+/-5 million years ago, whereas the earlier Rb/Sr age of approximately 540+/- 22 million years was actually obtained from the Pointe du Criarde intrusion. Although Tanczyk et al. reported results from a baked contact test which indicated that the 'B' component overprinted the 'A' direction, several authors have discarded this contact relationship and asserted that the 'B' component was most likely to be older, introducing an arbitrary tilt correction to bring it into concordancy with other 600 to 580 Ma results from Laurentia.

Our results confirm the exclusive association of the low-latitude 'A' component with the older Sept Îles mafic intrusion, and the presence of steep-inclination components in both intrusive complexes. Some fraction of these steep components are clearly associated with a viscous overprint of recent origin with high thermal stability, which was unrecognized in the previous analysis, but a high-stability 'B' component remains nevertheless, occasionally overprinting the 'A' component. The presence of flat-lying Ordovician limestones capping a central part of the intrusive complex, as well as horizontally-layered crystal settling features in the Pointe du Criarde intrusion, argues against introducing a regional tilt correction on any of the components. As the limestones are part of an extensive area with low conodont alteration indices on the stable portion of the Laurentian craton, and all of our rock magnetic and petrographic investigations have failed to find any evidence of secondary magnetic minerals, we find no support for the hypothesis that the 'A' component might be an overprint of late Ordovician age. Furthermore, U/He data from apatite in the Sept Îles complex indicate no heating at depth from mid Cretaceous time onwards; by comparison with the well-constrained APW path for North America this rules out a Tertiary age for the high-stability 'B' direction. We conclude that both the 'A' and 'B' components must predate Middle Cambrian time. Assuming that the Vendian and Cambrian Geodynamo was dominated by an axial geocentric dipole, these data support an equatorial position for Laurentia at ~564 Mry and a mid- to high-latitude position at ~540 Myr. Data from the earliest middle Cambrian Tapeats Sandstone indicate that it was back on the equator by about 510 million years ago. This is consistent with the hypothesis of Evans (1998) that there were multiple bursts of true polar wander during Vendian and Cambrian

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) J L Kirschvink, Dept. of Geological & Planetary Sciences, California Institute of Technology, Pasadena, CA 91125 (b) 626-395-6136 (c) 626-568-0935 (d) Kirschvink@caltech.edu 4. No

time, and is compatible with the suggestion that a double burst of TPW could enhance the methane storage and release which fueled the Cambrian evolutionary explosion (Kirschvink and Raub, in press).

Occurrence of Short-Lived Geomagnetic Features Through Time: the Late Miocene-Pliocene gap?

W Krijgsman Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, The Netherlands; ph. +31.30.253.1672; e-mail: krijgsma@geo.uu.nl

The recording of reversal excursions or subchrons smaller than the resolution of the marine magnetic anomalies ('cryptochrons' or tiny wiggles), especially during the Brunhes and Matuyama Chrons, have revolutionized our understanding of the geomagnetic field. Remarkably, however, such ubiquitous short-lived reversals are not found in the Pliocene and late Miocene (Messinian), despite the presence of many high-resolution paleomagnetic records. In contrast again, many tiny wiggles have been recorded in middle Miocene successions. In this contribution, we will present new detailed records from middle Miocene sequences, from both continental and marine environment, which confirm many of the earlier reported wiggles, but also show that some new ones may have been recorded. In addition, this poses the intriguing question if specific periods in time really exist during which short-lived geomagnetic features do not occur. In other words: is there a 'true' late Miocene-Pliocene gap? If correct, than it does not seem to support the hypothesis of Gubbins (1999) that short-lived geomagnetic features are an inherent property of the geodynamo.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3a. W. Krijgsman, Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherlands 3b. +31.30.253.1672 3c. +31.30.253.1667 3d. krijgsma@geo.uu.nl 4. No

High Resolution Global Paleointensity Stack Since 75 kyrs (GLOPIS-75) Calibrated to Absolute Values

C Laj C Kissel (Laboratoire des Sciences du Climat et de l'Environnement, Avenue de la Terrasse, 91198 Gif-sur-Yvette, France; ph. 33-1-6982-3538; fax 33-1-6982-3568; e-mail: laj@lsce.cnrs-gif.fr); R Muscheler; J Beer; M Vonmmos (EAWAG, Ueberlanstrasse 133, Postfach 611, CH-8600 Duebendorf;, ph. 81-1-823-5111)

We have obtained a global relative paleointensity stack using new results and a selection of published records from marine cores with sedimentation rates in excess of 10 cm/kyr, from the North and South Atlantic Oceans, the Mediterranean and the Indian Ocean. After correlation of the cores, the results were stacked using the new approach, based on progressive rejection of points distant by more than a standard deviation from the average (Laj et al., AGU Fall Meeting, 2002), to minimize possible local disturbances.

This relative paleointensity stack extends from 75 kyrs to about 10-12 kyr BP . Compared to the previously published NAPIS-75, this new stack extends further towards the recent period and presents a larger overlap with the archeomagnetic/volcanic absolute paleointensity determinations which all well constrained in age for this period. This allows a more precise calibration to absolute values.

The long-term features of this record are very consistent, in age and amplitude, with the geomagnetic field derived from cosmogenic isotopes data at Summit, Greenland. On a shorter time scale, some of the features perfectly correlate but others do not, suggesting a global (dipolar)

nature for the first group, while the origin of small scale features uncorrelated between the two records is more difficult to explain.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) C Laj Laboratoire des sciences du Climat et de l'Environnement Avenue de la Terrasse 91198 Gif-sur-Yvette France (b) ph. 33-1-6982-3538 (c) fax 33-1-6982-3568 (d) laj@lsce.cnrs-gif.fr 4. No Carlo Laj Laboratoire des Sciences du Climat et de l'Environnement Unité Mixte CEA-CNRS Avenue de la Terrasse, Batiment 12, 91198 Gif-sur-Yvette France Tel.: 33-1-6982 3538 Fax.: 33-1-6982 3568

Cryptochrons and Brief Subchrons Recorded at ODP Site 1218 (Equatorial Pacific)

L. Lanci Istituto di Geologia, Università degli Studi di Urbino, Campus Scientifico, 61029 Urbino, Italy, and Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08854); J.P. Pares (Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109); and J.E.T. Channell (Department of Geological Sciences, University of Florida, Gainesville, FL 32611

ODP Site 1218 yielded an exceptional record of the direction of the geomagnetic field during most of the Miocene and Oligocene. The sedimentation rate in the Oligocene and the lower Miocene carbonate-rich pelagic sediments is relatively high (> 10 m/Myr) and measurements on u-channel samples allowed a high-resolution magnetostratigraphy that, we believe, has the potential to resolve polarity chrons with duration as short as 10 kyr. An attempt to further improve the resolution was made by deconvolution of the original signal. This high-resolution magnetostratigraphy, recorded in a long sedimentary record with very uniform magnetic properties, has been used to test if the small-scale magnetic anomalies on the ocean floor (cryptochrons) represent short polarity subchrons or intensity fluctuations of the geomagnetic field. The results did not give a simple answer to this question. In the ODP Site 1218 record, we observe several short polarity subchrons, with duration of about 10 kyr. A few of them occur where cryptochrons are expected according to the Cande and Kent (CK95) geomagnetic polarity time scale, but other brief subchrons apparently occur where no cryptochron is expected. The majority

of the cryptochrons in CK95, such as those in polarity chron C12r, are not represented by corresponding reversals in the sedimentary record, suggesting that most of the cryptochrons represent fluctuations of field intensity.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) J.E.T. Channell (Department of Geological Sciences, University of Florida, POB 112120, Gainesville, FL 32611, USA; (b) 352 392-3658, (c) 352 392-9294, (d) jetc@ufl.edu 4. No

Reversal Excursions and the Future of High(er) Resolution Correlation

C.G. Langereis (Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, The Netherlands; ph. +31.30.253.1668; e-mail: langer@geo.uu.nl)

Although magnetostratigraphy has become crucial to global stratigraphic correlation, its practical resolution is limited, on average, to some 100,000 yr. The recording of reversal excursions or subchrons smaller than the resolution of the marine magnetic anomalies ('cryptochrons' or tiny wiggles) may, in principle, provide a higher-resolution correlation. Indeed, ubiquitous short-lived reversals are found during the Brunhes and Matuyama Chrons, and their (global) presence is increasingly confirmed. In addition, we continue to find new ones. There are a few problems, however. Firstly, a clear definition of (reversal) excursion vs. small subchron is lacking. The hypothesis of Gubbins (1999) that they are an inherent property of the geodynamo suggests that a distinction is not easily formulated. Secondly, to determine the existence of such short-lived feautures, a high-resolution sampling is required, which is increasingly facilitated by modern equipment, but yet not always feasible. Thirdly, to determine with certainty which reversal excursion has been recorded, often one either uses indirect evidence - e.g. a well-dated paleointensity record with minima that, through re-inforcement, suggest the presence of excursions - or a high-resolution (astro)chronology, in which case the records of excursions are redundant and not required for higher-resolution correlation. Finally, short reversal excursions are, as a rule, often not recorded because of the NRM acquisition mechanisms in sediments. Therefore, whether recorded reversal excursions are global or regional - e.g. due to an increase of reversed flux at the CMB - is not well determined. Clearly, many excursions have already been proven a globally occuring phenomenon, but a regional occurrence may only mean that suitable records are simply still lacking. Here, we discuss the above mentioned criteria, with an emphasis on the global versus regional occurrence of reversal excursions.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) C.G. Langereis, Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, Budapestlaan 17, 3584 CD Utrecht, The Netherland (b) +31.30.253.1668 (d) langer@geo.uu.nl 4. No

Characteristics of the Geomagnetic Field From the Present to the Middle Jurassic: The Perspective From Marine Magnetic Anomalies

R L Larson Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882-1197; ph. 401-874-6165; fax 401-874-6811; e-mail: rlar@gsosun1.gso.uri.edu

Lineated marine magnetic anomalies generated by sea floor spreading at oceanic ridges are the principal records of geomagnetic polarity reversals for the past 170 Ma. Very generally, the marine record shows two sequences of lineated magnetic anomalies (0-84 Ma and 121 to about 155 Ma) and two magnetic quiet zones where the anomalous fields are very small. Age calibration of the lineated magnetic anomalies suggests magnetic field reversal rates ranging from less than one to about five/m.y. The younger magnetic quiet zone at 84-121 Ma in the mid-Cretaceous is marked by abrupt boundaries in magnetic anomaly amplitudes, although the rate of reversals generally increases from 84 Ma towards the present. This quiet zone almost certainly results from a period of no magnetic reversals for about 37 m.y. called the Cretaceous normal superchron. The older quiet zone has a gradually emergent younger boundary in both rate and amplitude, characterized by gradually increasing anomaly amplitudes and decreasing reversal rate from about 155 Ma towards the present. Detailed marine magnetic surveys within this quiet zone and land-based reversal stratigraphy within the Middle Jurassic both suggest many magnetic reversals. Thus, the Jurassic quiet zone probably results, at least in part, from magnetic polarity transitions spaced so closely together within the seafloor as to attenuate their anomalous fields at the sea surface.

The Middle to Late Jurassic probably had a much larger reversal rate than at any subsequent time. If deep mantle convection (plume) activity exerts a control on reversal rate, then an increase in Cretaceous mantle plume activity, as evidenced by oceanic plateaus of that age, might have caused the Cretaceous normal superchron. Very little Jurassic seafloor remains to test the opposite possibility for the Jurassic quiet zone.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) R L Larson, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI 02882-1197 (b) 401-874-6165 (c) 401-874-6811 (d) rlar@gsosun1.gso.uri.edu 4. No

J C Liddicoat [*J C Liddicoat*](Department of Environmental Science, Barnard College, Columbia University, New York, NY 10027-6598; ph: 212-854-7089; fax: 212-854-5760; e-mail: jliddico@barnard.edu); R S Coe (Earth Sciences Department, University of California, Santa Cruz, Santa Cruz, CA 95064; ph: 831-459-2393; fax: 831-459-3074; e-mail: rcoe@es.ucsc.edu)

The Mono Lake Excursion (MLE) as recorded in the Mono Basin, California, has an older part that is negative inclination and west declination. Those paleomagnetic directions are closely followed by steep positive inclination and east declination. The negative inclination/west declination occurs during low relative field intensity. A path of the Virtual Geomagnetic Poles when examined from old to young and that represents negative inclination/west declination forms a clockwise loop that reaches 35 N latitude and is centered at about 35 E longitude. That loop is followed by a smaller one that is clockwise trending and is centered at about 70 N latitude and 270 E longitude; the younger loop corresponds to steep positive inclination/east declination (Denham and Cox, 1971; Denham, 1974; Liddicoat and Coe, 1979). Discoveries of the MLE outside the Mono Basin in western North America record nearly the full excursion (Negrini, et al., 1984) or, more often, the younger portion of steep positive inclination/east declination and high relative field intensity (Liddicoat, 1992, 1996; Coe and Liddicoat, 1994). >> >>In exposed lake sediments in the Bonneville Basin (Utah) and in southern Arizona we located anomalous paleomagnetic field

behavior that resembles the MLE as recorded in the Mono Basin. Carbon-14 dating of the sediments in Arizona indicates that the field behavior occurred about 28,000 years ago, a date that is within a few thousand years of the age assigned to the MLE in the Mono (Lund, et al., 1988) and Lahontan (Nevada) basins (Benson, et al., 2003).

1. Chapman Conference on Timescales of the Geomagnetic Field >>2. Contributed (oral) >>3. a) J C Liddicoat, Department of Environmental Science, Barnard College, Columbia University, New York, NY 10027-6598; b) 212-854-7089; c) 212-854-5760; d) jliddico@barnard.edu >>4. No -- Jim Channell Dept. Geological Sciences University of Florida 241 Williamson Hall PO Box 112120 Gainesville, FL 32611, USA

J C Liddicoat L V Benson (U S Geological Survey, 3215 Marine St, Boulder, CO 80303-1006; ph: 303-541-3005; fax: 303-447-2505; e-mail: lbenson@usgs.gov), [*J C Liddicoat*](Department of Environmental Science, Barnard College, Columbia University, New York, NY 10027-6598; ph: 212-854-7089; fax: 212-854-5760; e-mail: jliddico@barnard.edu), J P Smoot (U S Geological Survey, MS 955, National Center, Reston VA 22092; e-mail: jpsmoot@usgs.gov), A M Sarna-Wojcicki (U S Geological Survey, MS 975, Middlefield Road, Menlo Park, CA 94025; e-mail: asarna@usgs.gov), R M Negrini (Department of Physics and Geology, California State University, Bakersfield, CA 93311; e-mail: rnegrini@csub.edu), and S P Lund (Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089; e-mail: slund@usc.edu)

In the Pyramid Lake Basin, Nevada, a volcanic ash bed that is correlated chemically to Ash 15 in the Wilson Creek Formation in the Mono Basin, California, is assigned a date of 28,620+-300 Carbon-14 years B.P. and GISP2 age of 32,400 years. The ash is midway in the portion (about 30 cm) of the Wilson Creek Formation that records the Mono Lake Excursion (MLE) in the Mono Basin (Liddicoat and Coe, 1979). Using an assumed sedimentation rate of 30 years/cm for the Wilson Creek Formation where the MLE is recorded and the Carbon-14 age for the ash in the Pyramid Lake Basin, we believe that the MLE occurred between 33,300 and 31,500 GISP2 years B.P. This age for the MLE is consistent with its position in the NAPIS-75 paleointensity stack (Laj et al., 2000). Also, the date for Ash 15 is similar to the date assigned

to it by Kent et al. (2002) if a reservoir effect of 3100 years is assumed for the Carbon-14 dates in the Mono Basin.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. a) J C Liddicoat, Department of Environmental Science, Barnard College, Columbia University New York, NY 10027-6598; b) 212-854-7089; c) 212-854-5760; d) jliddico@barnard.edu 4. No

Laschamp and Mono Lake Excursions in the same Lacustrine Record from Western North America

J C Liddicoat R M Negrini and M Zic (Department of Physics and Geology, California State University, Bakersfield, CA 93311; ph: 661-664-2185; fax: 661-664-2040; e-mail: rnegrini@csub.edu), and [*J C Liddicoat*] (Department of Environmental Science, Barnard College, New York, NY 10027; ph: 212-854-7089; fax: 212-854-5760; e-mail: jliddico@barnard.columbia.edu)

Two excursions which we believe to be the Laschamp and Mono Lake excursions are present in a record from the 11.8 meter B&B sediment core taken from the depocenter of the Summer Lake basin in south-central Oregon. The age of this record is constrained by several independent methods including radiocarbon dating (on wood and ostracode shells), tephrochronology (of the Wono and Mt. St. Helens Cy volcanic ashes), thermoluminescence dating (of the Mt. St. Helens Cy ash), and correlation of lake level proxies at millennial time scales with the GISP2 O-18 record (Zic et al., 2002). Because the sediment accumulation rate for this core is very high (>50 cm/Kyr) the records of the excursions are quite detailed.

The lower (older) excursion, which we correlate with the Laschamp Excursion, is found in an interval correlated with the part of the GISP2 record containing interstadial (IS) numbers 10 through 8 (~41-37.5 Ka). The age of the lower B&B excursion is thus consistent with the currently accepted age for the Laschamp Excursion (e.g., Levi et al., 1990; Vlag et al., 1996; Wagner et al., 2000). Its VGP path is characterized by a CCW looping VGP path which occupies the North Atlantic Ocean. This observation is consistent with the only other published mention of the VGP path for the Laschamp Excursion (Vlag et al., 1996). The upper excursion is located ~2 meters higher in the core and we correlate this event with the Mono Lake Excursion. It is found in a time interval starting before IS 6 and ending after IS 5 (~34-31 Ka). The VGP path of the upper excursion is both distinctly different from that of the lower excursion and, at the same time, strikingly similar to that of the Mono Lake Excursion as found in the "type" record from the Wilson Creek Fm found in the nearby Mono Lake basin, California (e.g., Liddicoat and Coe, 1979).

Based on the ages and VGP paths of the two excursions found in the B&B core, we conclude that the Laschamp and Mono Lake excursions are separate events as previously suggested by several research groups (Levi and Karlin, 1989; Lehman et al., 1996; Nowazyk and Antonow, 1997; Benson et al., 1998; Wagner et al., 2000a; Nowazyk and Knies, 2000). In contrast, our conclusions are directly opposed to those of 1. Chapman Conference on Times Scales of the Geomagnetic Field 2. Poster 3. (a) R M Negrini Department of Physics and Geology California State University Bakersfield, CA 93311 (b) 661-664-2185 (c) 661-664-2040 (d) rnegrini@csub.edu 4. No

Kent et al. (2002) who suggest that the Mono Lake Excursion, as found at the type locality, is the Laschamp Event.

Magnetic Stratigraphy and Geomagnetic Reversal History

W. Lowrie Institute of Geophysics, ETH-Hoenggerberg, 8093 Zürich, Switzerland; ph. +41-1-633-2607; fax +41-1-633-1065; e-mail: lowrie@mag.ig.erdw.ethz.ch

During the past 40 years, mutually reinforcing records of geomagnetic polarity have been derived from the marine magnetic anomaly record and magnetic stratigraphy studies. The main features of the geomagnetic reversal record are securely established and reliably dated back to the mid-Jurassic. Consequently, the polarity record can be used to date sedimentary sequences that would otherwise remain undated. However, some polarity features remain to be explained. The reason for the Cretaceous Normal Polarity Superchron is not known, and, despite deep-tow marine studies and detailed magnetostratigraphy, field behavior during this long interval is controversial. Fine-scale magnetic polarity stratigraphy, especially in high-deposition rate sediments, often reveals short magnetozones that do not occur in matching sections or have no equivalent in the oceanic record. Likewise, surface and deep-tow magnetic profiles have shown short-lasting features that cannot be identified unequivocally as either polarity features or paleointensity fluctuations. These short features have a serious effect on analyses of the statistical properties of reversal sequences. It is more difficult to establish geomagnetic polarity history for older intervals that pre-date the onset of sea-floor spreading. In some cases, first-rate magnetic stratigraphies have been developed, yet it is difficult to tie them to each other, and especially to correlate continental and marine records. The number of successful studies in

Paleozoic sections is still small and correlations are difficult. The possible presence of appreciable persistent non-dipole components in older rocks could jeopardize the founding of a secure ancient polarity history.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) Prof. William Lowrie, Institute of Geophysics, ETH-Hoenggerberg, 8093 Zürich, Switzerland (b) +41-1-633-2607 (c) +41-1-633-1065 (d) lowrie@mag.ig.erdw.ethz.ch 4. No

Magnetic Reversals and Old Bones: Opdyke's Contributions to Cenozoic Mammal Evolution

B J MacFadden Florida Museum of Natural History, University of Florida, PO Box 112710, Gainesville FL 32611-2710; ph. 352-846-2000, ext. 207; fax 352-846-0253; email: bmacfadd@flmnh.ufl.edu

Prior to the advent of absolute dating techniques, the geological ages of vertebrate fossils were mostly determined by traditional stage of evolution faunal comparisons. This changed dramatically starting in the 1960's and 1970's, when K-Ar dating and magnetic polarity stratigraphy revolutionized the calibration of vertebrate evolution, particularly for the Cenozoic mammalian fossil record worldwide. Neil Opdyke has been a world leader in the calibration of mammalian evolution using magnetic polarity stratigraphy. In addition to the calibration of the Cenozoic mammal ages themselves, numerous related magnetostratigraphic studies have significantly advanced our understanding of evolution. For example: The magnetic polarity stratigraphy of the extensive Siwalik sequence of Pakistan not only calibrated Old World land mammal evolution, but also contributed to an understanding of the timing of hominoid phylogeny and late Cenozoic global change. Likewise, the precise calibration of mammalian faunas throughout the northern hemisphere resolved intercontinental dispersal events that were linked to eustatic sea-level changes, like faunas into North America during the early Miocene and the horse Equus into the Old World during the Pliocene. After a quarter-century, magnetic polarity stratigraphy now has been applied to terrestrial sequences world-wide. Most important vertebrate-bearing

localities amenable to magnetostratigraphic dating have been analyzed, including the type localities that define continental mammal ages. These advances have increased the temporal precision available to vertebrate paleontologists and revolutionized the kinds of interesting questions that can be answered about Cenozoic mammal evolution.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) B. J MacFadden Florida Museum of Natural History University of Florida PO Box 112710 Gainesville FL 32611-2710 (b) 352-846-2000, ext. 207 (c) 352-846-0253 (d) email: bmacfadd@flmnh.ufl.edu 4. No

The Geocentric Axial Dipole Hypothesis - Current Status

M W McElhinny Gondwana Consultants, 31 Laguna Place, Port Macquarie NSW 2444, Australia; ph. +61-2-65846483; fax +61-2-65846483; email: mikemce@midcoast.com.au

The GAD hypothesis has served the paleomagnetic community well over several decades. As more demands are made for greater accuracy in continental reconstructions and for determining second order aspects of the time-averaged field over the past 5 Myr, it has been proposed that significant departures from the GAD field are and have been present at many times in the Earth's history. These proposed departures from the GAD hypothesis are reviewed and placed in an historical context. Many of these supposed departures can be accounted for in a variety of ways as being due to attempts to obtain second order information from poorly constrained data. In particular it has been proposed that significant axial octupole fields have persisted at many times in the past. Unfortunately the nature of paleomagnetic data is such that many data artifacts manifest themselves by producing artificial axial octupole fields. These artifacts arise most often because there are still too few data of high enough quality globally (especially for pre-Mesozoic times). A small but significant axial quadrupole field seems to be clearly established from current paleomagnetic data. However, until more high quality data are obtained at critical times in the Earth's history (e.g. during the Carboniferous-Triassic) the reality of any proposed significant axial octupole field must be viewed with considerable suspicion.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) M W McElhinny, Gondwana Consultants, 31 Laguna Place, Port Macquarie NSW 2444, Australia (b) +61-2-65846483 (c) +61-2-65846483 (d) mikemce@midcoast.com.au 4. No

Non-Dipole Fields and Inclination Analysis: What is the low Inclination Bias Really Telling us?

J.G. Meert Department of Geological Sciences, University of Florida, Gainesville, FL 32611; ph. 352-846-2414; fax 352-392-9294; e-mail: jmeert@geology.ufl.edu); E. Tamrat (University of Florida); J. Spearman (University of Florida

Evans (1976) first noted that inclination-only studies could be used to test the validity of the Geocentric axial dipole assumption (GAD). Evans (1976) concluded that the GAD hypothesis was valid for Phanerozoic times. A subsequent study by Piper and Grant (1989) reached a similar conclusion using a much larger database. However, Piper and Grant (1989) misapplied the c-square test statistic in their analysis and corrected values show that the GAD hypothesis is violated by the observed inclination distributions. Kent and Smethurst (1998) showed that binned inclination data for the Precambrian and Paleozoic were significantly different from the GAD, but Mesozoic and Cenozoic data were similar to the expected GAD frequencies. Kent and Smethurst (1998) also misapplied the c-square test statistic and corrected values show that the Mesozoic distribution is also significantly different than the expected GAD distribution.

A number of possible explanations for this non-GAD distribution are proposed including: (a) inclination shallowing in sedimentary rocks; (b) unrecognized random tilting of igneous rocks; (c) indiscriminate use of all paleomagnetic results; (d) preferential cycling of continents into lower latitudes; (e) sampling biases; (f) late stabilization of the dipole via growth of the inner core; and (g) incomplete sampling. We have tested a number of these competing hypotheses for the observed low inclination bias by developing an interactive computer program and exploiting the paleomagnetic database. Of these myriad explanations we feel that the data are best explained by either (a) persistent octupolar and quadrupolar fields or (b) preferential cycling of continents into lower latitudes.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) J.G. Meert (Department of Geological Sciences, University of Florida, Gainesville, FL 32611; (b) ph. 352-846-2414; (c) fax 352-392-9294; (d) jmeert@geology.ufl.edu 4. No

A Snapshot of Secular Variation Near the Start of the Kiaman Superchron

R J Musgrave Department of Earth Sciences, La Trobe University, Bundoora, VIC 3068, Australia; ph. 61-3-9479-2145; fax 61-3-9479-1272; e-mail: R.Musgrave@latrobe.edu.au); M Fussell (Department of Environmental Management & Ecology, La Trobe University, PO Box 821, Wodonga, VIC 3689, Australia; ph. 61-2-6058-3876; fax 61-2-6058-3888; e-mail: mfussell@aw.latrobe.edu.au

Glacial varves at Abercrombie Quarry in the Hunter Valley of New South Wales, Australia, afford an opportunity to examine secular variation from the Kiaman (Permo-Carboniferous) Reversed Superchron on a yearly to centennial time-scale. This high-palaeolatitude record from the early part of the Kiaman provides a valuable counterpoint to red-bed studies from the low-palaeolatitude Dome de Barrot site in France, which were dated to late in the Kiaman. Thermal and AF demagnetisation thoroughly remove the Cretaceous normal overprint that is problematic in many Palaeozoic sequences in eastern New South Wales; the low permeability of these very fine grained, siliceous varves appears to have minimised invasion of fluids responsible for the CRM that carries this overprint. Rock-magnetic parameters indicate magnetite in its pseudo-single to single domain state as the magnetic carrier in the varves, qualifying them as likely to preserve a stable depositional magnetisation. Although a fold test is not available, the characteristic remanence averages close to the expected late Carboniferous pole after removal of bedding tilt, supporting the inference that the remanence is depositional.

A series of ten sites, each grouped over about 10 to 50 yearly varves, and spanning a total of about 600 varves, yield VGPs. These form a systematic arcuate track around the late Carboniferous palaeopole, similar to historic secular variation records. Inferences about the geodynamo, specifically the support for active outer core convection during superchrons, can now be extended into the early phases of the Kiaman superchron.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) R J Musgrave Department of Earth Sciences La Trobe University Bundoora, VIC 3086 Australia (b) 61-3-9479-2145 (c) 61-3-9479-1272 (d) R.Musgrave@latrobe.edu.au 4. No

Tethyan magnetostratigrapy from Pizzo Mondello and correlation to the Late Triassic Newark APTS

Giovanni Muttoni [*Giovanni Muttoni*] (Department of Earth Sciences, University of Milan, Via Mangiagalli 34, I-20133 Milan, Italy, email: giovanni.muttoni1@unimi.it); Dennis V. Kent (Department of Geological Sciences, Rutgers University, Piscataway, NJ 08854 & Lamont-Doherty Earth Observatory, Palisades, NY 10964, U.S.A., email: dvk@ldeo.columbia.edu); Paul E. Olsen (Lamont-Doherty Earth Observatory, Palisades, NY 10964, U.S.A.); Stefano Bernasconi, William Lowrie, Fátima Martín Hernández (Departement Erdwissenschaften, ETH-Zentrum, CH-8092 Zürich, Switzerland); Piero Di Stefano (Department of Geology and Geodesy, University of Palermo, Corso Tukory 131, I-90134 Palermo, Italy)

We present magnetostratigraphic data and preliminary stable isotope data from an expanded (‰430m-thick) Upper Triassic marine section at Pizzo Mondello from the Sicani Basin of Sicily and review biostratigraphic data from the literature that can be used to define the location of the Carnian/Norian and Norian/Rhaetian boundaries. Pizzo Mondello offers good potentials for magnetostratigraphic correlation of marine biostratigraphic and chemostratigraphic data with the continental Newark astrochronological time scale (APTS) for development of an integrated Late Triassic time scale. The relatively stable average values of d18O centered around 0" are a strong indication that the Cherty Limestone at Pizzo Mondello suffered very little diagenetic overprinting. The Carnian/Norian boundary at Pizzo Mondello seems to be associated with

a positive shift of dC13 although further work is necessary to evaluate its paleoenvironmental significance. A statistical approach was applied to evaluate various Pizzo Mondello to Newark magnetostratigraphic correlations. Two correlation options, neither unequivocal, have the highest and nearly equivalent correlation coefficients. Option #1 predicts the base of Pizzo Mondello to be correlative with the middle part of the Newark APTS, whereas in Option #2 the base of Mondello starts towards the early part of the Newark APTS. According to sampling density and average sediment accumulation rates of 20-30m/m.y., polarity intervals with durations equal to or less than ‰170 k.y. may have been undersampled at Pizzo Mondello. Accordingly, we filtered the high resolution Newark APTS and performed further statistical correlations from which we conclude that Option #2 is preferred. With this option, the Carnian/Norian boundary based on conodonts corresponds to basal Newark magnetozone E7 at about 228 Ma (adopting Newark astrochronology), implying a long Norian with a duration of ‰20m.y. and a Rhaetian of about 6 m.y. duration. These ages are in fact not inconsistent with the few high quality radiometric dates that are 1. 1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) D V Kent, Lamont-Doherty Earth Observatory, Palisades, NY 10964, U.S.A. (b) 845.365.8544 (c) 845.365.8158 (d) dvk@ldeo.columbia.edu 4. No available for Late Triassic time scale calibration. We suggest that Pizzo Mondello is a good candidate for a GSSP for the base of the Norian whereas we find that sections of the "Hallstatt" type , which may be more fossiliferous but have erratic and typically very low average rates of sediment accumulation, are more difficult to correlate.

Earth's Magnetic Field

N. D. Opdyke Victoria Mejia (Department of Geological Sciences, University of Florida, Gainesville, FL 32611; ph: 352 392-6127; fax 352 392-9294; e-mail: drno@ufl.edu)

Recent studies of the Paleosecular Variation of lavas (PSVL) by the authors and others, shows that the variability of Earth's magnetic field over the last several million years is less than the variability of the present Earth's magnetic field. The present magnetic field is asymmetric between the northern and southern hemispheres. The dispersion in the southern hemisphere being much greater than in the northern. If the present earth's magnetic field were a good template for the field in the past then a larger VGP dispersion would be expected then is observed. The present field may therefore be leading to an excursion or a reversal of Earth' magnetic field.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) N.D. Opdyke, Department of Geological Sciences, University of Florida, POB 112120, Gainesville, FL 32611, USA; (b) 352 392-6127, (c) 352 392-9294, (d) drno@ufl.edu 4. No

Tiny wiggles in the Cenozoic Magnetic Record: Short Polarity Events Obscured by Intensity Fluctuations?

J M Pares R Van der Voo (Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building, Ann Arbor, MI-48109; ph. 734-615-0472; e-mail: jmpares@umich.edu, voo@umich.edu)

Magnetic profiles from different oceanic basins reveal, in addition to the well-known reversal pattern, the occurrence of short-wavelength magnetic anomalies, called “tiny-wiggles”. Understanding the origin of tiny wiggles is one of the most important problems in geo- and paleomagnetism. Are tiny wiggles short paleointensity fluctuations of the geomagnetic field, as some authors suggest, or are they short-lived polarity intervals? Because it is difficult to resolve polarity intervals shorter than 20,000 years in the oceanic magnetic anomaly record, we need to rely on the paleomagnetism of volcanic and sedimentary rocks in order to decipher the origin of tiny wiggles. However, sediments can suffer from low resolution due to smoothing of the magnetization signal and are therefore not always perfect recorders of the geomagnetic field; hence the underlying cause of tiny wiggles remains unclear.

A number of tiny wiggles have been detected as short duration polarity events in a variety of sedimentary rocks, and their characteristics will be discussed. Specifically, in polarity chrons C1n, C2An.1n, C5n.2n, C12r and C13r, several tiny wiggles have been revealed as short events in both marine and continental deposits (e.g., NE Tibetan Plateau, Pyrenean Foreland Basin, Bighorn basin). In contrast, other polarity chrons where tiny wiggles are observed in the anomaly record have not produced any evidence of short polarity events in the stratigraphic record. The fact that short polarity events are found in some rocks, whereas other rocks of the same age do not reveal these events, suggests that the latter have likely acquired their remanence with much averaging over time or that there is a mechanism of overprinting after an interval of low geomagnetic intensity that masks short events. We will show a case study including the Blake Event as (imperfectly) recorded in Chinese Loess. It is intriguing that short polarity events in the last 2 million years have been documented in well-dated volcanic rocks, but that other tiny wiggles are not (or imperfectly) seen in the paleomagnetic records of sedimentary rocks. This suggests that short polarity events may be much more common than observed, and that they are preserved in the paleomagnetic record only when lock-in processes are rapid.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Oral 3. (a) Josep M. Pares (Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building, Ann Arbor, MI-48109; ph. 734-615-0472; e-mail:jmpares@umich.edu) 4. No

Paleogene and Neogene Magnetostratigraphy from ODP Leg 199 Sediments

J M Parés Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building, Ann Arbor, MI-48109; ph. 734-615-0472; e-mail: jmpares@umich.edu); L Lanci (Department of Geological Sciences, Rutgers University, 610 Taylor Road, Piscataway, NJ 08854-8066

ODP Leg 199 was designated to collect sediments along a latitudinal transect in the Pacific Ocean to better understand Paleogene sedimentation patterns and the system of equatorial currents. At ODP Sites 1217 through 1220, the magnetic record of the Paleogene Equatorial sediments extends back to Polarity Chron C20r (Middle Eocene), providing an unprecedented record of Paleogene magnetostratigraphy in Equatorial Pacific sediments. Paleomagnetic data were acquired on the JOIDES-Resolution pass-through cryogenic magnetometer from archive halves of core sections. Analyses on both u-channel and discrete samples support the polarity pattern obtained on the shipboard magnetometer. Natural Remanent Magnetization was measured at 5-cm intervals for each core section, and was followed by four to five steps of alternating field demagnetization up to a maximum of 15 or 20 mT. In addition, shipboard and shore-based measurements of discrete samples were also carried out, including alternating field and thermal demagnetization and rock-magnetic analyses. All measured lithologies, including an upper red clay, radiolarian ooze and nannofossil ooze/chalk yield reproducible results and have moderate magnetization intensity, well above the noise level of the cryogenic magnetometer. Stepwise demagnetization of discrete samples indicates that the Characteristic Remanent Magnetization (ChRM) mostly resides in magnetite and can be isolated for the most part of the sedimentary record. The obtained high-resolution magnetic stratigraphy allows to cross-calibrate magnetic reversal stratigraphy with biostratigraphy, including the placement of the Eocene-Oligocene and Oligocene-Miocene boundaries. Overall, results from Leg 199 provide the first complete magnetobiostratigraphic record for the Middle Eocene through the Pliocene in the Equatorial Pacific Ocean.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) Josep M. Pares (Department of Geological Sciences, University of Michigan, 2534 C.C. Little Building, Ann Arbor, MI-48109; ph. 734-615-0472; email:jmpares@umich.edu) 4. No

A pDRM Model Including Bioturbation by Macrofauna and Meiofauna, and Microbial Diagenesis: Time-Averaged Magnetizations Require One-Tier Sampling and Statistics.

T D Raub Geology and Geophysics Department, Yale University, P. O. Box 208109, New Haven, CT 06520-8109; ph: 203-432-9808; fax: 203- 432-3134; timothy.raub@yale.edu); J L Kirschvink (Division of Geological and Planetary Sciences, California Institute of Technology 170-25, Pasadena, CA 91125; ph: 626-395-6136; fax: 626-568-0935; kirschvink@caltech.edu)

Interpretation of short-duration geomagnetic phenomena from high-resolution sedimentary records depends on the fidelity of magnetizations acquired in a typical sample volume of rock or sediment. We suggest that recent experiment-based models for pDRM acquisition underestimate the effective time-averaging of magnetization by bioturbation and bioirrigation. Furthermore, laboratory studies of pDRM and field-analyses of ichnofabrics do not adequately account for microbiological and meiofaunal chemical and physical diagenetic effects, which may affect magnetizations heterogeneously within a seemingly undisturbed sedimentary horizon for significant times after its deposition and burial.

In standard paleomagnetic studies intent on determining best estimates of apparent pole positions, recognition that many random events affect the NRM of sedimentary rocks suggests that the most parsimonious and robust sampling method in the field is to sample densely through many layers in a vertical stratigraphic interval (as in magnetostratigraphy) rather than across a horizontal exposure or bedding layer, in a 'site' paradigm. For most sedimentary rocks, the Central Limit Theorem of the Calculus of Probabilities applied directly to principal magnetic components determined from individual samples justifies calculation of the mean magnetization direction in a 'one -tier' approach.

In high-resolution sedimentary paleomagnetic studies, this time-averaging effect may be informed by applying new paleomagnetic technologies, such as ultra-high resolution scanning SQuID microscopy (UHRSSM).

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) T D Raub Geology and Geophysics Department Yale University P. O. Box 208109 New Haven, CT 06520-8109 (b) 203-432-9808 (c) 203-432- 3134 (d) timothy.raub@yale.edu 4. yes - student

Report on Some Preliminary Attempts to Improve the on the Realism of Geodynamo Simulations

Paul H Roberts Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA90095-1567; ph. 210-206-2707; fax. 310-206-3051; e-mail: roberts@math.ucla.edu); John T Donald (Department of Mathematics, University of California, Los Angeles, CA 90095-1567; fax. 310-206-3051; e-mail: jdonald@math.ucla.edu

During the past decade, numerical simulations of the geodynamo have been published increasingly often. The character of the magnetic fields so created have generally been in encouraging agreement with what is known about the real magnetic field of the Earth. But there is a mystery: the agreement has been unreasonably good, bearing in mind the drastic simplifications that necessarily had to be made by the simulators. In particular, all simulations so far have seriously underestimated the effect of the Earth's rotation on the dynamics of the core, in its effect both on the numerically resolved scales of motion and on the unresolved scales. Results of preliminary attempts to eliminate this difficulty will be reported.

Chapman Conference on Timescales of the Geomagnetic Field Invited (a)
Paul H. Roberts, Institute of Geophysics and Planetary Physics, University of California, Los Angeles, CA90095-1567 (b) 210-206-2707 (c) 310-206-3051 (d) roberts@math.ucla.edu No

The Use of Quaternary Magnetostratigraphy in Long Distance Correlation and Depositional Processes

N Rutter Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB Canada T6J 2E3; ph. 780-492-3085; fax 780-492-2030; e-mail: nat.rutter@ualberta.ca); M E Evans (Institute for Geophysical Research, Physics Department, University of Alberta, Edmonton, AB Canada T6G 2J1; ph. 780-492-5517; fax 780-492-4256; e-mail: evans@phys.ualberta.ca

In collaboration with numerous colleagues, we are investigating and correlating Quaternary paleoclimatic records of long sequences of loess (eolian) deposits from many parts of the world. These include sequences in Argentina, United States, European Russia, Siberia and China. The most reliable region-to-region correlation tool has been magnetostratigraphy, following the seminal work of Shackleton and Opdyke (1973). Quaternary loess deposits clearly record the Brunhes, Matayuma and Gauss Chrons and the Jaramillo and Olduvai Subchrons. The presence or absence of these magnetic zones in each sequence has aided in the interpretation of the depositional and erosional patterns over wide areas. This is especially true in the Chinese Loess Plateau, where near-continuous records have been correlated to deep sea records expanding our understanding of terrestrial and oceanic processes. Magnetic susceptibility has been used in conjunction with magnetostratigraphy to establish the timing of hemispheric-wide climatic variations which has helped us to discern Milankovitch cyclicities corresponding to marine oxygen isotope stages. Efforts to exploit shorter timescale geomagnetic variability (excursions, secular variation) have generally been disappointing. It seems that remanence acquisition in loess is a lengthy process (on the order of 104 years). This tends to smooth out rapid fluctuations, but recent modeling results suggest that it can also generate artificial reversals.

Chapman Conference on Timescales of the Geomagnetic Field Contributed (a) N Rutter Department of Earth and Atmospheric Sciences University of Alberta, Edmonton, AB Canada T6J 2E3; (b) 780-492-3085; (c) 780-492-2030; (d) nat.rutter@ualberta.ca No

Deep-Tow Investigations of 'Tiny Wiggles' in the Western Pacific Jurassic "Quiet Zone"

William W. Sager Department of Oceanography, Texas A&M University, College Station, TX 77843; ph. 979-845-9828; fax 979-845-6331, wsager@ocean.tamu.edu; Maurice Tivey, Department of Geology & Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA02543; ph. 508-289-2265, fax 508-457-2023, mtivey@whoi.edu

The Jurassic "Quiet Zone" of the western Pacific is a region in which seafloor-spreading magnetic anomalies become progressively more subdued with increasing age, to the point that it is extremely difficult to correlate pre-M29 anomalies from sea surface data. It has been postulated that this trend indicates that the Jurassic magnetic field strength was significantly weaker than later, during the Cretaceous. In 1992, we investigated this phenomenon by collecting two long deep-tow magnetic profiles, extending ~600 km over seafloor older than M29, estimated to be as much as ~9 Ma older than this anomaly (Sager et al., JGR, 103, p. 4269, 1998). With the anomaly amplitudes increased by having the sensor nearer the magnetic source layer, it was possible to correlate many of the anomalies between the two tracks. All of the anomalies previously mapped via aircraft by Handschumacher et al. (Tectonophysics, 155, p. 365, 1988) were recognized, in addition to a number of older anomalies. Uncertainties for the deep-tow study were ambiguities arising from interpreting some anomalies that did not match from one profile to the other, and the fact that the profiles showed both large and small amplitude anomalies. The smallest anomalies ("tiny wiggles") have 50-75 nT amplitudes with wavelengths of a few km and are superimposed on larger fluctuations, with amplitudes of 100-200 nT and wavelengths of >50 km. Depending on whether the tiniest wiggles or the larger anomalies were modeled as field reversals, the resulting time scale differed in the number of pre-M29 reversals by a factor of two. Both models indicate rapid reversal rates in late Jurassic time with implications for unusual magnetic field behavior during the Jurassic. Although it was impossible to tell which magnetic model was best, we felt that the more conservative interpretation (fewer anomalies) was best and that the tiny wiggles probably resulted from paleofield intensity fluctuations, rather than reversals. Nevertheless, the possibility of extraordinary field behavior recorded in seafloor magnetic anomalies has made it possible to collect additional deep-tow data. During December 2002 and January 2003, we will collect new deep-tow lines to extend the prior lines past ODP Site 801 (where unusual magnetic behavior has been deduced from cored basalts), we will duplicate some of the previous lines to check anomaly correlations, and we will conduct small, dense surveys over Site 801 and another spot in the lineation sequence to investigate anomaly coherence and structure.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) W. W. Sager Department of Oceanography, Texas A&M University, College Station, TX 77843-3146, (b) 979-845-9828 (c) 979-845-6331 (d) wsager@ocean.tamu.edu 4. No

Polarity Record in the Klippen of Bhutans

E Schill Institute of Geophysics, ETH Zürich, CH-8093 Zürich; ph. #41-1-6333667; fax #41-1-6331065; e-mail: schill@mag.ig.erdw.ethz.ch); W Lowrie(Institute of Geophysics, ETH Zürich, CH-8093 Zürich; ph. #41-1-6332607; fax #41-1-6331065; e-mail: lowrie@mag.ig.erdw.ethz.ch

Continuous cooling of metasediments in the Tang Chu Klippe (central Bhutan) from metamorphic temperatures above 400 C causes a time-dependent remanence acquisition of thermal origin. Along a 640m vertical profile 5 sites from different altitudes have been investigated. Rock-magnetic analysis indicates pyrrhotite and magnetite as characteristic remanence carriers. Pyrrhotite unblocks between 195 C and 325 C revealing a well-grouped overall mean direction. During thermal demagnetization a polarity change is observed between 263 C and 290 C depending on the position on the profile. The magnetite component unblocks below 520 C and reveals either a normal or reverse polarity in the different sites. Intermediate directions are statistically not significant. Both unblocking and calculated blocking temperatures indicate one to three polarity records per sample. The evaluation of these polarity records in terms of thermo-magnetostratigraphy may have implications for the tectonic interpretation of paleomagnetic results based on secondary remanences. They allow accurate determination of the age of remanence acquisition as well as the high-resolution estimation of cooling rates.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) E Schill Institute of Geophysics ETH Zürich, CH-8093 Zürich (b) #41-1-6333667 (c)#41-1-6331065 (d) schill@mag.ig.erdw.ethz.ch 4. No

How Variable Was the Late Archaean Field?: Paleointensity and Paleomagnetism of the Stillwater Complex, MT

P A Selkin [*P A Selkin*] (Scripps Institution of Oceanography, La Jolla, CA, 92093-0220; ph. 858-822-4879; fax 858-534-0784; e-mail: pselkin@ucsd.edu) J S Gee (Scripps Institution of Oceanography, La Jolla, CA, 92093-0220; ph. 858-534-4707; fax 858-534-0784; e-mail: jsgee@popmail.ucsd.edu) W P Meurer (Department of Geosciences, University of Houston, Houston, TX 77204-5007; ph. 713-743-0214; fax 713-748-7906; e-mail: wpmeurer@mail.uh.edu)

Few reliable paleointensities exist from the Proterozoic and the Archaean eras, in spite of the high value of such data to paleomagnetists and geodynamo modelers. We present a large set of high-technical-quality Thellier paleointensity data from the Stillwater Complex, a 2700 Ma layered mafic intrusion on the northwestern edge of the Wyoming craton. We have sampled most of the Stillwater's igneous stratigraphy along several transects across the East Boulder Plateau, and have supplemented our field samples with drill core from the two adits of the Stillwater Mining Company. The characteristic remanences of these samples unblock over a discrete range of high temperatures: 550-580 degrees C for samples from the Upper Banded Series (UBS) near the top of the complex and 500-560 degrees C for Ultramafic and Lower Banded Series (UM/LBS) samples near the bottom of the intrusion. The mean direction of the UBS characteristic component is 070/-58 (geographic coordinates), corresponding to a tilt-corrected inclination of ~70 degrees. There is also a lower-temperature (500-550 degrees C) overprint in the Middle and UBS with mean direction 113/-61, corresponding to a tilt-corrected inclination of ~30 degrees. UBS paleointensities from the high-temperature component range from 28 to 60 microT. UM/LBS paleointensities are substantially lower, ranging from 4 to 6 microT. We estimate the variability in direction and intensity of the Archaean geomagnetic field using these data and thermal models.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Poster 3. (a) P A Selkin, Scripps Institution of Oceanography, Mail Code 0220, La Jolla, CA, 92093-0220 (b) 858-822-4879 (c) 858-534-0784 (d) pselkin@ucsd.edu 4. Yes

An 40Ar/39Ar Based Geomagnetic Instability Timescale (GITS) for the Brunhes and Matuyama Chrons

B S Singer Department of Geology and Geophysics, University of Wisconsin-Madison, WI 53706; ph. 608-265-8650; fax 608-262-0693; e-mail: bsinger@geology.wisc.edu; K A Hoffman (Physics Department, California Polytechnic State University, San Luis Obispo, California 93407; ph. 805 756-1357; fax 805 756-2435; e-mail: khoffman@calpoly.edu

Using modern 40Ar/39Ar incremental heating techniques we have obtained high precision ages for transitionally magnetized lava flows in several volcanic sequences distributed about the globe. Radioisotopically dated periods of geomagnetic instability include: (1) short excursions of the field when VGPs approach or cross the equator, (2) brief periods of opposing polarity bounded by full reversals, or (3) full reversals that define Chron or Subchron boundaries. The timing of the Punaruu Event (1120 ± 10 ka; ± 2 sigma), the onset and termination of the Jaramillo Subchron (1068 ± 12 ka and 1001 ± 10 ka), the Santa Rosa Event (936 ± 8 ka), the Kamikatsura Event (900 ± 5 ka), the Matuyama-Brunhes reversal (798 to 776 ka), and the Big Lost Event (579 ± 8 ka) provide the initial calibration points of a new time scale for the Matuyama and Brunhes Chrons. These transitional periods recorded in lavas, as well as many others that are not yet 40Ar/39Ar dated, have been correlated with directional changes or paleointensity lows in high sedimentation rate marine sediment cores. We hesitate to include lavas dated at 822 ± 9 ka that possess weakly transitional VGPs over southern Africa prior to the Matuyama-Brunhes reversal in the compilation, thereby highlighting the need to develop criteria by which periods of instability may be distinguished from normal secular variation. Notwithstanding, we contend that an accurate geochronology of reversals and events, together with a detailed accounting of paleomagnetic field behavior, are critical to a complete understanding of geomagnetic processes, and may provide important input regarding the dynamics of Earth's interior from the mantle on down. For example, Gubbins [1999] claimed that the occurrence of excursions 10 times more frequently than reversals–consistent with our dating results thus far-- may reflect the probability of exceeding the characteristic time required to diffuse the magnetic field from the outer vs. the inner core. Moreover, numerical simulations of the geodynamo [Glatzmaeir et al., 1999] that impose various heat flux patterns at the core-mantle boundary also spontaneously generate a variable number of excursions and reversals over several hundred thousand year periods that can be evaluated against our observations. We thus propose that a Geomagnetic Instability Timescale (GITS) be pursued on the basis of a more systematic and rigorous characterization of both the known and

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) B S Singer, Department of Geology and Geophysics, University of Wisconsin-Madison, WI 53706 (b) 805-608-265-8650 (c) 608-262-0693 (d) bsinger@geology.wisc.edu 4. No

suspected geomagnetic instabilities of the past several million years. The GITS will be of great value to advancing not only geodynamo theory and testing future numerical simulations, but also to quantifying the next generation of stratigraphic, paleoclimatic and oceanographic studies founded upon the global marine sediment record. Finally, a note of caution: The 40Ar/39Ar ages reported above are calculated relative to those of standard minerals based on a recent intercalibration of several standards that resulted in an age of the Fish Canyon Tuff sanidine of 28.02 Ma which is 1% older than the standard values used in the Cande and Kent [1995] GPTS. It is important to note which standard ages are used in each study that involves 40Ar/39Ar dating and, where appropriate, to normalize ages to a common standard value.

Ultra-Fast Geomagnetic Field Reversals in the mid-Jurassic: ~10,000-yr Polarity Intervals Recorded by Jurassic Quiet Zone Crust

Maureen Bernice Steiner Maureen Bernice Steiner (Department of Geology & Geophysics, University of Wyoming, Laramie, WY 82071; ph. 307-766-6584; fax 307-766-6679; e-mail: magnetic@uwyo.edu)

The remanent magnetizations of tholeiitic basalt of the Jurassic Quiet Zone (JQZ) crust indicate that the Jurassic Quiet Zone is "quiet" because of exceedingly rapid reversals of the geomagnetic field. The remanent magnetic signature of 400 meters of tholeiite displays six changes of the geomagnetic field polarity. In addition, quasi-continuous changes of inclinations exist between polarity intervals. Several possibly aborted reversals also are suggested within polarity intervals. Petrologic, petrographic, and rock magnetic investigations all indicate that the Jurassic oceanic crust is extraordinary unaltered and well preserved; these basalts contain typical MORB titanomagnetites, consistent with their petrological definition as N-MORB tholeiites. This 400 m record represents the magnetic signature of most of oceanic Layer 2A. Spreading rates extrapolated from nearby anomalies (15-16 cm/yr) and recent seismic estimates that the whole of Layer 2A of the East Pacific Rise is constructed of within 1-3 km spreading off the rise crest, implies durations of 2500 to 9500 years for these mid-Jurassic (~170 Ma) geomagnetic polarity intervals. Assuming a constant spreading rate for the during the duration of the Jurassic Quiet Zone, the width of sea-floor with this extant magnetic signature suggests that this ultra-fast reversal behavior of the geomagnetic

field was sustained for a minimum of 15 m.y.; Jurassic magnetostratigraphy suggests that the rate may have endured for twice that time interval.

1. Chapman Conference on Timescales of the Geomagnetic field 2. Contributed 3. (a) Maureen B. Steiner Department of Geology & Geophysics, University of Wyoming, Laramie, WY 82071 (b) 307-766-6584 (c) 307-766-6679 (d) magnetic@uwyo.edu 4. No

A Pilot Paleointensity Study of 19th and 20th Century Bricks from the New York City Area

Rob Sternberg Department of Geosciences, Franklin & Marshall College, Lancaster, PA 17604-3003; ph. 717-291-4134; fax 717-291-4186; e-mail: Rob.Sternberg@FandM.edu); Allan S Gilbert (Department of Sociology and Anthropology, Fordham University, Bronx, NY 10458; ph. 718-817-3854; fax 718-817- 3846; e-mail: Gilbert@Fordham.edu); Stephen Crabtree (Department of Geosciences, Franklin & Marshall College, Lancaster, PA 17604-3003; ph. 717-291-4133; fax 717- 291-4186; e-mail: Stephen.Crabtree@FandM.edu

Secular variation observations from historic times can be supplemented by archaeomagnetic data. This potentially rich source of information has not been tapped in North America. A pilot paleointensity study was done using six bricks fired in the New York city area between 1840 and 1926. Three samples from each brick were cut into 2-cm cubes, oriented relative to each other, and used for the Coe version of the Thellier-Thellier double heating paleointensity experiment. One yellow brick with low iron content had aberrant magnetic properties, did not yield an interpretable paleointensity, and will not be considered further below. For the other samples, NRMs varied from 2.2-16 A/m. NRM directions were stable upon thermal demagnetization. Median destructive temperatures ranged from 240- 330 degrees. Loss on ignition was as high as 10%. Room temperature susceptibilities increased above 350 degrees by 10-40%, and repeat pTRMs also increased above 300 degrees. Four bricks had three samples with consistent paleointensities; the fifth brick had one aberrant result. Quality

factors varied from 24-81. One brick gave paleointensity results consistent with British Geological Survey secular variation models, but the other four bricks gave results 5-15% too low. Results were not corrected for fabric anisotropy (assumed to be low) or cooling rate, which was 20 minutes in the lab, and likely several days in the field. Aitken et al. (1987) suggested that self-demagnetizing effects were responsible for low archaeointensities from strongly magnetized samples from a historic kiln; we will explore that possibility further for our samples.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. POSTER 3a. Rob Sternberg, Department of Geosciences, Franklin & Marshall College, Lancaster, PA 17604-3003 3b. 717-291-4134 3c. 717-291-4186 3d. Rob.Sternberg@FandM.edu 4. No

Paleosecular Variation of the Geomagnetic Field in Alaska: The Aleutians Islands and Wrangell Mountains Revisited

D.B.Stone P.W.Layer, (Geophysical Institute, University of Alaska, Fairbanks, Ak 99725; fax. 907-474-5163, ph. (DBS) 907-474-7622, ph. (PWL) 907-474-5514, e-mail: dstone@gi.alaska.edu; player@gi.alaska.edu)

Two studies were undertaken in the late 1960s to investigate paleosecular variations in the geomagnetic field as recorded in volcanic rocks. One was in the Aleutian Islands, and the other in the Wrangel Mountains. The results were internally consistent, but to be wholly credible by today's standards, further demagnetization, including thermal demagnetization was needed. We have used the duplicate samples from the original collections and applied complete thermal demagnetization protocols.

The Aleutian samples are from six sequences of volcanic flows, two with ages of about 2 Ma, and the other four within the Bruhnes chron. The results are generally similar to those obtained earlier, but show somewhat lower angular dispersions for the Virtual Geomagnetic Poles (VGP). With the exception of the only reversely magnetized site (Ashishik Point, about 2Ma) all sites give lower angular dispersions than those predicted by Secular Variation models for their present day latitudes. Several show clear patterns of clumped and sequential VGP positions. A possible interpretation of the low dispersion and sequential poles is that the time represented by the flows is short, and that the clumps represent flows erupted in quick succession. The available radiometric ages for the individual sections, using both K-Ar and 40Ar/39Ar methods

indicate time spans from about 400,000 years (Driftwood Bay) to less than a few thousand years (Crater Creek). In all sections there are significant rubble beds between the flows that argues against an extremely short time-span for the sequence of lava flows to be erupted. The alpha 95 confidence limits for the mean VGPs include the geographic pole for all four of the younger sections with the mean VGPs for the 2 Ma sections being displaced by less than 10 degrees. The mean of all flows from all sections is within 2 degrees of the geographic pole.

For the Wrangell Mountains study a sequence of 21 flows was sampled. The age of the sequence based on K-Ar determinations is 3.5 Ma, and 40Ar/39Ar ages are pending. The five lowermost flows give very dispersed VGPs, including three with negative magnetic inclinations. Although these flows appear to be stratigraphicaly conformable with the flows higher in the sequence, it is possible that they represent an earlier volcanic episode. The next twelve flows are

1. Chapman conference on Timescales of the Geomagnetic Field
2. contributed 3. (a) D.B.Stone, Geophysical Institute, University of Alaska, Fairbanks, 99775-7320 (b) 907-474-7622 (c) 907-474-5163 (d) dstone@gi.alaska.edu 4. No

more or less evenly distributed in space within a section covering an altitude change of about 200m. These flows give a tightly grouped set of VGPs with an angular deviation of less than 6 degrees and a mean pole at about 40 degrees north latitude. The next four flows give VGPs that trend directly towards geographic north reaching a latutude of 66 degrees. Ancient horizontal is well determined from sediments deposited between the flows, and in small ponds subsequently covered by new lava flows. At face value, the small dispersion of the VGPs would indicate a stable field during the excursion, but could also be due to very rapid extrusion of the flows. We are trying to address this latter problem with more Argon-Argon dating.

Timescales of Variability of the Geomagnetic Field: New Constraints From High Resolution Continental Margin Sediments

4. No

J. S. Stoner INSTAAR, University of Colorado, Boulder CO 80309 USA; ph: 303 492-7641, email: joseph.stoner@colorado.edu); G. St-Onge (GEOTOP-UQAM & McGill, Montreal Quebec H3C 3P8 Canada; email: d363574@er.uqam.ca); S. P. Lund (Department of Earth Sciences, University of Southern California, Los Angeles, CA 90089 USA; email: slund@usc.edu) J. T. Andrews (INSTAAR, University of Colorado, Boulder CO 80309 USA; email: andrewsj@colorado.edu); F. Lamy (Fachbereich Geowissenschaften, Universitaet Bremen, Bremen, Germany; email: flamy@uni-bremen.de) J. E. T. Channell (Department of Geological Sciences, University of Florida, Gainesville, FL 32611 USA; email: jetc@nersp.nerdc.ufl.edu) J. F. McManus (Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543 USA; email: jmcmanus@whoi.edu

Ocean Drilling Program Leg 202 Shipboard Scientific Party

To understand the outer core dynamics involved in the geomagnetic field generation process it is necessary to document the fundamental timescales of field variability over a range of spatial scales. Recent observations made possible through high resolution data acquisition from pass-through magnetometers (on both u-channel and half round samples), coring of continental margin sedimentary environments with high accumulation rates (often greater than 1 m /kyr) and high-quality chronostratigraphic control are providing new constrains on the temporal variability of the geomagnetic field. Here we present data from three continent margin locations (St. Lawrence Estuary MD99-2220 - Lat. 48.38 N, Long. 68.37 W, water depth 320 m; North Iceland Shelf MD99-2269 - Lat: 66.13 N, Long. 23.15 W, water depth 106 m; and Southern Chilean Margin ODP Site 1233 [Leg 202]- Lat. 41.0 S, 74.26 W, water depth 838 m) that provide new observations from high-accumulation rate archives. Holocene relative paleointensity (RPI) proxies from MD99-2220 compare favorably with RPI records from North America and Europe at millennial and even centennial timescales. MD99-2220 RPI proxies can be matched to the 10Be flux record from the Greenland Summit (GISP2) ice core and to a smoothed 14C production rate record implying that the RPI record reflects millennial scale changes in the global-scale geomagnetic field. The Late Pleistocene RPI record from ODP Site 1233, derived from shipboard normalized remanence, can be correlated to the highest resolution sedimentary RPI and cosmogenic isotope records suggesting that the millennial scale content of this record reflects global-scale changes of the geomagnetic field. New directional record, specifically declination, from cores MD99-2220 and MD99-2269 are coherence 1. Chapman Conference on Timescales of the Geomagnetic Field 2. CONTRIBUTED 3a. Joseph S. Stoner, INSTAAR, University of Colorado, Campus Box 0450, Boulder, CO 80309-0450 3b. 303 492 7641 3c. 303 492 6388 3d. joseph.stoner@colorado.edu with lake records from North American and European and vary at millennial timescales similar to those observed from the RPI records.

Strata Bound Reversal Stratigraphy in the Middle and Upper Semri Group of the Lower Vindhyanchal Basin (India): Preliminary Paleomagnetic Results

E. Tamrat Department of Geological Sciences, University of Florida, 241 Williamson Hall, Gainesville, FL 32611; ph. 352-846-3710; fax 352-392-9294; e-mail: endale@geology.ufl.edu); J. Meert, L. Sohl, R. Tucker, D. Banerjee and M. Pandit

The Lower Vindhyanchal basin (Semri Group) in India preserves a sequence of sedimentary and volcanic ashfall deposits that formed in the interval from 1800 to 1200 Ma. This sequence includes a 2500 meter section of strata that were deposited in the 45 million year interval from ~1630-1590 Ma. Paleomagnetic samples are collected from two sequences of Lower Vindhyanchal Basin of peninsular India, Eastern Son Valley (Mirzapur, Deonar, Kheinjua and Rohtas Groups) and Rajasthan (Satola, Sand, Lasrawan and Khorip Groups), respectively. Our preliminary paleomagnetic data show strata bound series of normal and reverse polarity directions observed within the Lower part of the Semri groups (Mirzapur-Satola Groups through the lower Kheinjua-Lasrawan Groups). In the upper part of the Semri Group (Rohtasgarh Limestone, Son Valley and the Nimbahera-Suket Limestone at Rajasthan) we also observe a strata bound reversal stratigraphy.

The preliminary paleomagnetic data also suggest that this part of peninsular India occupied intermediate latitudes (~45 degrees) during the onset of Vindhyan sedimentation (~1800 Ma) and then drifted to lower latitudes during Middle Semri time (1630 Ma). Data from the uppermost Semri Group indicate that India moved to high paleolatitudes (~60-70 degrees) at around 1200-1400 Ma. This suggests either a period of rapid motion during the interval from the end of Kheinjua (Middle Semri) deposition into the Rohtas-Khorip (Upper Semri) time or a hiatus in sedimentation between these Groups.

1. Chapman Conference on Timescales of the Geomagnetic Field
2. Contributed 3. (a) E. Tamrat Department of Geological Sciences, University of Florida, 241 Williamson Hall, Gainesville, FL 32611; (b) ph. 352-846-3710; (c) fax 352-392-9294; (d) endale@geology.ufl.edu

4. No

The Long-term Nature of the Geodynamo Based on Coupled Analyses of Paleointensity and Paleosecular Variation

John A. Tarduno Rory D. Cottrell and Alexei V. Smirnov (Department of Earth and Environmental Sciences, University of Rochester, Rochester, N.Y. 14627, tel. 585-275-5713, fax. 585-244-5689, e-mail john@earth.rochester.edu)

To gain a complete picture of the long-term nature of the geodynamo we must characterize the morphology, secular variation and intensity of the field versus reversal frequency. Fortunately, magnetic polarity stratigraphy, as pioneered by Neil Opdyke in the 1960's, has led to a robust geomagnetic polarity timescale from which we can select study intervals during which reversals were relatively more or less common.

Arguably the most reliable way to determine the past strength of the magnetic field is the Thellier technique whereby igneous rocks are subjected to a stepwise progression of paired heating steps. Unfortunately, many whole rock samples are unsuitable for Thellier analysis. One complicating factor is the growth of new magnetic minerals associated with the thermal alteration of clays (which are ubiquitous in pre-Quaternary whole rock samples) during Thellier experiments. Hence, this geologic (and associated experimental) alteration often prohibits the simultaneous definition of past field directions and intensities.

We have developed an approach for the determination of paleointensity that uses single plagioclase crystals separated from mafic igneous rocks. These crystals contain magnetic inclusions which are less affected by experimental alteration and thus may allow us to overcome the obstacles described above. Transmission electron microscopy and a host of rock magnetic methods reveal that these crystals contain small single to pseudo-single domain, equant to slightly elongated magnetic inclusions (50 to 250 nm). In a test of the method, Thellier analyses of plagioclase crystals from a modern lava flow yielded an intensity that agreed with that recorded by magnetic observatories. Here we discuss applications of the method to the nature of the geomagnetic field during superchrons and that of the early Earth.

If relationships exist between the frequency of geomagnetic reversals and the other basic characteristics of the field, they should be well expressed during superchrons, intervals tens of millions of years long lacking reversals. We have been studying secular variation (recorded by whole rock samples) and paleointensity (recorded by single plagioclase crystals) from Arctic lavas of the Cretaceous Normal Polarity Superchron that formed on the North American craton near the 1. Chapman Conference on Timescales of the Geomagnetic Field 2. INVITED 3a. Corresponding address: John A. Tarduno, Department of Earth and Environmental Sciences, 227 Hutchison Hall, University of Rochester, Rochester, NY, 14627 3b. Corresponding author's telephone number: 585-275-5713 3c. 585-244-5685 3d. john@earth.rochester.edu

tangent cylinder (that imaginary cylinder about the rotation axis that is tangent to the solid inner core). These data suggest a time-averaged field that is remarkably strong and stable.

The Arctic directional data, when combined with data from lower latitude North American sites, provides an opportunity to examine the geometry of the field (thus touching on another major contribution of Neil Opdyke). These North American data define a time-averaged field that is overwhelmingly dominated by the axial dipole (octupole components are insignificant). This conclusion is also supported by a consideration of global high-resolution paleosecular variation studies. These observations suggest that the basic features of the geomagnetic field are intrinsically related. Superchrons may reflect times when the nature of core-mantle heat flux allows the geodynamo to operate at peak efficiency, as suggested in some numerical models.

On even longer time scales, paleointensity data from Proterozoic-Archean rocks are of interest as this interval brackets the time suggested in some models for the initiation of inner core growth. We have been investigating this interval through Thellier analyses of plagioclase separated from mafic dikes. Although our results to date are unlikely to adequately represent the time-averaged field, the mean and range of values is similar to that of the present-day field. These values suggest that the inner core, which may stabilize the geodynamo, had started to grow by Early Proterozoic times (~2.45

Ga).

Strength of the Geomagnetic Field in the Cretaceous Normal Superchron: New Data from Submarine Basaltic Glass of the Troodos Ophiolite

L Tauxe Scripps Institution of Oceanography, University of California, San Diego, CA 92093-0220; ph. 858-534-6084; fax 858-534-0784; e-mail: ltauxe@ucsd.edu); H Staudigel (Scripps Institution of Oceanography, University of California, San Diego, CA 92093-0225; ph. 858-534-8764; hstaudigel@ucsd.edu

After decades of effort, much is known about the behavior of the geomagnetic field. We know that the frequency of reversals has changed profoundly through time from periods of frequent reversals (as for the 50 million years) to periods of no reversals for 40 or more million years (as in the mid-Cretaceous and Permian). We also know that when the field reverses, its strength drops dramatically. We do not know what causes reversals or what inhibits them, although numerical simulations have provided some tantalizing hints (e.g., Glatzmaier et al. Nature, 401, 885, 1999). The observation that reversals are associated with low field strength has long led to the suggestion that low fields are a precondition for reversal and that a high average field strength would inhibit the reversal process. It is reasonable therefore to hypothesize that periods of no reversals had high average field intensities. The data, however, are scarce. The published record includes constraints from fewer than two dozen specimens that meet the minimum criteria of internal consistency (e.g., Selkin and Tauxe, Phil. Trans., R. Soc. Lond., A, 358, 1065, 2000). We will present new paleointensity data from over 300 specimens from 77 sites obtained from submarine basaltic

glasses collected from the Troodos Ophiolite (~92 Ma). About half meet the strictest standards; 22 sites having from 2 to 6 specimens meet the criteria of Selkin and Tauxe (2000) and have reasonable within site standard deviations. These yield a grand mean of 33 +/- 17 microtesla suggesting a dipole strength equivalent to the present field. Whether this is considered "high" depends on what is taken as average. Following, for example, Selkin and Tauxe (2000), we believe that the present field is nearly twice the average; hence the field at 92 Ma was "high", although not as high as argued by Tarduno et al. (Science, 291, 1779, 2001) based on a much smaller data set.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Invited 3. (a) J S Smith Department of Geology University of California Santa Barbara, CA 93106-3060 (b) 805-893-2309 (c) 805-893-2578 (d) imfirst@crseo.ucsb.edu (a) L Tauxe Scripps Institution of Oceanography, University of California, San Diego, CA 92093-0220 (b) 858-534-6084 9c) 858-534-0784; e-mail: ltauxe@ucsd.edu); 4. No

Geomagnetic Moment Variation and Excursions Since 400 ka BP: Paleomagnetic and Authigenic 10Be/9Be Sedimentary Records from the Portuguese Margin

N. Thouveny CEREGE, Europôle Méditerranéen de l'Arbois, BP 80, Aix en Provence, cedex 4, France, ph: 33 442 97 15 58, email: thouveny@cerege.fr); J. Carcaillet (carcaillet@cerege.fr), D. L. Bourlès (bourles@cerege.fr), Eva Moreno (Moreno@ingv.it

A paleomagnetic study was performed along several parallel cores collected in clayey-carbonate sedimentary sequences deposited over the last 3 climatic cycles in area of high accumulation rate of the Portuguese margin. The stable magnetization of depositional origin is carried by pseudo-single and small multidomain titano-magnetites. A high resolution continuous proxy-record of variations of direction and intensity of the geomagnetic field documents over the last 400 ka a regime of paleosecular variation interrupted by numerous episodes of weak relative paleointensity often accompanied by strong deviations of paleomagnetic directions. Among these features, three are assignable to well-known excursions or events (Laschamps, Blake, Jamaica/Pringle falls), four confirm the occurrence of excursions recently reported (Icelandic basin, Calabrian ridge 0 and 1, Levantine) and three suggest the occurrence of other excursions at 95, 240 and 290 ka BP. Most of these paleointensity lows and accompanying excursions are recorded at the times of d18O interglacial or interstadial stages. A detailed investigation of authigenic 10Be/9Be variations was performed along along the same cores. Authigenic 10Be/9Be ratio variation is the most reliable proxy of cosmonuclide production variation which is over such time scales- primarily driven by variation of the strength of the magnetosphere, itself modulated by variation of the geomagnetic moment. The phases of significant authigenic 10Be/9Be enhancement support the paleomagnetic evidences of geomagnetic moment drops associated with global scale paleomagnetic excursions. The lack of significant delays in the authigenic 10Be/9Be signal in recording dipole moment variations allows a more accurate timing of dipole moment lows. 10Be/9Be data confirm the preferential occurrences of dipole moment lows during or at the end of interglacial episodes, with a quasi-period of 100 ka.

1. Title: Chapman Conference on Timescales of the Geomagnetic Field 2. CONTRIBUTED 3a. Corresponding address: Thouveny CEREGE, Europôle Méditerranéen de l'Arbois, BP 80, 13545 Aix en Provence, France; 3b. 33 4 42 97 15 58 3c. 33 4 42 97 15 90 3d. thouveny@cerege.fr

A Comparison of Hotspot and Palaeomagnetic frames (0-95 Ma) and Estimates of non-dipole Fields

Trond H. Torsvik Geological Survey of Norway, Leiv Eiriksonsvei 39, N-7491 Trondheim, Norway; phone 47 73904411; trond.torsvik@ngu.no <mailto:trond.torsvik@ngu.no>); Rob Van der Voo (Dept. Geological Sciences, University of Michigan, Ann Arbor, MI. 48109-1063, USA; e-mail voo@umich.edu

In the Indo-Atlantic realm, hotspots have remained relatively stationary with respect to the spin axis for the last 95 million years. However, small but systematic discrepancies (c. 5o) between Late Cretaceous and Tertiary fixed hotspot and paleomagnetic reference frames can be interpreted as the result of plume drift within a convective mantle, non-dipole field contributions or a combination of these causes. In order to test for non-dipole fields we recalculated all paleomagnetic poles (globally) with different non-dipole field contributions (2 to 16%), calculated new APW paths and rotated the new mean poles into the fixed hotspot frame. An octupole contribution of 10% yields the lowest discrepancy (3.1 ± 2.1o) for the last 95 million years. We also tested the palaeomagnetic data against mantle models for the last 65 Ma, and Mantle-Model 2 produces the best fit (2.6 ± 1.8o). Comparing the paleomagnetic and fixed hotspot frame over the 95 Ma range shows that a mean octupole field contribution of 10% uniformly improves the Tertiary record whilst the Cretaceous section shows a worse fit. The latter may imply that octupole field contributions vary with time.

1. Chapman conference on Timescales of the Geomagnetic Field
2. Invited by J. E. T. Channell 3. (a) Trond H. Torsvik, Geological Survey of Norway, Leiv Eiriksonsvei 39, N-7491 Trondheim, Norway (b) 47 73904411 (c) 47 73921620 (d) trond.torsvik@ngu.no
4. No

Long-term Phanerozoic Octupole Fields

Rob Van der Voo Dept. Geological Sciences, University of Michigan, Ann Arbor, MI. 48109-1063, USA, phone 734-764-8322, fax 734-763-4690, e-mail voo@umich.edu); Trond H. Torsvik (Geological Survey of Norway, Leiv Eiriksonsvei 39, N-7491 Trondheim, Norway; trond.torsvik@ngu.no

The assumption that the ancient geomagnetic was purely dipolar is fundamental to paleomagnetism. However, one sign that something may be amiss is that observed inclinations at mid-latitudes are often lower than expected. A zonal octupole field in the late Paleozoic, Mesozoic and Early Tertiary was revealed by comparing the observed paleomagnetic paleolatitude distributions for Laurussia (North America, Greenland, and Europe) with those predicted from the mean paleopoles. When only volcanics are analyzed, the pattern remains unchanged, indicating that inclination error in sediments is not the culprit. Estimates of the magnitude of the octupole/dipole field ratio center around 0.1, which could cause errors in conventional paleopoles of about 7.5 degrees; because of the antisymmetry of octupole fields a comparison of paleomagnetic poles from mid-northern and mid-southern hemisphere locations could thus be off by as much as 15 degrees. The well-known misfit between the paleomagnetic results from the Laurentia-European and Gondwana continents in a classical Pangea A configuration could be explained by such errors due to octupole fields. This explanation would negate the need to seek tectonic (Pangea B type) solutions for the misfit. Another misfit based on too-low inclinations is seen in a comparison of Central Asian

poles with those for the Eurasian reference path, and here as well do octupole fields provide a possible solution, although sedimentary inclination shallowing is another possibility. When including Pre-Permian poles for Gondwana in a similar test for non-dipole fields, an increase in the percentage octupole contribution is suggested for older times. Undoubtedly, the octupole field contributions have varied in magnitude over shorter time scales as well.

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2. Invited by J. E. T. Channell 3. (a) Rob Van der Voo Dept. Geological Sciences, University of Michigan, Ann Arbor, MI. 48109-1063 (b) 734-764-8322 (c) 734-763-4690 (d) voo@umich.edu
4. No

Towards a Continuous Record of Earth Magnetic Field Reversals by Secondary Pyrrhotite pTRMs

F Wehland Institute of Geoscience, University of T¨¹bingen, 72074 T¨¹bingen, Germany; phone: ++49-7071-2974698; fax: ++49-7071-295842; e-mail:florian.wehland@uni-tuebingen.de);U Alt-Epping(Institute of Geoscience, University of T¨¹bingen, 72074 T¨¹bingen, Germany; phone: ++49-7071-2978931; fax: ++49-7071-295842; e-mail:ulrich.alt-epping@student.uni-tuebingen.de); S Braun(Institute of Geoscience, University of T¨¹bingen, 72074 T¨¹bingen, Germany; phone: ++49-7071-2978931; fax: ++49-7071-295842; e-mail:steffi.braun@student.uni-tuebingen.de); C Crouzet(Institute of Geoscience, University of T¨¹bingen, 72074 T¨¹bingen, Germany; phone: ++49-7071- 2978931; fax: ++49-7071-295842; e-mail:christian.crouzet@uni-tuebingen.de); E Appel(Institute of Geoscience, University of T¨¹bingen, 72074 T¨¹bingen, Germany; phone: ++49-7071-2974132; fax: ++49-7071-295842; e- mail:erwin.appel@uni-tuebingen.de

Partial Thermoremanent Magnetisations (pTRMs) by secondary pyrrhotite, recorded during fast cooling in contact metamorphic limestone, were used for the first time to test the ability of recording Earth Magnetic Field (EMF) Reversals within a single sample. For this propose, samples from marly limestones were taken in the vicinity of intrusions from the Tethyan Himalaya (Manaslu), Elba Island, Toscany and the Isle of Skye. For each location pyrrhotite was identified by the unblocking spectra of the NRM and the thermal demagnetisation of IRM. Thellier-Thellier-tests of a

laboratory TRMs incl. MD checks have proven that pyrrhotite particles are predominantly in the SD range and, therefore, are able to record independent pTRMs. Additionally FORC analysis have shown that the magnetic particles do not interact. In selected sites from Elba Island thermal demagnetisation of the NRM reveals a reversed low temperature (150¡ãC-250¡ãC) and a normal high temperature (290¡ãC-320¡ãC) component. The two components include an angle of ~150¡ã and are linked by a gradual transition over an average temperature range of ~40¡ãC. Positive fold tests on the low (k = 10.2 ; |Á95 = 11.0) and the high temperature component (k = 20.4 ; |Á95= 8.4) evidence that the NRM is a TRM. A scenario where the low temperature component is caused by a second heating event is unlikely due to the gradual transition of the NRM and the lack of evidence for a multiple intrusion. An estimation of the time enveloped in the transitional temperature range retrieved by thermal modelling of the contact metamorphism lies at 10000 yr. This time span is comparable with an average value for EMF reversals.

1.Chapman Conference on Timescales of the Geomagnetic Field 2.Contributed 3.(a)F Wehland Institute of Geoscience University of T¨¹bingen 72074 T¨¹bingen, Germany(b)0049-7071-2974698(c)0049-7071-295842(d)florian.wehland@uni- tuebingen.de 4.Yes

Possible Overestimation of Absolute Paleointensity Data for the Last 5 Ma

Y Yamamoto Institute for Marine Resources and Environment, Geological Survey of Japan, AIST, Tsukuba 305-8567, Japan; ph. +81-298-61-3596; fax +81-298-61-3589; e-mail: yuhji-yamamoto@aist.go.jp

To recover the ancient geomagnetic field, absolute paleointensity determinations play an important role. Among several determination methods, the Thellier method with pTRM check (Thellier and Thellier, 1959; Coe, 1967) is regarded as the most reliable (e.g. Juarez and Tauxe, 2000; Selkin and Tauxe, 2000). However, this method sometimes failed accurate determinations from historical lavas (e.g. Calvo et al., 2002; Tanaka and Kono, 1991; Yamamoto et al., in press). Usual selection criteria (e.g. N>=4; q >=5; N: number of data points; q: quality factor by Coe et al. (1978)) could not discriminate inappropriate paleointensities in these studies.

For example, the Hawaiian 1960 lava yielded systematic high paleointensities up to about twice as large as the expected by the Thellier method (Yamamoto et al., in press), resulting in a mean of 49.0 +/- 9.6 micro-T (expected intensity is 36.2 micro-T, DGRF 1965). Such ones had also been observed in Tanaka and Kono (1991) and Hill and Shaw (2000). They suggested that one of the possible causes was NRM (natural remanent magnetization) of non-TRM (thermoremanent magnetization) origin.

These phenomena seem to be occurred not only in the present Hawaiian 1960 lava but also in the older Hawaiian lavas. This is because thermomagnetic properties of the pre-

historic Hawaiian lavas (e.g. last 420 kyr, Laj and Kissel, 1999) resembled those of the 1960 lava, which are characterized by a single magnetic phase with low Ti titanomagnetites. To examine this aspect, we selected the last 0.3-5 Ma Thellier data with non-transitional polarities from the latest absolute paleointensity database ("Montpellier 2002 database"; Perrin, 2002), and calculated average VADMs (virtual axial dipole moments) separately for the Hawaiian data and the non-Hawaiian data. The reasons why we choose this time span are that (1) data for the last 0.3 Ma and those for 0.3-5 Ma seem to belong to different parent populations (Juarez and Tauxe, 2000; Selkin and Tauxe, 2000) and that (2) this span is important to know recent geomagnetic field behaviors.

The selected data are further subjected to statistical criteria as follows; (1) each mean paleointensity is determined from more than 3 individual results; (2) its standard deviation is less than 20% of the 1. Chapman Conference on Timescales of the Geomagnetic Field 2. POSTER 3. (a) Y Yamamoto, Institute for Marine Resources and Environment, Geological Survey of Japan, AIST, Tsukuba 305-8567, Japan (b) +81-298-61-3596 (c) +81-298-61-3589 (d) yuhji-yamamoto@aist.go.jp 4. No

mean. As a result, average VADMs for 0.3-5 Ma are calculated to be 8.81 +/- 2.42 x 10^22 Am^2 (N=91) for the Hawaiian data while 6.70 +/- 3.02 x 10^22 Am^2 (N=108) for the non-Hawaiian ones. This significant difference indicates that there may be a number of misread paleointensity data which are originated from pre-historic Hawaiian volcanic rocks with NRMs of non-TRM origin, though time coverage of both data set somewhat differ each other.

This non-Hawaiian average VADM is, however, still about twice as large as a recently reported mean VADM of 3.63 +/- 1.95 x 10^22 Am^2 (N=26) for the last 5 Ma which obtained from the Society volcanic rocks by the LTD-DHT Shaw method with same statistical criteria (Yamamoto et al., 2002 AGU Fall Meeting). Since the LTD-DHT Shaw method successfully yielded appropriate mean paleointensity for the Hawaiian 1960 lava while the Thellier method did not (Yamamoto et al., in press), there is a still possibility of overestimation even in the non-Hawaiian data.

Persistent Non-dipole Components and Intensity-Inclination Correlation

T Yamazaki Geological Survey of Japan, AIST, Tsukuba, Japan 305-8567; ph. +81-298-61-2414; fax +81-298-61-3589; e-mail: toshi-yamazaki@aist.go.jp); H. Oda (GSJ, AIST, also Utrecht University, 3584 CD Utrecht, The Netherlands; ph. +31-30-253-1672; fax +31-30-253-1677; e-mail: h.oda@geo.uu.nl

It is well known that persistent non-dipole components occur in the time-averaged field. At least within the last few million years, they are dominated by the quadrupole term, and this component changes its sign in accordance with the reversals of the main dipole field. On marine sediment cores, they are observed as inclination anomaly (delta-I), which is defined as observed inclination minus the expected inclination from GAD. In low latitudes, delta-I is negative in Brunhes and positive in Matuyama in general, but there may be significant spacial variations as suggested by records from the North Fiji Basin (Elmaleh et al., 2001). We reported intriguing correlation between intensity and inclination of long-term secular variations, in-phase in Brunhes but antiphase in Matuyama, from sediment cores in the western equatorial Pacific where delta-I is large, and proposed a model that strength of GAD fluctuates with ~100 kyr periodicity, whereas persistent non-dipole components do not (Yamazaki and Oda, 2002). We expect that further studies on intensity-inclination correlation, which drew little attention previously, may provide a key for better understanding the behavior and origin of persistent non-dipole components. Technically, improvement of inter-core correlation benefited by the recent progress in relative paleointensity studies has enabled to detect small long-term fluctuations of inclination.

1. Chapman Conference on Timescales of the Geomagnetic Field 2. Contributed 3. (a) Toshi Yamazaki, Geological Survey of Japan, AIST, Tsukuba, Japan 305-8567 (b) +81-298-61-2414 (c) +81-298-61-3589 (d) e-mail: toshi-yamazaki@aist.go.jp 4. No