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on Palaeo, Rock  
and Environmental Magnetism  
BOOK OF ABSTRACTS**

Edited by

*Stanislav Frančišković-Bilinski, Harald Böhnel,  
Ramon Egli, Ann Hirt, Eduard Petrovský, Simo Spassov,  
Tomasz Werner*

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Croatia

**Editors:**

Stanislav Frančišković-Bilinski, Ruđer Bošković Institute, Zagreb, Croatia  
Harald Böhnel, Centro de Geociencias UNAM, Queretaro, Mexico  
Ramon Egli, Central Institute for Meteorology and Geodynamics, Vienna, Austria  
Ann Marie Hirt, Institute for Geophysics, ETH Zurich, Switzerland  
Eduard Petrovsky, Institute of Geophysics ASCR, Prague, Czech Republic  
Simo Spassov, Royal Meteorological Institute of Belgium, Brussels, Belgium  
Tomasz Werner, Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland



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## Preface

**Preliminary palaeomagnetic results of Late Ordovician Carbonates,  
south-central Sweden**

Nastaran Ahanin, Stuart A. Gilder

Dept. of Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Munich, Germany

Correspondence to: [nastaran.ahanin@geophysik.uni-muenchen.de](mailto:nastaran.ahanin@geophysik.uni-muenchen.de)

**Keywords:** Baltica, Ordovician, paleomagnetism.

Central Sweden (Baltica) contains several sections of Early Silurian to Ordovician (420 to 485 Ma) sedimentary rocks. In Dalarna Province, we obtained 164 oriented drill cores from 13 sites at 7 locations, primarily from Early Ordovician units. The samples underwent a suite of polarized light microscopy, paleomagnetism, and rock magnetism experiments. Stepwise alternating field (AF) demagnetization up to 100 mT typically removed only 50-60% of the natural remanent magnetization and did not appear to successfully isolate characteristic magnetization components. Stepwise thermal demagnetization generally isolated well defined, characteristic magnetization components. The first lies in the low unblocking temperature range (25-325 C) parallel to the present-day field direction at the site. The second, of dual polarity, occurs above 325 C until complete unblocking at 560 C, which might or might not decay toward the origin. Magnetization increases above 560 C and the magnetization directions become chaotic- likely due to alteration and the creation of ferrimagnetic phases. Although complete unblocking occurs at similar temperatures as titanomagnetite, the inability to fully AF demagnetize the samples by 100 mT and on-going rock magnetic experiments suggest the remanence is likely carried by titanohematite. The high temperature component passes fold and reversals tests at 95% confidence limits suggestive of a primary remanence. The paleopole derived from our study is consistent with published studies on Ordovician rocks from Baltica, which further corroborates that the high-temperature magnetization component in the Dalarna limestones is pre-folding, being likely coeval with sedimentation.

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**First Neoproterozoic key pole for Amazonia:  
implications for the assembly of Rodinia**

P.Y.J. Antonio (1), R. Trindade (2), A. Heuret (3), F. Lasmar (2), C. Lana (4), A. Casanova (5),  
A. Proeitti (6), C.I. Martínez Dopico (7), H. Théveniaut (8), M. Ibanez-Mejia (9)

- 1) Géosciences Montpellier, University of Montpellier, CNRS, 34090 Montpellier, France
- 2) Universidade de São Paulo (USP), Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG), Rua doMatão, 1226, Cidade Universitária, 05508-090 São Paulo, SP, Brazil
- 3) Université de Guyane / Géosciences Montpellier (UMR 5243), 97300 Cayenne, France
- 4) Universidade Federal de Ouro Preto (UFOP), Applied Isotope Research Group, Departamento de Geologia, Escola de Minas, Rua Diogo de Vasconcelos, 122, 35400-000 Ouro Preto, MG, Brazil
- 5) Université de Guyane , 97300 Cayenne, France
- 6) Centre de Microcaractérisation Raimond Castaing, 3 Rue Caroline Aigle, 31400 Toulouse, France
- 7) INGEIS- Instituto de Geocronología y Geología Isotópica, Av. Int. Güiraldes, Ciudad Universitaria, Ciudad Autónoma de Buenos Aires, Argentina
- 8) BRGM, 3, avenue Claude-Guillemin, BP 6009, 45060 Orléans cedex 2, France
- 9) Department of Geosciences, University of Arizona, Tucson, AZ 85721, USA

Correspondence to: paulantonio0931@gmail.com

**Keywords:** Amazonia, Neoproterozoic, Tonian, Rodinia, paleomagnetism.

Amazonia is one of the major cratons in the Rodinia jigsaw puzzle (~1000–750 Ma). Whereas Amazonia is classically connected to Laurentia, Baltica and West Africa in the literature, no paleomagnetic data are available to constrain its position within the Rodinia supercontinent and its evolution during the entire Neoproterozoic. In this study we present a combined paleomagnetic and geochronological investigation for the Makinet dyke swarm in the Guiana Shield, northern Amazonia (French Guiana). Despite challenging access conditions in the Amazonian jungle, we sampled both thin dykes with a fine-grained texture and large dykes (> 10 m) with medium to coarse-grained texture for a total of 12 dykes. They are fresh and undeformed olivine-clinopyroxene dolerite composed of plagioclase, augite, olivine, and Fe-Ti oxides. These NW-SE Makinet dykes can be followed for several kilometers in aeromagnetic maps crosscutting all observed Paleoproterozoic rocks in the southwestern of French Guiana. Multiple radiochronometric determinations reveal a Tonian emplacement at ~860–850 Ma, highlighting the presence of a previously unknown mafic event in Amazonia. A single polarity remanence was obtained at high unblocking temperature (>500°C) and carried by stable single to pseudo-single domain (SD-PSD) magnetite. With several positive baked-contact tests to support the primary origin of this remanence, our new paleomagnetic dataset satisfy 6 criteria of reliability. The ~850 Ma Makinet pole can thus be considered as the first key Neoproterozoic paleomagnetic pole for Amazonia. This new key pole is of paramount importance to: (i) compare the position of Amazonia in relation with West Africa for which a ~860 Ma key pole is available, (ii) define their positions in the Rodinia supercontinent, and (iii) test the existence of different megacontinents, as the Umkondia or Wabambo, as continental precursors in the formation of the Rodinia.

## Reversible irreversible effect in thermomagnetic curves of magnetic susceptibility

Erwin Appel (1), Qi Zhang (2)

1) Dept. of Geosciences, Univ. of Tübingen, Germany

2) Center for Marine Magnetism (CM2), Dept. of Ocean Science and Engineering, Southern Univ. of Science and Technology, Shenzhen, China

Correspondence to: [erwin.appel@uni-tuebingen.de](mailto:erwin.appel@uni-tuebingen.de)

**Keywords:** fine magnetite behavior, hump-like thermal variation of magnetic susceptibility, reversible thermal hysteresis, dipolar coupling

Thermomagnetic curves of magnetic susceptibility ( $k$ ) are crucial for identifying magnetic mineralogy. A decaying trend of  $k$  at c. 300-400°C for magnetite-bearing samples is frequently interpreted as maghemite-to-hematite inversion. Little attention is paid to an often observed preceding increase of  $k$ , and the resulting hump-shape is usually irreversible after 700°C heating. We present hump-shaped  $k$ - $T$  curves for basalt and red soil showing thermal hystereses in partial runs to c. 350°C. After cooling,  $k$  returns to about the initial value, and in subsequent runs this behavior repeats in a similar way. Heating rate and external field variation have only little influence on this ‘reversible irreversible effect (RIE)’. In contrast, partial thermal cycling of saturation magnetization ( $M_s$ ) is reversible, no hump or increased decaying trend at 300-400°C occur, and repeated runs are nearly identical. The RIE in partial  $k$ - $T$  runs together with the reversible partial  $M_s$ - $T$  curves rules out maghemite inversion or Ti-rich titanomagnetite as a cause of the hump. The origin of the RIE could rather be related to transition of superparamagnetic (SP) and stable single-domain (SSD) behaviors in response to thermal relaxation variation with temperature. FORC diagrams support dominant SP and SSD domain states at room temperature and a shift towards stronger SSD contribution after heating to 700°C. The red soil contains aggregates of 10-15 nm sized magnetite nanoparticles, while for basalt the SSD and SP behavior may be explained by magnetite in fine lamellar structures and internal subdivision due to heterogenous stress. We modeled the principle RIE based on quantification of susceptibility with thermal variation of relaxation times, and a shifting particle size range during thermal cycling. For this, we considered an ensemble of 20-55  $\mu\text{m}$  magnetite particles that gradually transforms into finer (5-25  $\mu\text{m}$ ) particle behavior during heating up to 400°C, remaining in this state during the first cooling phase, before switching back to the 20-55  $\mu\text{m}$  behavior. The underlying size-range variation is clearly not a change of the physical particle size. Rather, it must be related to thermal variation of dipolar coupling in fine particle assemblages or between particle-internal sub-volumes. Thermal hysteresis in the  $k$ - $T$  behavior was found in different materials and attributed to either magnetic phase transitions (Erdem et al., 2015) or dipolar interaction producing transitions between dipolar spin-flop and vortex states, varying differently for heating and cooling (Pedrosa et al., 2018; Souza et al., 2019). We assume that dipolar coupling is also important for the RIE in our studied samples. The structure of coupled particle moments may remain in local energy minima configurations, as it was suggested by micromagnetic modeling of coupled spin moments. Welding of interfaces may occur during heating to 700°C, turning SP into SSD behavior as indicated by the FORC results.

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## Using Preisach theory to model chemical remanent magnetisation acquisition and making comparisons to thermoremanent magnetisation acquisition

Evelyn B Baker (1), Adrian R Muxworthy (1) and David Heslop (1,2)

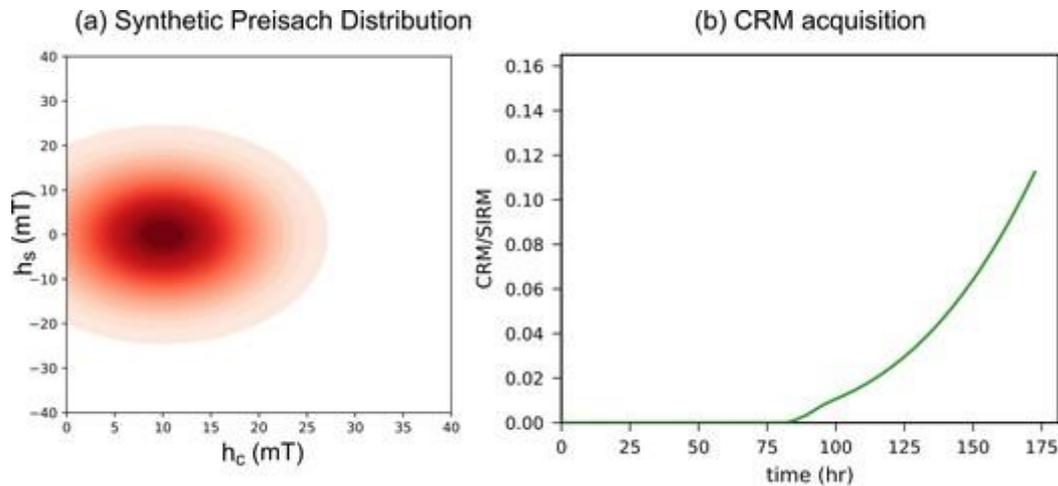
1) Imperial College London, United Kingdom

2) The Australian National University, Australia

Correspondence to: evelyn.baker15@imperial.ac.uk

**Keywords:** Chemical remanent magnetisation, Preisach model, Palaeointensity

Chemical remanent magnetisations (CRM) are widespread in nature. They are recorded when magnetic minerals form or alter in rocks below the Curie temperature. They are known to contribute to magnetic signals but their properties and ability to record past magnetic fields is much less understood than for thermoremanent magnetisations (TRM); recorded when rocks cool through the Curie temperature. There is a need for a better understanding of CRMs and how they contribute to palaeointensity determinations. Thermoremanence (TRM) acquisition has previously been successfully modelled using a thermally activated Preisach model and used to determine TRM palaeointensity estimates, without the need to heat samples. Here we use a similar approach to model grain-growth CRM. We use this model to explore how CRM intensity varies as a function of growth rate and when varying magnetic properties and make comparisons to TRMs.



**Fig. 1:** a) Example synthetic Preisach distribution, b) modelled chemical remanent magnetisation (CRM) acquisition with time during growth. CRM intensity is normalised to the saturating isothermal remanence magnetisation (SIRM).

## **Demagnetization energy and internal stress in natural magnetite bearing samples from temperature-dependent hysteresis measurements**

Annemarieke Béguin, Karl Fabian, Nathan Church, Suzanne McEnroe

NTNU, Trondheim, Norway

Correspondence to: [annemarieke.beguin@ntnu.no](mailto:annemarieke.beguin@ntnu.no)

The acquisition and stability of remanent magnetization in magnetic particles of Earth and planetary rocks are controlled by the magnetization state. Magnetic properties are primarily characterized by magnetic grain size. Also, internal stress, magnetostatic interactions, and grain shape can influence magnetic stability. Internal stress in magnetite may influence remanence acquisition, and thereby, might be responsible for enhanced remanence in rocks for which the processes are often still enigmatic. Magnetite is the most abundant magnetic remanence carrier in natural rocks. To further the understanding of the role of internal stress on the efficiency of remanence acquisition in magnetite, the internal stress contribution needs to be separated from the magnetostatic and demagnetizing energy contributions. Since magnetite is a soft magnetic material, the magnetization structure and behavior are largely controlled by its demagnetizing field. This demagnetizing field influences the magnetic behavior through shape anisotropy and particle interaction. Direct observation of the influence of other anisotropies – like magnetocrystalline or stress anisotropy – on the magnetic behavior of magnetite are hampered by these large demagnetizing effects. Recently, Béguin & Fabian (2021) presented a method to separate the demagnetizing energy and internal stress from temperature-dependent hysteresis measurements in the approach-to-saturation region at sufficiently high magnetic field values. The method was demonstrated for a suite of synthetic magnetite samples under different induced stress conditions. Here, we present the results and challenges of applying the new method to a set of natural magnetite bearing samples with different expected internal stress ranges.

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## Dating Quaternary sediments by the use of magnetostratigraphy

Claus Beyer

CB-Magneto, Nørregade 27, DK-8670 Låsby, Denmark

Correspondence to: claus.beyer@cb-magneto.com

**Keywords:** Quaternary, Magnetostratigraphy

The Quaternary sedimentary record in Denmark is fragmentary due to several, maybe 12 glacier progradations during the last 1 million years. The Harreskovian Interglacial has frequently been referred to when dating sediments with a similar pollen assemblage and fauna evolution. Yet, no good dating exists for this interglacial, which has been referred to somewhere in the Cromerian complex in the middle Pleistocene possibly MIS 15 or MIS 17. This magnetostratigraphic study, carried out on 3 well cores and one outcrop, documents that the sediments referred to the Harreskovian interglacial in 3 wells, have reverse polarity and therefore must belong to the Early Pleistocene. The outcrop consists of a lacustrine, partly varved, rapidly deposited sequence, which was deposited in front of a retreating glacier. The sediments in the well cores as well as the outcrop is rich in clay of which 70-80% was smectite. In two of the wells a significant inclination shallowing was found correlating reversely with the grain size, while in one well core and in the outcrop no shallowing occurred. The well cores only gave the inclination values while the outcrop also provided declination values. These data were used for calculation of a pole direction close to the south pole and comparison with data from ODP wells at Rock All. This result suggests an age of c.871 000 years for this lacustrine deposit, thus correlating it with the delta-O18 peak MIS.22, which indicates the first major glacier progression over Denmark (Fig. 1). The Harreskovian is correlated to the following interglacial at MIS21. This new dating of the Harreskovian moves the age at least 150 000 years back in time. Interesting is the discovery of a normal polarity zone at the bottom of one of the well at Starup below the Harreskovian sediment and an interval of glacial lacustrine sediment. The normal polarity zone is referred to the Jaramillo subchron. This almost 1 million year old sediment is the oldest Quaternary sediment hitherto found in Denmark.

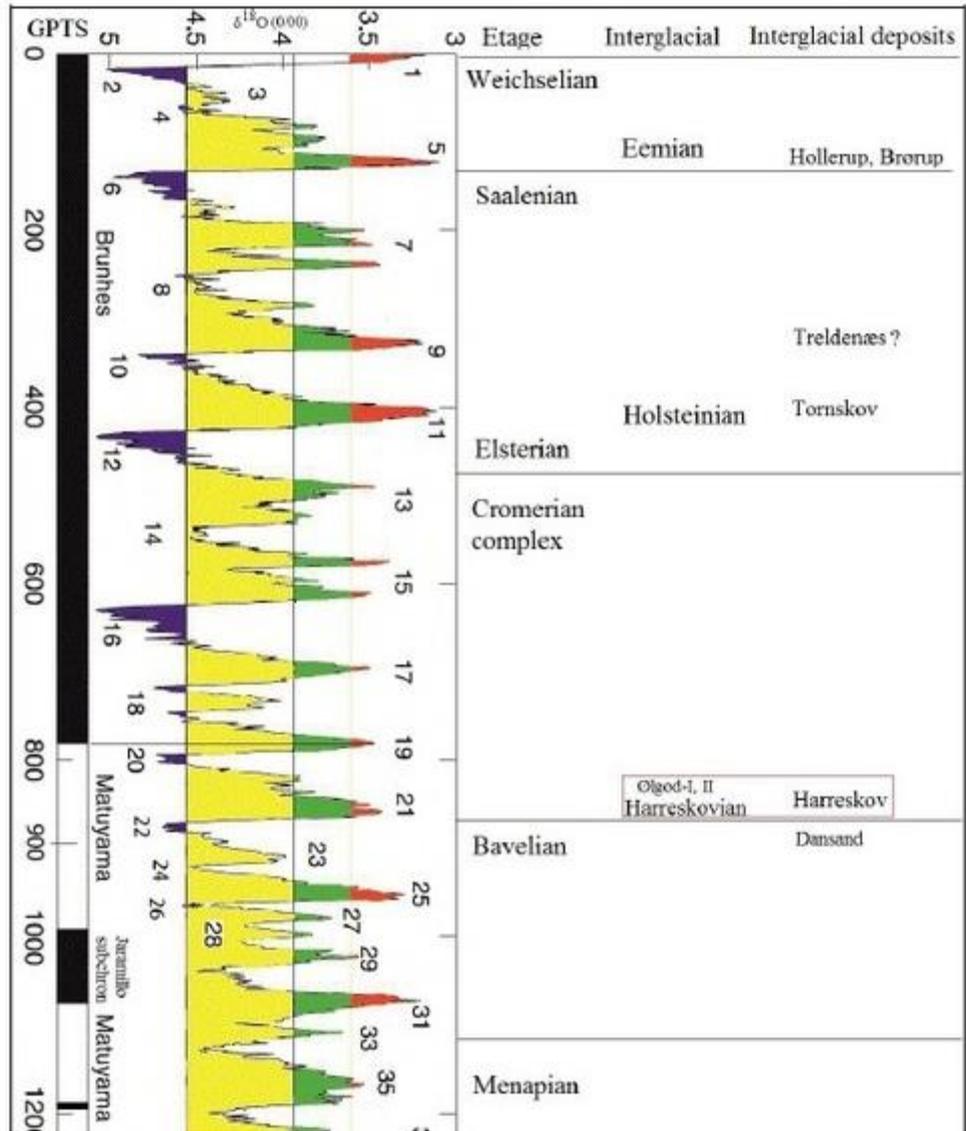


Fig. 1: Dating the Harreskovian.

## Numerical and experimental study on magnetic pore fabrics

Andrea R. Biedermann (1), Yi Zhou (1), Michele Pugnetti (1), Anneleen Foubert (2)

1) Institute of Geological Sciences, University of Bern, Switzerland

2) Department of Geosciences, University of Fribourg, Switzerland

Correspondence to: andrea.regina.biedermann@gmail.com

**Keywords:** magnetic anisotropy, pore fabric, numerical simulation, ferrofluid

Understanding the details of a rock's pore space is crucial in hydrogeologic and rock mechanic applications. In particular, anisotropy of the pore fabric defines preferred flow directions, with important consequences for fluid migration. Due to the large range of pore sizes and shapes, and the necessity to capture a full 3D image of the pore space and distinguish between connected and isolated pores, the characterization of a rock's pore space and its anisotropy is challenging. A promising emerging technique is the study of magnetic pore fabrics (MPF), i.e., the anisotropy of magnetic properties of ferrofluid-impregnated samples. Empirical relationships between (1) the average pore elongation direction and maximum susceptibility direction, (2) maximum permeability and maximum susceptibility direction, (3) average pore shape and degree of magnetic anisotropy, and (4) degree of permeability anisotropy and degree of magnetic anisotropy illustrate the potential of the technique. Previous studies reported that pores down to 10 nm can be captured with the MPF technique. However, the variability between empirical relationships observed in different studies is considerable, indicating that the relationship between magnetic anisotropy and pore space parameters (e.g., pore shape, orientation, distribution) is not yet fully and quantitatively understood. We performed numerical simulations as well as experiments on synthetic and natural samples to characterize the factors that contribute to the measured MPF. Numerical simulations illustrate that in addition to pore shape, as indicated by empirical correlations, also the pore distribution, and the intrinsic magnetic properties of the ferrofluid together define the MPF. Any given pore shape leads to larger anisotropy when impregnated with a more strongly magnetic ferrofluid, and this may explain some of the variability in published empirical relationships. This numerical result was confirmed by anisotropy measurements on synthetic samples with equal cavities, and filled with ferrofluid at different concentrations. X-ray computed tomography (voxel resolution  $\sim 10 \mu\text{m}$ ) was performed on natural samples to characterize the pore fabric, and He pycnometry to quantify the total porosity. The orientation and shape of best-fit ellipsoids of each pore was then used as an input for the anisotropy model, and modelled anisotropy compared to MPF measurements. This analysis suggests that the entire shape of the pore, approximated here by best-fit ellipsoids, rather than solely the orientation of the longest axis, is relevant for the MPF. Given the limitations (e.g., approximating the 3D connected network of pores with a series of ellipsoids, difference in spatial resolution between tomography and magnetic approaches, incomplete ferrofluid impregnation), the models show an overall good agreement with the measurements. These results increase the applicability of magnetic methods in pore fabric characterization.

## **Interactions between ferrofluid and rock, and their influence on impregnation behaviour and interpretation of magnetic pore fabrics**

A.R. Biedermann, P. Hartmeier, M.A. Prieto Casallas, Y. Zhou

Institute of Geological Sciences, University of Bern, Bern, Switzerland

Correspondence to: andrea.regina.biedermann@gmail.com

**Keywords:** magnetic anisotropy, magnetic pore fabrics, rock magnetism, pore space characterization, ferrofluid

Magnetic pore fabrics are a powerful and efficient tool to characterize pore space anisotropy and directional dependence of transport properties. Anisotropy of magnetic susceptibility is measured after the pore space was impregnated with ferrofluid, and because the ferrofluid has a large susceptibility compared to rock, the magnetic anisotropy then reflects the average shape and arrangement of the pores. This in turn controls transport properties. The interpretation of magnetic pore fabrics relies on the assumption that the ferrofluid fills the pore space homogeneously, and that there are no mechanical (e.g., filtering), physical (e.g., aggregation), or chemical (e.g., changes in mineralogy) interactions between the ferrofluid and the minerals in the rock. We tested these assumptions using a series of impregnation experiments with mineral and rock powders, and investigating the magnetic properties of impregnated rocks over time. Our results show that the impregnation front of the carrier liquid moves faster than that of the magnetic nanoparticles, which indicates mechanical filtering of the magnetic nanoparticles in the fluid. Further, we observe that in particular oil-based ferrofluid leads to increasing susceptibility of the rock over time, which is most likely explained by chemical reactions. This has important consequences when evaluating impregnation efficiency based on the difference in susceptibility before and after impregnation. Any mineralogical change that affects the magnetic properties, and susceptibility in particular, will cause bias in these estimates of impregnation efficiency. Our results indicate that previous statements on the impregnation efficiency of oil- vs water-based ferrofluids will need to be re-considered. Additionally, the results presented here help understand why some rocks are more difficult to impregnate than others.

## **Paleointensity estimates of the Middle Devonian obtained from German pillow lavas**

R.A. de Boer (1), A. van der Boon (2), P. Königshof (3), L.V. de Groot (1)

1) Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, The Netherlands

2) Center for Earth Evolution and Dynamics, University of Oslo, Norway

3) Historical Geology and Facies, Senckenberg Research Institute, Frankfurt, Germany

Correspondence to: r.a.deboer1@uu.nl

The nature and behavior of the Earth's magnetic field in the Devonian is largely enigmatic. Several studies targeted material that should be well-suited for paleomagnetic analyses, but results are often difficult to interpret. Devonian paleodirections and/or paleointensities do not fit with e.g. plate-tectonic reconstructions for that time, or exclude a dipolar behavior of the Earth's magnetic field. These problematic data are usually interpreted as a result of overprinting during the Kiaman reversed superchron, but recently it was hypothesized that the behavior of the field in the Devonian may have been complex, i.e. non-dipolar. Paleointensity estimates from the Devonian are almost without exception very low, further supporting the hypothesis of a non-dipolar Earth's magnetic field. In this study we aim to determine the paleointensity of the Middle Devonian period from what macroscopically seem to be ideal recorders of the Earth's magnetic field. We sampled fifteen Middle Devonian pillow lavas in the Philipstein Quarry, Braunfels, Germany. These lavas are unmetamorphosed and relatively unaltered basalts, with traces of minor faulting. Pillow lavas generally cool quickly when they are formed, which leads to an instantaneous record of the geomagnetic field. Furthermore, quick cooling is associated with the formation of small iron-oxide grains in the material, that are often believed to be the most reliable and stable recorders of the Earth's magnetic field. This makes these rocks well-suited for paleomagnetic analyses. The magnetic properties of the samples were determined with curie balance measurements, thermal demagnetization and AF demagnetization. Thellier-type experiments with the ZIIZP-protocol were conducted to derive the paleointensity recorded in the pillow lavas. Overprints are typically found in the low temperature domain (0°C-300°C); data from the high temperature domain (300°C-580°C) show a large variation but do suggest a weak to extremely weak Middle Devonian magnetic field, with values similar to the Ediacaran. Here we present our results and discuss the implications of our findings on the Devonian paleomagnetic field.

## Eruption history of El Metate volcano from paleomagnetic data, v. 3.0

Harald Böhnell (1), Sergio Salinas (2), Alejandro Rodriguez Trejo (1)

1) Centro de Geociencias – Universidad Nacional Autónoma de México, Campus Juriquilla, Mexico

2) Instituto de Geofísica UNAM, Mexico

Correspondence to: hboehnel@geociencias.unam.mx

**Keywords:** Paleomagnetism, paleomagnetic dating, monogenetic volcanism, Mexico

El Metate volcano was born 750 yrs ago and emplaced about 10 km<sup>3</sup> of lava, probably within only <50 yr and thus affecting seriously ancient dwellers in the region and forcing them to migrate. Volcanologists proposed that this volcano must be considered as a monogenetic one, and paleomagnetic studies of Mahgoub et al. (2017) confirmed this view. Later, Perez et al. (2020) challenged this interpretation and proposed a polygenetic nature of this volcano, based on their paleomagnetic results. These were much less detailed particularly in terms of sampling, in most cases by only one site per lava flow. In the present work we first present a detailed overview of previous results, including field observations and sampling strategies, and secondly new data from three sites of the same lava flow debated by Perez et al. (2020) and leading to their interpretation. Finally, we present new data from the youngest lava flows not studied before at all because of their difficult access. All in all, evaluation of previous sampling and results of new studies will resolve the question if this volcano is monogenetic or not.

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## **NGOD: Next generation orienting device**

Harald Böhnel, Alejandro Rodriguez Trejo, Hector Ibarra-Ortega

Centro de Geociencias – Universidad Nacional Autónoma de México, Campus Juriquilla, Mexico

Correspondence to: hboehnel@geociencias.unam.mx

**Keywords:** paleomagnetism, field work, instrumentation

Paleomagnetic studies are generally done using drill cores recovered in the field, which must be oriented with respect to the horizontal and to magnetic/geographic north. For that purpose, devices as proposed since the 1950's without much changes have been used, which implement a tube to be slipped over the drill core and a platform that has to be levelled with a protector scale pointing to that platform for measuring the inclination of the drill core. A magnetic or sun compass collocated on that platform provide azimuthal information. In this work we present a completely new approach based on a fully digital measurement system. This includes an inclinometer attached directly to the tube slipped over the drill core, which has a precision/resolution of about  $0.1^\circ$ . The magnetic azimuth is determined by a magnetic compass using two precision fluxgate sensors also providing a precision  $<0.5^\circ$ . A sun compass still has to be read personally. All sensors are read by a microcontroller that sends data via WiFi to a Smartphone or Tablet, which captures these data and also calculates the sun azimuth, using the available geographical and time data, and sends the results to a cloud-based database. Optionally, photographs of outcrop conditions may be stored in that database. This way, data are always secured, and lost field data are no longer a problem. The NGOD will provide precise orienting data and simplify paleomagnetic field and laboratory work, as it allows using orienting data stored in the cloud.

## First full vector archaeomagnetic data for the last millennia from Central Asia

R. Bonilla-Alba (1,2), M. Gómez-Paccard (3), E. Beamud (4), F.J. Pavón-Carrasco (5),  
V. Martínez-Ferrerías (6), J.M. Gurt-Esparraguera (6), E. Ariño-Gil (7), F. Martín-Hernández (8,9),  
J. del Rio (10), M.L. Osete (8,9)

- 1) Department of Physics of the Earth and Astrophysics, Complutense University of Madrid (UCM), Avd. Complutense s/n, 28040-Madrid, Spain
- 2) Institute of Geosciences IGEO (CSIC-UCM), Spanish National Research Council, c/ del Doctor Severo Ochoa 7, Edificio Entrepabellones 7 y 8, 28040, Madrid, Spain
- 3) Institute of Geosciences IGEO (CSIC-UCM), Spanish National Research Council, c/ del Doctor Severo Ochoa 7, Edificio Entrepabellones 7 y 8, 28040, Madrid, Spain
- 4) Paleomagnetic Laboratory CCI-TUB-Geo3Bcn, Geosciences Barcelona CSIC, C/ Lluís Solé i Sabarís s/n, 08028, Barcelona, Spain
- 5) Department of Physics of the Earth and Astrophysics, Complutense University of Madrid (UCM), Avd. Complutense s/n, 28040-Madrid, Spain
- 6) ERAAUB, Department of Ancient History and Archaeology, University of Barcelona, Carrer de Montalegre, 6-8, 08001 Barcelona, Spain
- 7) Department of Prehistory, Ancient History and Archaeology, University of Salamanca, C/ Cervantes s/n, 37002, Salamanca, Spain
- 8) Department of Physics of the Earth and Astrophysics, Complutense University of Madrid (UCM), Avd. Complutense s/n, 28040-Madrid, Spain
- 9) Institute of Geosciences IGEO (CSIC-UCM), Spanish National Research Council, c/ del Doctor Severo Ochoa 7, Edificio Entrepabellones 7 y 8, 28040, Madrid, Spain
- 10) Laboratorio de Paleomagnetismo (Dpto. Física), Escuela Politécnica Superior Edificio A1, Avda Cantabria s/n, ES09006 Burgos, Spain

Correspondence to: raquelbo@ucm.es

**Keywords:** Archaeomagnetism, Intensity, Direction, Geomagnetism

Archaeomagnetism enables to know the past variations of the past geomagnetic field through the study of the remanent magnetization acquired by the iron oxides present in archaeological materials when heated at high temperatures. The biggest challenge of this discipline is to achieve a global and temporal coverage of directional and intensity data. Currently, the 98% of the archaeomagnetic data are concentrated in the Northern Hemisphere, and the 46% come from archaeological sites located in Europe. To provide information on the magnetic field in Central Asia, an area lack of data, we present 9 full vector data of the geomagnetic field. These data have been obtained from 9 kilns collected in three different archaeological sites in South Uzbekistan, with ages ranging between 200 BCE and 1400 CE. It should be noted that, nowadays, no directional data exist for Central Asia for this space-time window. During the first stage of the study we performed rock-magnetic experiments including thermomagnetic curves and hysteresis loops. The results performed on 27 specimens, show that magnetite and maghemite are the main magnetic carriers in our samples. In addition, by an intensive rock-magnetic study carried out in one of the kilns, we identify different rock magnetic properties depending on the position of the samples within the kiln and the maximum temperature achieved in the archaeological past. The new full vector data were obtained by AF demagnetization and Thellier and Thellier experiments. In order to obtain high-quality palaeointensity data, different protocols have been carried out, including pTRM checks, TRM anisotropy, and cooling rate corrections. In this work we present 9 full vector data, the first ones provided in Central Asia for the first millennium CE. Directions have been compared with global geomagnetic models, showing significant deviation from predictions given by the models.

## Insights into the occurrence and characteristics of iron-bearing magnetic phases of playground sand

A. Bourliva (1), E. Aidona (1), L. Papadopoulou (2), C. Sarafidis (3), N. Kantiranis (2)

1) Department of Geophysics, School of Geology, Aristotle University of Thessaloniki, 54124 Thessaloniki, GREECE

2) Department of Mineralogy-Petrology-Economic Geology, School of Geology, Aristotle University of Thessaloniki, 54124 Thessaloniki, GREECE

3) Laboratory of Physics, Department of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

Correspondence to: aidona@geo.auth.gr

**Keywords:** Magnetic properties, geochemical analysis, playgrounds, sand, Greece

Recreation and green areas play a vital role in the socio-economic development and sustainability of large urban centers. Many researchers have highlighted the need to control soil/dust quality in recreation sites of urban agglomerations, especially in those where children are exposed. Particularly, in children's play sites it is imperative to quantify the levels of Potential Harmful Elements (PHEs) in soils and dusts, with a large number of researchers focusing on the determination of their chemical composition. On the other hand, extensive reports in the international literature on the observed relationship between anthropogenic pollution and magnetic signature of soils/dust, reinforce the effectiveness of magnetic mapping of urban areas in determining their degree of pollution. Specifically, the use of magnetic methods is proposed as a quick and inexpensive first step in assessing soil/dust pollution by providing qualitative data on its degree and extent. However, the studies focused on magnetic measurements in children's recreation and exposure areas are to our knowledge rather limited. The aim of the present study was to perform thorough magnetic analyses in order to provide information regarding the type, concentration, and relative grain-size distribution of iron-bearing magnetic phases in playground sand. For this reason, sand samples were collected within the top layer at 37 public playgrounds in the broader area of the city of Thessaloniki. Composite samples from 2-5 different points from the playground were collected. The sampling criteria used were the following: the sampling spots were not covered by the treetops, they were not at the edge of the playground or near to vegetation or urban furniture and they were visibly dry. Unexposed samples were not dispensable, however freshly replaced sand samples were gathered. Sampling was conducted in a dry period (August-September 2019) when no rain event had occurred for several weeks. Information regarding maintenance activities (i.e. disinfection, sand renewal) were not available. Magnetic measurements including mass specific magnetic susceptibility ( $\chi$ ) at low and high frequencies, frequency-dependent susceptibility ( $\chi_{FD}\%$ ), temperature-dependence magnetic susceptibility represented by thermomagnetic curves, anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization (IRM) were carried out. Magnetic measurements will be combined with geochemical analysis and health risk indices in order to be verified as potential rapid, non-destructive and low cost in-situ monitoring strategy for the detection of high impacted playgrounds.

## Linking the rock magnetic properties to environmental proxies of a dirty speleothem from Portugal

Ana Raquel Brás (1), Eric Font (1,2), Ana Sofia Reboleira (3), Paulo Fonseca (2)

1) Department of Earth Sciences, University of Coimbra, 3030 790 Coimbra, Portugal.

2) Instituto Dom Luís (IDL), Faculdade de Ciências, Universidade de Lisboa, 1749-026 Lisboa, Lisboa, Portugal

3) Departamento de Biologia Animal, Faculdade de Ciências, Centre for Ecology, Evolution and Environmental Changes (cE3c), Universidade de Lisboa, Lisbon, Portugal

Correspondence to: raquel.ana.b@hotmail.com

**Keywords:** speleothem, magnetism, Portugal, climate, stable isotope, mercury

Rock magnetic properties of speleothems have also been used to aid paleoclimatic reconstructions based on oxygen and carbon isotopic records. An increase in the concentration of magnetite trapped in the calcite laminae of the stalagmites was correlated to increased precipitation acting on soils (Bourne et al., 2015; Burstyn et al., 2022) or to less stable soils resulting from drier periods (Jaqueto et al., 2016). Here we study a dirty stalagmite from the Ceramics Cave, in Penela, Portugal. We conducted isothermal remanent magnetization curves to estimate the magnetite content and compare it with the carbon and oxygen isotope composition. We also measured the color using diffusive reflectance spectrometry, as well as the mercury concentration, to study the relationship between magnetic properties and the detrital component. Results provide new insights into the link between environmental changes and the magnetic signature of speleothems.

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This work was funded by the Foundation of Sciences and Technology of Portugal (refs. PTDC/CTA-GEO/0125/2021; MIT-EXPL/ACC/0023/2021) and IDL (ref. FCT/UIDB/50019/2020).

**A new application for archaeomagnetic dating method on the mining firesettings. The directionnal record of the oldest southern Alps copper mine (Mines de Roua, France).**

R. Bussone (1), P. Camps (1), M. Peyret (1), F. Suméra (2), O. Lemerrier (3), M. Dubois (1)

1) Géosciences Montpellier, Université de Montpellier, Montpellier, France

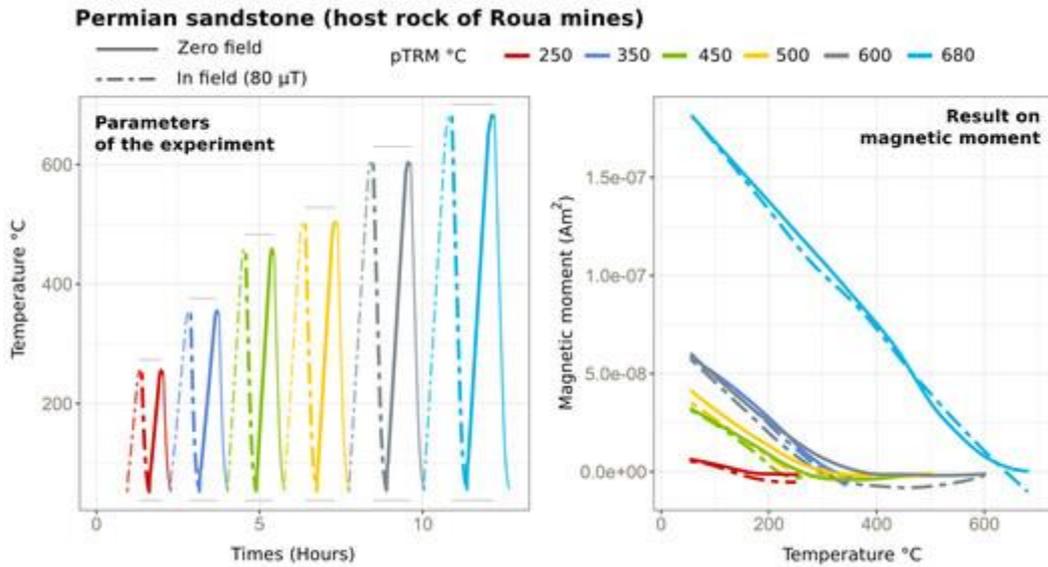
2) CCJ, Ministère de la Culture, Université Aix-Marseille, France

3) ASM, Université Paul Valéry Montpellier, Montpellier, France

Correspondence to: romain.bussone@hotmail.fr

**Keywords:** archaeomagnetic dating, prehistory, directional analysis, permian rocks, mining firesetting

The native copper mines dug on Permian sandstones in the Dôme du Barrot (southern Alps, France) provide vestiges of ancient firesettings and prehistoric tools (4000 – 450 BCE). The objective of this study is to obtain an archaeomagnetic dating and a relative chronology of 6 galleries among the forty mapped up to now. In a preliminary study, we demonstrated the feasibility of the archaeomagnetic dating of firesettings by overprinting at different temperatures a laboratory partial Thermal Remanent Magnetization (pTRM) of normal polarity on the Detrital Remanent Magnetization (DRM) of reversed polarity recorded in the Permian rocks. For these rocks, we showed that a pTRM can be successfully recorded and then retrieved from a set temperature as low as 200°C. At total of 24 oriented blocks were taken for the archaeomagnetic dating, that is, one fireset is sampled on each gallery with 4 oriented blocks. Their orientation is achieved in situ with a magnetic compass and then refined in the laboratory with a 3D photogrammetric analysis. A minimum of 10 specimens were prepared from each block. The holocene normal remanent magnetization components were retrieved from a stepwise paleomagnetic cleaning by heating, the remanence is measured with a cryogenic magnetometer (2G) at Géosciences Montpellier laboratory. We were able to isolate a well-defined pTRM on 5 firesets among the 6 sampled. The average pTRM directions of the mining-firesetting are compared to the reference curves BIGMUDI4K, SHA.DIF.14K and the local French curves calculated for the location of the Roua mines. In addition, we also developed a new local directional reference curve based on a Bayesian approach from a compilation of archaeomagnetic data located within a distance of 1000 km around the mines and data from high resolution speleothem near Queyras valley with the hope to refine the global models. We obtained prehistoric ages on 5 firesets. To our knowledge it is the first time that the archeomagnetic dating is successfully applied to vestiges of mining-firesettings. Radiocarbon and OSL dating confirm that the dates obtained are between the middle of the 4th millennium and the second half of the 3rd millennium. This is the oldest dated mine in the Southern Alps.



**Fig. 1:** Simulation of prehistoric mining-firesetting with CatVTM(3) to study magnetic remanence on Permian sandstone during continuous heating between 250 and 680 degrees Celsius. Heated Permian sandstones can be analysed for archaeomagnetic dating.

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## **Progressive widespread remagnetizations. Paleomagnetic and rock magnetic contains in the turbiditic Jaca Basin (Western Pyrenees)**

Pablo Calvín (1), Emilio L. Pueyo (1), Esther Izquierdo-Llavall (1), Juan C. Larrasoaña (1), Pablo Sierra (1), Adriana Rodríguez-Pintó (2), Ramon Egli (3)

- 1) Instituto Geológico y Minero de España - CSIC
  - 2) Independent research
  - 3) Zentralanstalt für Meteorologie und Geodynamik, Viena
- Correspondence to: calvinballester@gmail.com

**Keywords:** chemical remagnetization, burial, pseudo-Thellier, Pyrenees

Sedimentary rocks are very often affected by pervasive chemical remagnetization related with burial. This is consequence of the progressive increase in temperature during diagenesis causing the formation of authigenic minerals. As sedimentation continues, deeper sediments become slowly remagnetized as they pass through a threshold temperature barrier leading to the formation of authigenic magnetic minerals. Although remagnetizations of this kind are a common process in sedimentary basins and orogenic wedges worldwide, the kinetics of these processes remains unsolved, partly because some of the most studied widespread remagnetizations occurred during superchrons. The sedimentary sequence of the Eocene Jaca turbiditic basin (Western Pyrenees) displays a widespread remagnetization carried by magnetite. A preliminary study along different valleys shows different chrons were recorded along the sedimentary sequence. The dual polarity of this remagnetization provides a framework to try to deal with this open question, i. e. to shed light on the process of authigenic formation of ferromagnetic s.l. grains during burial. Samples from more than 150 new sites were taken from six N-S-trending Pyrenean valleys (from W to E; Salazar, Esca, Veral, Aragón-Subordán, Aragón and Gállego valleys). Thermal demagnetizations show a characteristic component (280-450°C) with normal and reverse polarity and in the deepest part of the basin some samples show an intermediate component (250-360°C) with opposite polarity than the ChRM. Preliminary data based on several fold-tests allow us to draw the remagnetization front and to compare it with the development of regional cleavage and with previous and new paleotemperature indicators. Once the remagnetization framework is constrained, we aim to correlate the chrons recorded in the different valleys, and to relate them by means of geological cross-sections with the sedimentary load along each transect. In this work we are focused on the rock magnetic results. On one hand, the amount of ferromagnetic s.l. grains as well as the grain-size along the different sections are evaluated by means of classic rock magnetic experiments. On the other hand, we use the ratios between NRM and ARM through the Pseudo-Thellier plot (Tauxe et al., 1995). Although this procedure is initially intended to evaluate intensities in sediments with primary magnetizations, we use it to look at the proportion of SSD grains carrying the ChRM within the general population of authigenic magnetite. Since the remagnetization process has occurred over a long period of time and records several polarity chrons, the same sample may contain grains that record different polarities and cancel their magnetic signal, and therefore do not contribute to the ChRM. The pseudo-Thellier plot therefore allows us to evaluate the magnetic effectiveness throughout the basin and provides new clues on how the remagnetization process has occurred.

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**African speleothems: a promising archive of the secular variation  
of the Earth's magnetic field over the last millennia  
for a continent lacking in experimental data**

P. Camps (1), M. Dubois (2)

1) University of Montpellier and CNRS

2) University of Montpellier

Correspondence to: mathildedubois07@gmail.com

**Keywords:** Earth's magnetic field (EMF), Holocene, Speleothems, secular variation, Geomagia database.

The study of the Earth's magnetic field (EMF) is one of the most interesting and important topics in geophysical research for two reasons. First, it is the only signal from the liquid outer core that can be detected at the Earth's surface, and second, it is potentially continuously recorded. We know that its secular variation is marked by a strong geographic dependence and can present rapid fluctuations [1]. The rates of these variations are still being debated [2]. Answering this questioning involves acquiring new data obtained from reliable archives, which have to be continuous over a significant time interval and distributed as homogeneously as possible at the Earth surface. We cannot model and therefore cannot understand a phenomenon as complex as the EMF if we do not observe it correctly. It is thus relevant to collect data in regions that are still poorly documented. In the Geomagia database [3], Holocene African records, without any selection based on quality criteria, are of only 138 data and 428 data relating to its direction and to its intensity, respectively. This is explained by a rather unique manufacture in Africa of archeological ceramic material based on a technique of drying in the sun and baking at low temperature in open fires. Very few potter kilns have been excavated as in Europe or in the Middle East. The only remains of archeological kilns correspond to metallurgical furnaces that are ill-suited in archeomagnetism given the probable presence of metallic masses near the workshop. The local EMF may be marred by an unknown error. Thus, it is necessary to target alternative archives such speleothems. With this in mind, we analyzed speleothems collected and oriented manually from the Lihouma cave in the town of Lastourville in Gabon. The stalagmites have been sectioned at the base level. The speleothems were dated with the Ur/Th technique. We will present the acquisition of paleomagnetic results, which on this type of archive are always difficult to obtain especially when looking for a signal with high temporal resolution. The quality of our measurements will be discussed by comparing our data with the 2 global models [4] and [5]

**References:**

## A low cost and fast system for measuring materials with Curie temperatures up to about 1100°C

P. Camps, T. Poidras, P. Nicol, S. Letaief

Géosciences Montpellier, University of Montpellier and CNRS, Montpellier, France.

Correspondence to: pierre.camps@umontpellier.fr

**Keywords:** Low-cost device, Curie Temperature, iron and steel, brake pads

Rock magnetism laboratories are equipped to analyze geomaterials whether of natural or anthropogenic origin. The magnetic minerals present in these materials all have Curie temperatures below 700°C, also, usual equipment present in rock magnetism laboratories are not designed to reach higher temperatures.

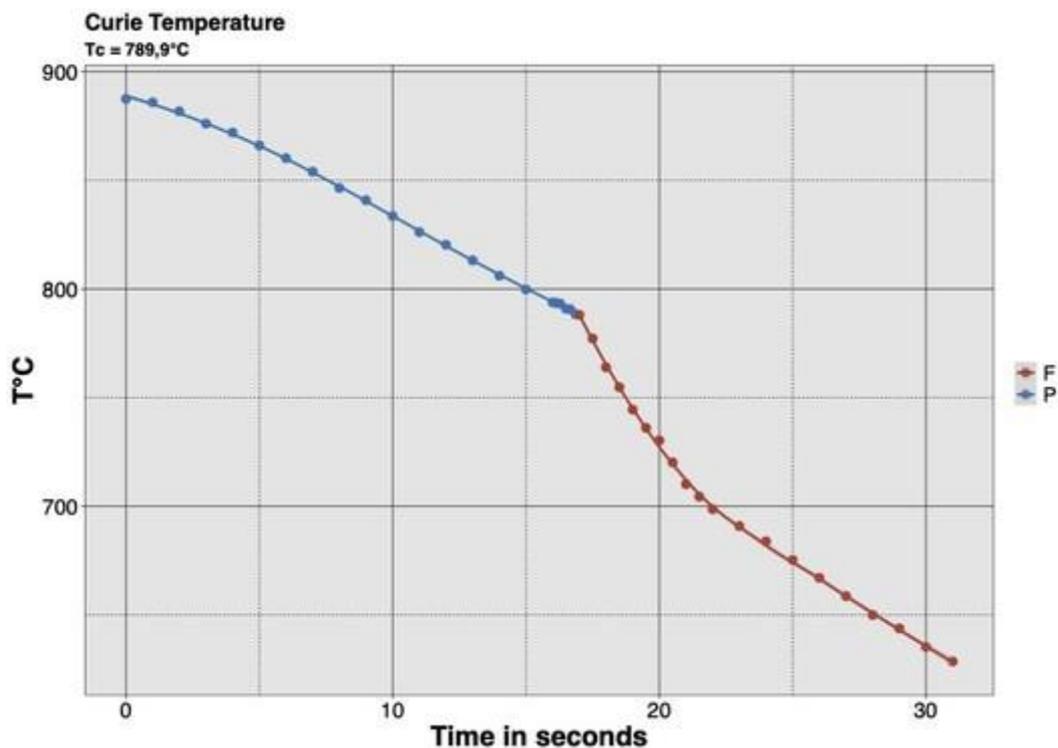
Environmental magnetism techniques are widely used to assess air quality by measuring dust depositions on accumulative surfaces since the correlation between magnetic properties of Fe-bearing nanoparticles with PM concentrations seems now well established (Gonet & Maher, 2019). The problem is that the iron present in these nanoparticles can be pure iron, or included in steels or even ferrites which are materials with Curie temperatures generally above 700°C. The determination of the Curie temperature of these particles is therefore not possible with conventional equipment in our laboratories. We were confronted with this issue in a study where we wanted to characterize in an exhaustive way the magnetic properties, including the Curie temperature, of the various sources of particulate emissions related to traffic (Letaief et al., 2022).

To this end, we implemented the experimental device presented by Velasco & Román (2007). This device allows of simply experimenting the force of attraction of a magnet on a ferromagnetic material when the latter passes from the paramagnetic state to the ferromagnetic state during its cooling from a temperature higher than its Curie temperature.

The sample is heated with the flame of the butane torch that can allow to raise temperature up to 1100°C in our case. The temperature in this experiment is controlled by a type S thermocouple placed in the center of the sample. When the sample is attracted by the magnet during its cooling, the extremity of the thermocouple will be in the open air. At this precise moment we therefore observe a break in the slope of the cooling curve which is treated as the sample Curie temperature.

To determine this temperature precisely, it is however important to properly characterize the experimental system. To this end, we modelled the behavior of the sample subjected to the influence of a magnet with the software tools gmsh (<https://gmsh.info/>) and getdp (<https://getdp.info/>) available in the Onelab app (<https://onelab.info/>). To do this, we modified the commented code of the “MagneticForces” tutorial available at the following address: <https://gitlab.onelab.info/doc/tutorials/-/blob/master/MagneticForces/magnets.pro>

With Gmsh we modified the geometry code of the magnets to model and generate the meshes of the rings, cylinders or parallelepipeds of different dimensions and positions which correspond to our experimental device. Getdp performs the calculations. For verification purposes, we compared an analytical solution (Camacho & Sosa, 2013) calculated for the ring magnet used in our experimental device with the solution modeled with Onelab. The results are similar. Our approach is validated with a sample of magnetite for which the Curie temperature is known thanks to a standard measurement carried out with the Kappabridge. We will present the results obtained on different brake pads and steels.



**Fig. 1:** Example of transition from para (blue curve) to ferromagnetic (red curve) behavior.

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## Rock magnetic study of the Dejvice loess/paleosol sequence (Prague, Czech Republic)

M. Chadima (1), M. Žatecká (2), J. Kadlec (3)

1) AGICO Inc., Brno, Czech Republic

2) Institute of Geology and Palaeontology, Charles University, Prague, Czech Republic

3) Institute of Geophysics of the Czech Academy of Science, Prague, Czech Republic (deceased)

Correspondence to: chadima@agico.cz

**Keywords:** magnetic susceptibility, frequency dependent susceptibility, magnetic fabric, loess

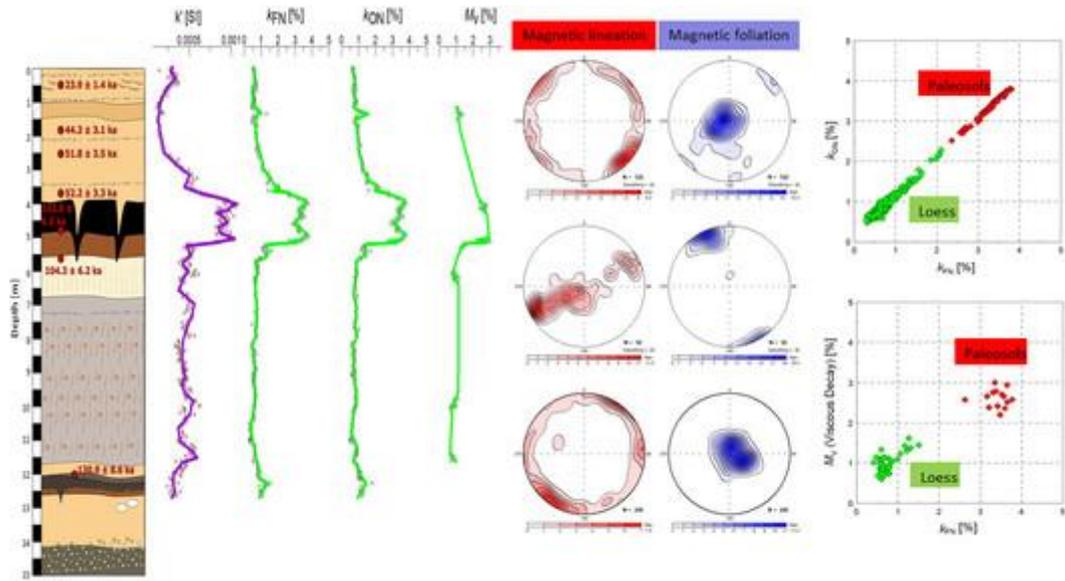
In this contribution, we present a rock magnetic and magnetic fabric study of the Dejvice loess/paleosol sequence with an aim to demonstrate how rock magnetic methods can be very effective tools for detecting paleoenvironmental, pedogenic, and post-depositional processes. This study covers the 15-meter-long loess/paleosol section which was recently temporarily accessible during the underground construction works in the Vienna House Diplomat Hotel in Prague (Fig. 1). The exposed part of the sequence contained at least four different paleosol horizons and covered the time interval from ca. 130 ky to recent. For the purpose of this study, 425 orientated samples (8 ccm) were collected evenly covering the studied section.

In general, loess sequences contain variable amount of detrital magnetic particles derived from the source material. In addition, in warmer interglacial periods, pedogenesis results in formation of paleosol horizons which are magnetic enhanced by the in-situ neo-formed nanoscale ferromagnetic particles.

The applied rock-magnetic techniques included measurements of (1) magnetic susceptibility (MS), (2) frequency-dependent susceptibility (kFD), (3) out-of-phase magnetic susceptibility (opMS), and (4) viscous magnetization (M<sub>v</sub>). While MS very sensitively reflects the relative amount of all magnetic particles, the other methods (kFD, opMS, and M<sub>v</sub>) mirror solely the contribution of the neo-formed nanoscale particles. In addition to these rock magnetic parameters, (5) anisotropy of magnetic susceptibility (AMS) was measured in order to obtain magnetic fabric reflecting the preferred orientation of magnetic minerals. Magnetic fabric can be primarily interpreted in terms of paleotransport directions but it may also provide some evidences for post-depositional reworking and/or movements.

All paleosol horizons possess significantly higher values of MS, kFD, opMS and M<sub>v</sub> (Fig. 1). This indicates that the increased amount of magnetic particles in paleosols is exclusively due to the magnetic enhancement caused by the neo-formation of nanoscale particles during pedogenesis. In addition, the values of kFD, opMS, and M<sub>v</sub> mutually intercorrelate very tightly. This indicates that all these independent methods are reliable proxies for the quantification of ultra-fine particles in loess/paleosols horizons.

In addition to the paleotransport direction, the magnetic fabric reflects secondary sedimentary processes. This involves the displacement of clastic particles by flowing water and the redeposition of the material along the slope. The direction of movement of these sediments corresponds to the current geomorphology of the surroundings. We can conclude that the section was not deposited solely by the aeolian processes.



**Fig. 1:** A simplified sketch of studied Dejvice cross section showing variations of rock magnetic parameters and magnetic fabric principal directions.

## **Anisoft: Major updates of long-popular magnetic anisotropy processing software**

M. Chadima (1,2)

1) AGICO Inc., Brno, Czech Republic

2) Institute of Geology of the Czech Academy of Sciences, Prague, Czech Republic

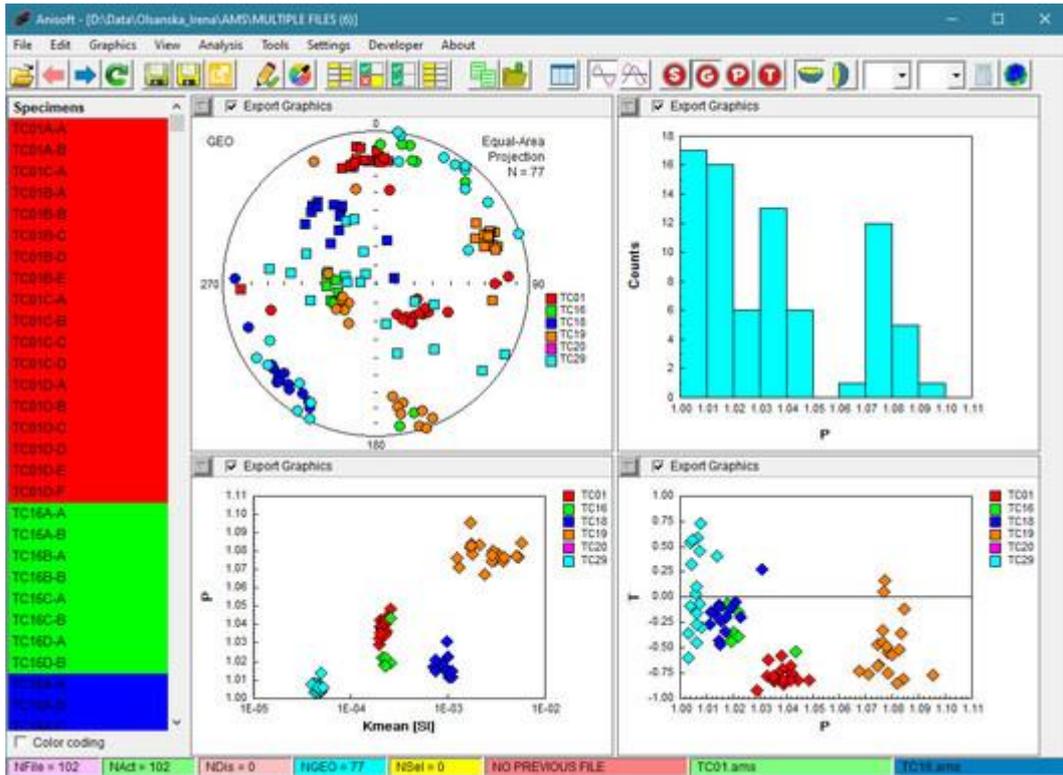
Correspondence to: chadima@agico.cz

**Keywords:** magnetic anisotropy, magnetic fabric

Since its first release, Anisoft software has gained widespread popularity mainly due to its straightforward and user-friendly interface enabling visualization and processing of magnetic anisotropy data. Here, major updates of Anisoft are presented transforming a simple data viewer into a platform offering complex treatment of magnetic anisotropy data.

The updates include:

- New enlarged binary data format (\*.ams) to store both tensors of anisotropy of in-phase or out-of-phase (if exist) magnetic susceptibility or anisotropy of magnetic remanence including their confidence ellipses and tests for anisotropy values
- Storing sampling angles and parameters enabling post-acquisition corrections of directional data or coordinate transformations with respect to various structural elements (i.e., foliations or lineations)
- Data import from external data formats or manual creation of data files (if data are not in electronic form)
- Data exported to text files (for processing by external software)
- Sub-classing of anisotropy data manually or according their magnetic anisotropy parameters
- Fitting of magnetic remanence tensor on a set of directional magnetizations
- Subtraction or addition of magnetic anisotropy tensors
- Modelling of gradual combined contribution of two end-member magnetic anisotropy tensors to the overall anisotropy data
- Contour plots of principal anisotropy directions
- Bootstrap statistics on a group of magnetic anisotropy tensors
- Export of graphics into vector or raster formats or to clipboard to be pasted directly into a presentation or a publication manuscript



**Fig. 1:** A printscreen of Anisoft major window showing an example of combined processing of multiple color-coded anisotropy files.

## Three-dimensional morphology of magnetite-ulvöspinel exsolution: controlling factors and implications for magnetic properties

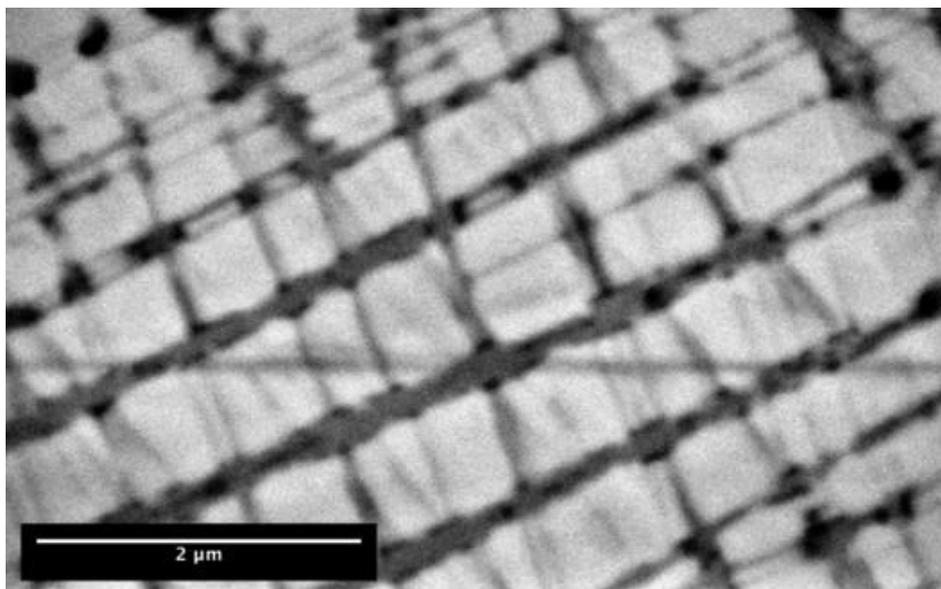
Nathan S Church, Even Nikolaisen, Annemarieke Beguin, Suzanne A McEnroe

NTNU, Trondheim, Norway

Correspondence to: nathan.church@ntnu.no

**Keywords:** Magnetite-ulvöspinel, mineral microstructures, computed nanotomography

Spinodal decomposition of titanomagnetite is an exsolution process occurring in slowly-cooled rocks that yields finely subdivided blocks of near endmember magnetite ( $\text{Fe}_3\text{O}_4$ ), separated by paramagnetic ulvöspinel ( $\text{Fe}_2\text{TiO}_4$ ). Because of the small size of the resulting magnetite particles, this exsolution microstructure has been proposed as a stable paleomagnetic recorder. In addition, the potential for magnetostatic interactions between closely spaced blocks makes this intergrowth a tantalising testbed to examine its effect on bulk behaviour. However, the range and consistency of size, shape and spacings of the magnetite blocks has not been rigorously examined. These attributes not only determine the paleo- and rock magnetic properties of the exsolved intergrowth, but also may reflect the original composition and thermal history of the titanomagnetite grains. To characterise a variety of magnetite-ulvöspinel microstructures, focused ion beam-scanning electron microscopy (FIB-SEM) tomography was applied to a selection of samples from localities in Scandinavia and South Africa. This technique yields three-dimensional models of the mineral intergrowth at a resolution of 10 nm, with each tomographic model containing up to 100s of magnetite particles. These observations therefore provide the ability to statistically quantify the morphology of this microstructure, revealing clear differences in the size distributions that likely reflect cooling history and potentially total titanium content. In the model from at least one locality, there is also a clear fabric to the magnetite blocks, which may reflect processes such as tectonic stress at the time of the exsolution event. The statistical quantification of the morphology of this microstructure will be used to discuss this intergrowth as a magnetic recorder and for future micromagnetic simulations examining magnetostatic interactions.



**Fig. 1:** Backscattered electron image of magnetite (light) – ulvöspinel (grey) microstructure. The magnetite blocks have a variety of size and shapes, with some equidimensional and 100s of nm on a side, and others strongly anisotropic and much smaller.

**Magnetic recording of Earth's history:  
3D nano-scale characterisation of natural basalts**

A. Cowan (1), A. Muxworthy (1), J. Einsle (2), W. Williams (3)

1) Royal School of Mines, Imperial College, London, United Kingdom, SW7 2AZ

2) School of Geographical and Earth Sciences, University of Glasgow, United Kingdom, G12 8QQ

3) School of GeoSciences, The University of Edinburgh, Edinburgh, United Kingdom, EH8 9XP

Correspondence to: a.cowan@imperial.ac.uk

Advanced electron microscopy techniques are used to better understand some of the oldest planetary magnetic records, helping uncover the underlying rock magnetic properties of the sample. Natural samples are made up of magnetic grains of different size, shape, and chemical composition. In this work we present a range of electron microscopy approaches to uncover the real spread of grain size distributions present in a range of natural basalt samples. Here we use the latest slice-and-view techniques on a FEI Helios Dual Beam Focused Ion Beam – Scanning Electron Microscope (FIB-SEM) instrument to determine a 3D reconstruction of the magnetic recording carriers within each sample, allowing for the generation of quantitative particle analysis for 1000s of individual grains. This approach links the underlying nanostructures of individual particles to the sum of these particles in the millimetre (or larger) scale to form of bulk magnetic measurements.

## Relative paleointensity stack for the western equatorial Pacific ocean over the last 35 ka : inter-hemispheric correlation and climatic signature

L. Dauchy-Tric (1), J. Carlut (1), L. Meynadier (1), F. Bassinot (2), J.P. Valet (1)

1) Institut de Physique du Globe de Paris, Paris, France

2) Laboratoire des Sciences du Climat et de l'Environnement, Université Paris-Saclay, Paris, France

Correspondence to: dauchy@ipgp.fr

**Keywords:** Relative paleointensity, Western equatorial Pacific Ocean, Glacial-interglacial transition, Oruanui eruption

Magnetic signal recorded in marine sediment cores can be used in favorable cases to reconstruct paleointensity variations during the past few million years. Despite a good global agreement, regional paleointensity reference curves sometimes show discrepancy. In this work we focused on the north Atlantic vs the south Atlantic datasets (NAPIS and SAPIS) during the past 35 ka. This period is interesting as both curves strongly disagree at the onset of the last deglaciation with a maximum intensity on NAPIS and a minimum on SAPIS. Instead of adding new data to the Atlantic region, we turned to the near equatorial western Pacific region with the aim of acquiring a high resolution paleointensity reference curve for this region. We have selected the two high sedimentation rate cores MD98-2165 (9.65°S, 118.34°E) and MD01-2385 (0.22°S, 134.24°E). They were both sampled using adjacent 2 cm x 2 cm x 2 cm paleomagnetic cubes. The Karm/K parameter measured in core MD01-2385 suggests that a progressive grain size decrease was initiated 17 ka ago during the last glacial-interglacial transition. Contrary to what can be found in the literature, this core shows low susceptibility peaks during the Younger Dryas event and the first Heinrich stadial. A high susceptibility interval is indicative of coarser magnetic grains around 28 ka associated with a volcanic event which likely caused a local ecological disaster as revealed by the very high fossil content of the layer. A pumice has also been found in the same core that could be linked to the Oruanui eruption which occurred 26.5 ka ago (Taupo, New Zealand). This new paleointensity record has been stacked with the datasets from core MD97-2134 (Blanchet *et al.* 2006) and core MD98-2181 (Lund *et al.* 2017). A comparison with NAPIS and SAPIS indicates that the same structure would be present between 20 and 30 ka in the three stacks, but with a progressive shift in time from south to north. Thereby, the peak of maximum in intensity around 28 ka on SAPIS would be shifted to 26 ka on the paleointensity reference curve of this study and to 24 ka on SAPIS. These preliminary results need further confirmation and support a change in sediment input that would have been generated by a large reorganization of oceanic currents as well as a delay in the acquisition of magnetic signal during the interglacial transition.

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## **A magnetic approach to reconstructing the mineral dust flux in the Chinese Loess Plateau during the Mid-Pleistocene Transition (MPT)**

Ynse Declercq, Simo Spassov

Royal Meteorological Institute of Belgium

Correspondence to: ynse.declercq@meteo.be

**Keywords:** dust flux, Chinese Loess Plateau, Mid-Pleistocene Transition, citrate-bicarbonate-dithionite leaching, magnetic susceptibility

The Earth's energy balance is constantly perturbed by different components of radiative forcing. The contribution of most components, such as greenhouse gases and ozone, is well known, but much uncertainty still exists on the effect of mineral dust (Pachauri et al., 2014). The extent to which cooling or warming occurs, depends on the dust radiative properties and thus on the size, shape and composition of dust particles. However, the short nature of instrumental dust records prevents establishing exact forcing relationships at low uncertainty. Here, in contrast, we draw upon the long-term and continuous dust deposition on the Chinese Loess Plateau to provide a high resolution (2 ka) aeolian dust flux record covering the Mid-Pleistocene Transition (0.7-1.25 Ma). It enables to further study mineral dust radiative forcing by relating dust flux to palaeoclimatic feedback variables and assessing chemical and morphological dust properties. Palaeogenic dust deposits have been sampled at Lingtai (China) and were dated by tuning the magnetic susceptibility record to the astronomically calibrated marine oxygen isotope stage timescale (Maher & Possolo, 2013). Dust fluxes, expressed as mass accumulation rates (MAR), are reconstructed here by multiplying the sedimentation rate with the bulk density and the aeolian fraction ( $f_{\text{aeolian}}$ ) of the deposit. While  $f_{\text{aeolian}}$  is often assumed to be 1 for simplicity reasons, it varies to the extent of pedogenic enrichment, which is closely related to the loess/palaeosol sequence in the deposit. Therefore, a novel approach is suggested in which  $f_{\text{aeolian}}$  is estimated by the magnetic susceptibility ratio of bulk material to its extract, i.e. obtained after leaching with citrate-bicarbonate-dithionite (CBD). CBD dissolves easy soluble magnetic iron minerals as formed during loessification, loess alteration or pedogenesis, so that leached extracts contain only purely aeolian magnetic mineral fractions, allowing to assess  $f_{\text{aeolian}}$ . Although a standardised leaching method is available, sample-specific fine-tuning might render better results or allow more time-efficient leaching. Therefore, the number of leaching and rinsing steps, leaching time and amount of CBD were varied and susceptibility was measured on selected loess/palaeosol samples, resulting in an optimised leaching method strongly reducing analysis time. Magnetic property analyses at low and ambient temperature (hysteresis, viscosity, magnetisation warming curves) confirmed the efficiency of the method. Alongside this methodological study, we present preliminary results on dust flux reconstruction in Lingtai during the Mid-Pleistocene Transition. By employing CBD leaching to estimate  $f_{\text{aeolian}}$ , improved MARs can be calculated accounting for pedogenic iron oxides and alterations after dust deposition. The MARs render a high resolution, robust dust flux record enabling to gain further insight into how mineral dust radiative forcing drives climate change and vice versa.

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## Taenite in fast-cooled meteorites thermally stable over billion-years timescales

José A. P. M. Devienne (1), Thomas A. Berndt (1), Wyn Williams (2), Lesleis Nagy (3)

1) Department of Geophysics, School of Earth and Space Sciences, Peking University, Beijing 100871, China

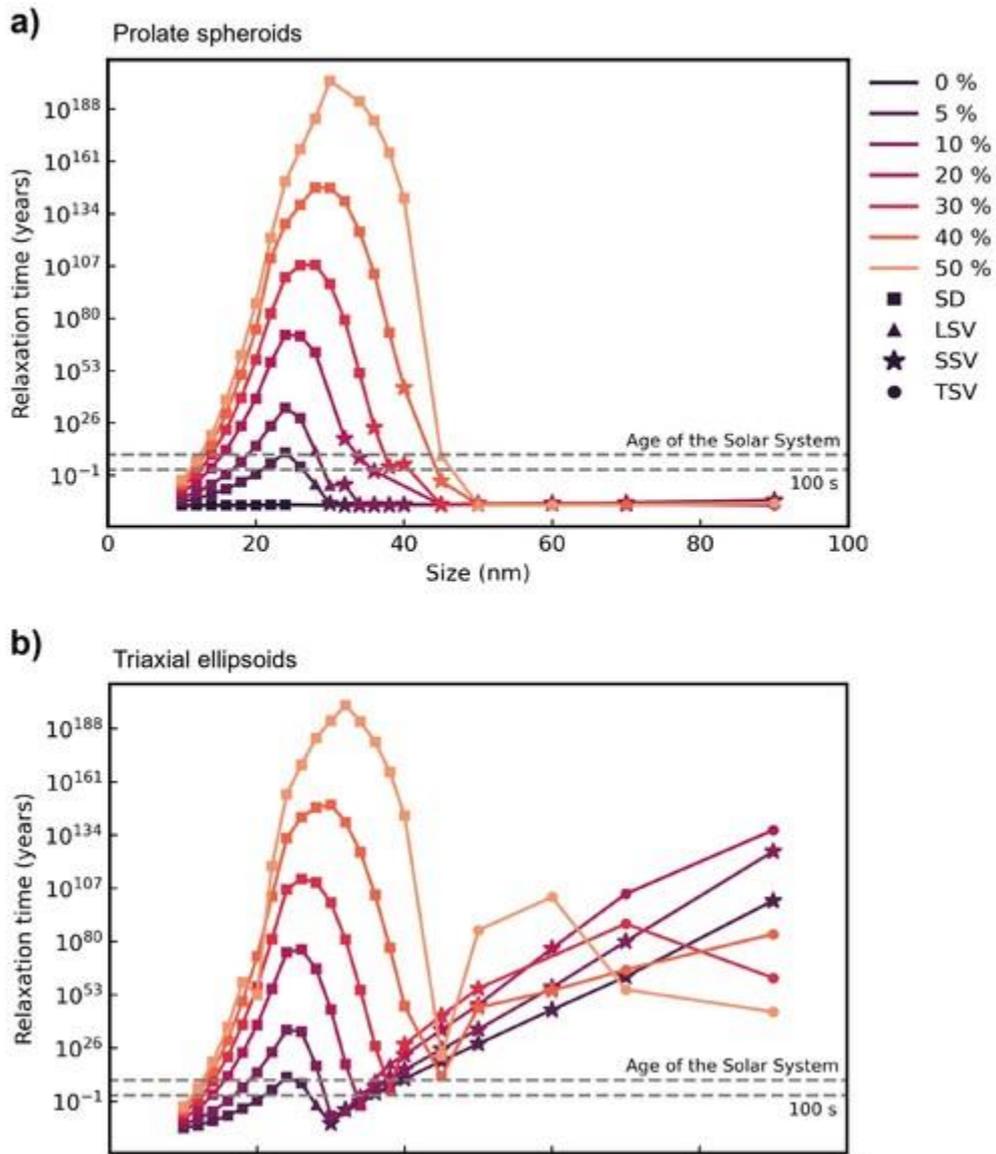
2) School of GeoSciences, University of Edinburgh, Edinburgh, United Kingdom

3) Department of Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool, United Kingdom

Correspondence to: devienne@stu.pku.edu.cn

**Keywords:** Taenite; cloudy zone; paleomagnetism; thermal stability; fast-cooled meteorites.

Meteorites, in particular iron and stony-iron meteorites, have received much attention in the paleomagnetic community in the last decades, mainly due to their potential to reliably record ancient magnetic fields. These materials, therefore, became a pivotal source of information about the magnetic and thermal evolution of planetesimals formed in the early solar system. The cloudy zone (CZ) forms within meteoritic metal as a nanometric-sized intergrowth of Ni-rich taenite or tetrataenite islands embedded in a paramagnetic matrix. The CZ has recently been recognized as the most promising magnetic phase to have possibly recorded magnetic activity of the parent body, mostly due to the presence of tetrataenite, commonly reported as “the” ideal paleomagnetic recorder due to its high coercivity and resistance to remagnetization. The formation of tetrataenite, nevertheless, is sensitively dependent on the cooling rate of meteoritic metal; some fast-cooled meteorites are believed to have a CZ predominantly comprised of small (< 40 nm) taenite islands, as a consequence of the rapid cooling that prevented both the formation of tetrataenite as well as the growth of bigger islands. Taenite, in contrast with tetrataenite, is generally considered as a poor paleomagnetic recorder, mostly based on its soft magnetic behavior observed in bulk ( $\mu\text{m}$ - to  $\text{cm}$ -) scale. In this work, however, we show through an extensive, systematic series of micromagnetic simulations that, contrary to what is commonly believed, nm-sized taenite is thermally stable over billion-years timescale. Additionally, we find a narrow range of island sizes ( $\sim 15$  to  $\sim 35$  nm) for which taenite forms stable single-domain (SD) structures, which implies that slowly cooled iron meteorites – in which taenite undergoes a phase transition to form tetrataenite – would likely retain a previous natural remanent magnetization in this size range, while larger grains might possibly record a new (chemical) remanent magnetization when tetrataenite forms.



**Fig. 1:** Relaxation times for nm-sized taenite grains with different grain sizes and elongations.

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**An environmental magnetic reconstruction of catastrophic subglacial  
outburst floods from the Laurentian Channel Ice Stream (Atlantic Canada)  
during the last deglacial period (Invited Talk)**

Tilo von Dobeneck (1), Wei Leng (1), Fenna Bergmann (1), David Piper (2), Guillaume St-Onge (3),  
Cristiano Chiessi (4), Aline Govin (5)

1) FB05/MARUM, Universitaet Bremen, Germany

2) Geol. Survey of Canada, Bedford Institute of Oceanography, Canada

3) ISMER, Université du Québec à Rimouski, Canada

4) University of Sao Paulo, Brazil

5) LSCE, Université Paris-Saclay à Gif-sur-Yvette, France

Correspondence to: [dobeneck@uni-bremen.de](mailto:dobeneck@uni-bremen.de)

A characteristic sequence of five reddish-brown, non-fossiliferous silt units of up to several meters thickness was detected in four marine sediment cores collected at the Grand Banks slope off southern Newfoundland (Leng et al., 2018). These ‘red plume’ units are deposits of catastrophic deglacial meltwater discharges of the retreating Laurentide Ice Sheet. We established a first consistent <sup>14</sup>C-chronology of these subglacial outburst events (22.0, 21.6, 19.5, 18.1, 17.9 cal ka), placing their ages between Heinrich events 2 and 1. The huge extent of these outburst plumes around the Laurentian Fan as well as their causes and consequences was investigated with rock magnetic, grain-size, and major element analytics. The five event layers show uniform systematic changes of their rock-magnetic properties: Hematite contents are high and increase over time and proximally while magnetite grain sizes fine upwards and spatially away from the Laurentian Fan. The magnetic properties of these layers contrast strongly with their hemipelagic interlayers; their ice rafted debris (IRD) content is also much lower or absent, supporting abrupt regime changes in sedimentation. Based on the sediment composition, grain-size and total load, we argue that the plumites were formed by recurrent erosion of glacial mud deposits in troughs of the Laurentian Channel by meltwater outbursts. Alternative glaciological event scenarios are evaluated; in each case, the provenance of the transported sediment is not an indicator of the precise source of the meltwater, but of subglacial lakes acting as sediment traps. We analyzed major element and magnetic mineral contents of these event beds and compare them with a new collection of 80 source reference samples from the Gulf of St. Lawrence area (Leng et al., 2019). Their magnetic properties place event beds on the source mixing trend of four reference samples groups, which represent two magnetite-rich sources (Canadian Shield and/or Southern Newfoundland) and two hematite-rich sources (both Appalachian red beds). Using a deterministic linear source mixing model based on IRM100mT, HIRM and Ca%, we find that the earlier two outburst events had higher contributions from granitic and calcareous sources than the later three events. An analogous mixing model of major element contents shows a significant offset from reference sample compositions. We can demonstrate, that grain-size and mineral/element partitioning during suspension transport and sorting leads to a systematic shifts of their source area element ratios (Loring and Nota, 1973). This effect is far less critical with magnetic mineral unmixing calculations. Combining materials, timing and scenarios of the outburst events with ice-sheet retreat and ice-stream dynamics, we argue that the subglacial sediment depocenter of the earlier two event beds was located in the lower Laurentian Channel while that of the later three events was upstream from Cabot Strait.

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## The secular variation of the Earth's magnetic field over the last millennia: experimental study of an African speleothem

M. Dubois (1), P. Camps (2), I. Bentaleb (2)

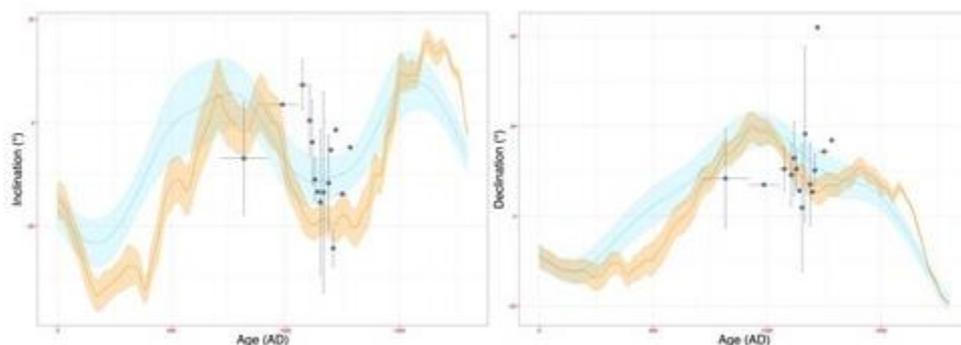
1) University of Montpellier

2) University of Montpellier and CNRS

Correspondence to: mathildedubois07@gmail.com

**Keywords:** Earth's magnetic field (EMF), Holocene, secular variation, The speleothems, Geomagia database

The study of the Earth's magnetic field (EMF) is one of the most interesting and important topics in geophysical research for two reasons. First, it is the only signal from the liquid outer core that can be detected at the Earth's surface, and second, it is potentially continuously recorded. We know that its secular variation is marked by a strong geographic dependence and can present rapid fluctuations [1]. The rates of these variations are still being debated [2]. Answering this questioning involves acquiring new data obtained from reliable archives, which have to be continuous over a significant time interval and distributed as homogeneously as possible at the Earth surface. We cannot model and therefore cannot understand a phenomenon as complex as the EMF if we do not observe it correctly. It is thus relevant to collect data in regions that are still poorly documented. In the Geomagia database [3], Holocene African records, without any selection based on quality criteria, are of only 138 data and 428 data relating to its direction and to its intensity, respectively. This is explained by a rather unique manufacture in Africa of archeological ceramic material based on a technique of drying in the sun and baking at low temperature in open fires. Very few potter kilns have been excavated as in Europe or in the Middle East. The only remains of archeological kilns correspond to metallurgical furnaces that are ill-suited in archeomagnetism given the probable presence of metallic masses near the workshop. The local EMF may be marred by an unknown error. Thus, it is necessary to target alternative archives such speleothems. With this in mind, we analyzed speleothems collected and oriented manually from the Lihouma cave in the town of Lastourville in Gabon. The stalagmites have been sectioned at the base level. The speleothems were dated with the Ur/Th technique. We will present the acquisition of paleomagnetic results, which on this type of archive are always difficult to obtain especially when looking for a signal with high temporal resolution. The quality of our measurements will be discussed by comparing our data with the 2 global models [4] and [5]



**Fig. 1:** This figure represents the evolution of the direction parameters (I, D) as a function of time. The error bars on the directions correspond to the data from our analyses of the stalagmite specimens. The blue curves represent the curves of secular variation from global scale modeling for the BIGMUDI4k.1 models (Arneitz et al., 2019) in orange, COV-ARCH in light blue (Hellio and Gillet, 2018). The 95% confidence intervals are shown.

**References:**

## Temperature-dependent in- and out-of-phase magnetic susceptibility as an indicator of thermal histories of different pyroclastic deposits

Katarzyna Dudzisz (1), Agnes Kontny (2), Luis Alva-Valdivia (3)

1) Institute of Geophysics, Polish Academy of Sciences, Ksiecia Janusza 64, PL01-452 Warsaw, Poland

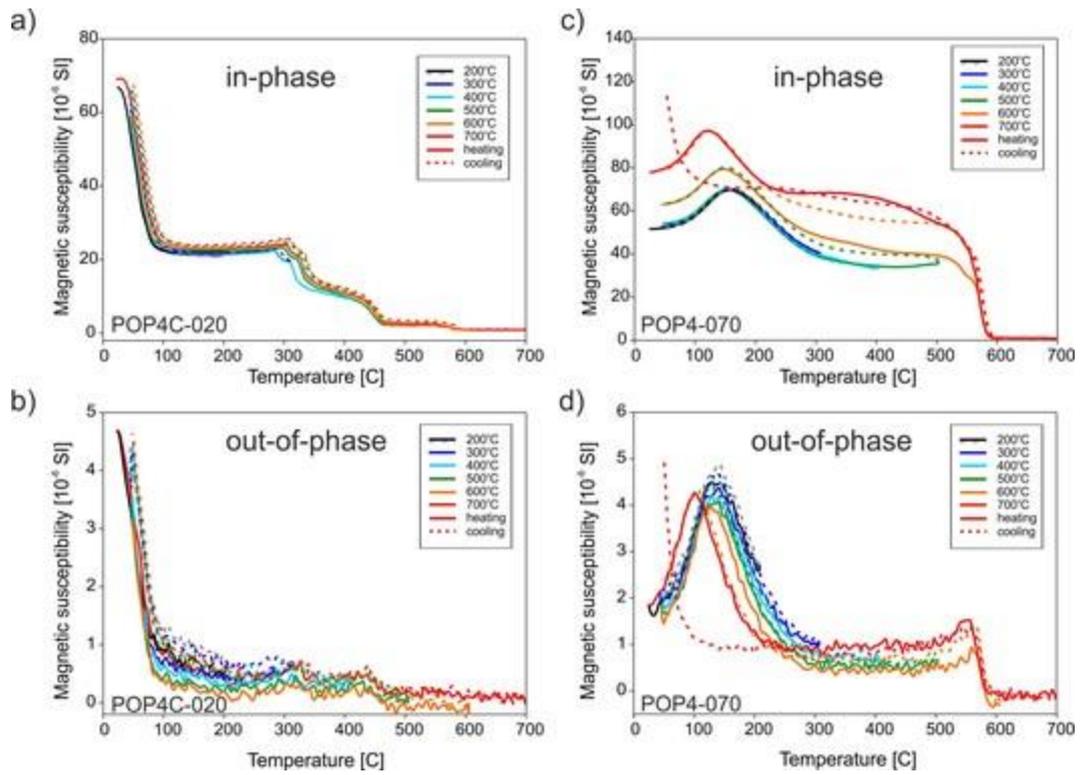
2) Karlsruhe Institute of Technology (KIT), Institute of Applied Geosciences, Adenauerring 20a, 76131, Karlsruhe, Germany

3) Universidad Nacional Autónoma de México (UNAM), Instituto de Geofísica, Laboratorio de Paleomagnetismo, Ciudad Universitaria 04510, Ciudad de México, Mexico

Correspondence to: katarzyna.dudzisz@gmail.com

**Keywords:** pyroclastic deposits, titanomagnetite, magnetic susceptibility

Volcanoclastic deposits from Popocatepetl volcano (<14ky) were studied to check whether Fe-Ti oxide mineralogy is sensitive to the thermal history of different pyroclastic depositional types and can be used as a proxy for their distinction. Rock magnetic analyses, including temperature-dependent in-phase and out-of-phase magnetic susceptibility as well as a microscopic study on eruptive sequences of various ages, were carried out to determine magnetic properties and chemical composition. We found that different pyroclastic materials can be separated based on temperature dependence [ $\kappa(T)$ ] and field dependence of magnetic susceptibility ( $H_{fd}$ ). The  $\kappa(T)$  runs revealed usually two to four different Curie temperatures ( $T_C$ ) present in the studied material and show either reversible or irreversible Curie temperatures dependent on the type of pyroclastic deposits (Fig. 1). Pumice sample POP4c-020 shows several  $T_C$ s from which the main one below 100°C is reversible and related to a Ti-rich homogeneous titanomagnetite ( $U_{sp} \sim 0.7$ ). In general, the magnetic properties of pumice layers are consistent and have the highest  $H_{fd}$  (~20%) among all types of deposits. Both, in- and out-of-phase susceptibility show the same  $T_C$  for this phase (Fig. 1a, b). The minor  $T_C$ s between 300-350°C, 450°C, and 580°C are nearly invisible in the out-of-phase curve indicating that these phases do not show an out-of-phase signal. Stepwise heating-cooling cycles do not indicate any alteration during the heating. In contrast, a sample of block and ash flow (POP4-070) shows an irreversible behaviour of the Ti-rich titanomagnetite with a difference in  $T_C$  from the heating and cooling curve ( $\Delta T_C$ ) of approx. 100°C, when heated up to 700°C (Fig. 1c, d). In addition to a better definition of the  $T_C$  related to the Ti-rich titanomagnetite, the  $k(T)$  of out-of-phase magnetic susceptibility shows a Hopkinson peak at 580°C indicating that the nearly pure magnetite shows a viscous relaxation due to very small grain sizes. The block and ash flow unit is characterized by decreasing magnetic susceptibility and low  $H_{fd}$  of magnetic susceptibility (<10%), which is untypical for ulvöspinel-rich titanomagnetite. Stepwise heating-cooling cycles are reversible up to 500°C whereas significant irreversibility occurs upon further heating which is expressed by a shift in  $T_C$  towards lower values at 700°C. At 600°C a second feature is observed as the magnetic susceptibility increases due to new magnetite formation. This feature is related to the hematite to magnetite transition seen in reflected light microscopy as the hematite from the original sample is nearly totally transformed to magnetite in the heated sample.



**Fig. 1:** Progressive temperature-dependence of in- and out-of-phase magnetic susceptibility for selected samples from pyroclastic deposits. Heating – cooling cycles up to maximum temperatures between 200 and 700°C in an argon atmosphere.

## Archaeomagnetic study of bell-casting workshop at the Belfry of Gembloux in Southern Belgium

S. Ech-chakrouni

Centre de Physique du Globe de l'IRM, 1 rue du Centre Physique, B-5670 Dourbes (Viroinval), Belgium

Correspondence to: sechchak@meteo.be

**Keywords:** Fireplace, Bell molds, Geomagnetic field, Direction, Archaeomagnetic dating

The archaeological rescue excavations carried out by Wallonia Heritage Agency (AWaP) at end of 2019 at the Belfry of Gembloux (UNESCO World Heritage site since 2005) in southern Belgium, have discovered a bell-casting workshop. It was found in an exceptional state of preservation, probably used during the restoration of the church “*Saint-Sauveur*” following a violent fire in Gembloux city in 1678. The workshop contained fourteen bell molds, one of which was well preserved and remains of a fireplace. The latter was of circular shape (1.20 m in diameter) without a wall, baked to a thickness of a few centimeters and located at a higher level than the bell molds. Its function is unknown; according to archaeologists, this fireplace was probably used for melting metal. Due to the lack of objects and artefacts in the workshop, except for some pieces of failed bells with Latin inscriptions, the chronological and functional relation between fireplace and bell molds are unknown. This discovery was an excellent opportunity for an archaeomagnetic dating and related magnetic property analyses in order to establish a chronology of the fireplace and its possible chronological relation with bell molds and the belfry of Gembloux.

To this end, baked clay samples were taken from both structures: bell mold and fireplace. The directions of the characteristic component of the natural remanence ChRM's of the samples of the fireplace are well grouped as indicated by the high Fisherian concentration parameter  $K$  ( $K = 2205$ ), the corresponding structure average direction could be determined with high confidence ( $\alpha_{95} = 0.6^\circ$ ). This indicates that the direction of the ambient magnetic field was well recorded during the last cooling of the structure. In contrast, the sample ChRM's of the bell mold are highly scattered ( $K = 2$ ), resulting in a large uncertainty for the structure average direction ( $\alpha_{95} = 30.5^\circ$ ).

A look to the magnetic hysteresis and viscosity parameters, determined with an induction coercivity meter, reveals that some bell mold samples contain substantial contributions of magnetically viscous grains and hematite. This is not the case for the fireplace, whose magnetic properties are more consistent; these samples grains have a lower viscosity and contain less hematite.

Eventually, archaeomagnetic dating was performed using the directional secular variation reference curve for the last 3ka for France, which is referred to Paris (Gallet et al., 2002), by applying Rendate software. For fireplace, three intervals of possible ages were obtained at the 95% confidence level. One of them is [1654; 1714] A.D., which is probably close to the archaeological context of the site. However, regarding the bell mold, the poor results obtained, did not allow to date archaeomagnetically the structure. At this stage, it is difficult to establish a chronological relation between bell mold and fireplace.

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## Key signatures of magnetofossils: recent results

R. Egli

Zentralanstalt für Meteorologie und Geodynamik, Hohe Warte 38, A-1190 Vienna, Austria

Correspondence to: ramon.egli@zamg.ac.at

**Keywords:** Environmental Magnetism, Magnetotactic Bacteria, Magnetofossils, Magnetite

Magnetotactic bacteria (MTB) produce single- or multi-stranded chains of magnetic nanoparticles that contribute to the magnetization of sediments and rocks. Their magnetic fingerprint can be detected in ancient geological samples and serve as a unique biosignature of microbial life. However, some fossilized assemblages bear contradictory signatures pointing to magnetic components that have distinct origin(s). Micromagnetic simulations and mutant MTB producing looped magnetosome chains have been used to demonstrate that the observed magnetofossil fingerprints are produced by a mixture of single- and multi-stranded chains, and that diagenetically-induced chain collapse, if occurring, must preserve the strong uniaxial anisotropy of native chains. This anisotropy is the key factor for distinguishing magnetofossils from other populations of natural magnetite particles, including those with similar individual crystal characteristics. Furthermore, the detailed properties of magnetofossil signatures depends on the proportion of equant and elongated magnetosomes, as well as on the relative abundances of single- and multi-stranded chains (Fig. 1). This outcome has important paleoclimatic, paleontological and phylogenetic implications, as it provides reference data to differentiate distinct MTB lineages according to their chain and magnetosome morphologies, which will enable the tracking of the evolution of some of the most ancient biomineralizing organisms in a time-resolved manner. It also enables a more accurate discrimination of different sources of magnetite particles, which is pivotal for gaining better environmental and relative paleointensity reconstructions from sedimentary records.

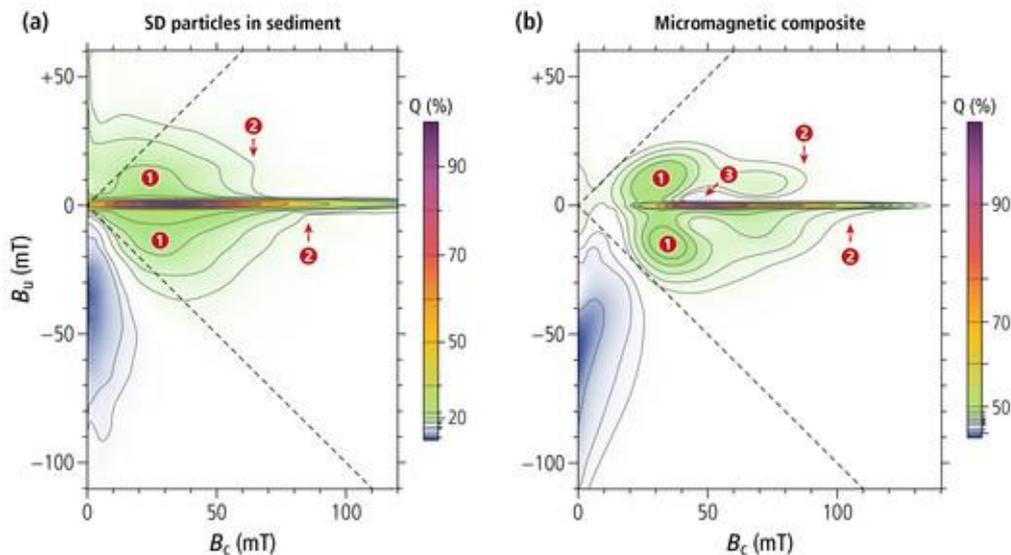


Figure 1: Comparison between the FORC signature of SD particles in a magnetofossil-rich sediment and a simulated magnetofossil composite. (a) FORC diagram of in-situ secondary magnetite particles (mostly magnetofossils) in a pelagic sediment (data from Ludwig et al., 2013). (b) FORC diagram of a simulated composite obtained from micromagnetically modelled chain structures.

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## Exceptionally high emplacement rate of the Afar mantle plume head

B. Eid (1), F. Lhuillier (1), S.A. Gilder (1), J.A. Pfänder (2), E.F. Gebru (3), D. Aßbichler (1)

1) Department of Earth and Environmental Sciences, Ludwig-Maximilians-Universität, Munich, Germany

2) Institut für Geologie, Technische Universität Bergakademie Freiberg, Freiberg, Germany

3) School of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia

Correspondence to: eid.baha.89@gmail.com

**Keywords:** Paleomagnetism, Geochemistry, Geochronology, Paleosecular Variation Geochronometer

The Ethiopia-Yemen Traps are the expression of an important geodynamic process where a mantle plume pierced the lithosphere, resulting in the massive outpouring of a few million km<sup>3</sup> of basaltic lava over a geologically-brief (1–3 Myr) interval. We investigated a 1-km-thick sequence of lava flows that erupted over the Afar plume axis in order to better understand the emplacement history of the ~30 Ma Ethiopia-Yemen Traps. Geochemical analyses reveal high-titanium concentrations (TiO<sub>2</sub> 3.9 ± 0.5 wt%) in basalts close to picritic compositions. Indistinguishable <sup>40</sup>Ar/<sup>39</sup>Ar ages throughout the section define a weighted-mean of 31.18 ± 0.28 Ma (95% confidence). This date, together with solely normal polarity magnetization directions in 68 geomagnetically independent horizons, constrain the eruption to within chron C12n, with a maximum duration of a few hundreds of kyr for the entire 1-km-thick section. The rate of geomagnetic secular variation used as a chronometer refines the duration to only a few tens of kyr, leading to a local extrusion rate of 4–13 km<sup>3</sup>/yr for the Afar plume head, which greatly exceeds the average rate of 0.3–1.2 km<sup>3</sup>/yr for the entire Ethiopia-Yemen Traps.

## Do changes in geomagnetic secular variation, dipole moment and polarity reversal frequency correlate over the past 155 Myr?

B. Eid (1), F. Lhuillier (1), V.P. Scherbakov (2), V.V. Scherbakova (2)

1) Department of Earth and Environmental Sciences, Ludwig Maximilian University, Munich, Germany

2) Geophysical Observatory Borok of IPE RAS, Yaroslavskaja Oblast, 151742 Russia

Correspondence to: eid.baha.89@gmail.com

**Keywords:** Palaeomagnetism, Palaeointensity, Magnetic field variations through time, Rock and mineral magnetism

Changes in palaeosecular variation, dipole moment and polarity reversal frequency are salient features of the Earth's magnetic field over the geological past, yet how these changes are linked by the geodynamo remains controversial. To further this issue, we provide new absolute (API) and relative (RPI) palaeointensities from the ~1-km-thick basaltic sequence of Waja (North Ethiopia) emplaced around 31 Ma, yielding a mean virtual dipole moment of  $58 \pm 11 \text{ ZAm}^2$  ( $N = 18$ ) and a relative variability in intensity  $\varepsilon_F = 0.39 \pm 0.07$  ( $N = 19$ ). Our analysis of the API database with strict selection criteria (inclusion of Thellier-style determinations with pTRM checks only, at least 5 determinations per cooling unit, within-unit dispersion lower than 15%) fails to identify any robust correlation between changes in dipole moment and reversal frequency over the past 155 Myr. More convincingly, the available RPI results are consistent with an increase of the paleosecular-variation proxy  $\varepsilon_F$  with reversal rate, as predicted by numerical dynamo simulations. We also find that the API-based estimate  $\varepsilon_F = 0.39 \pm 0.03$  ( $N = 105$ ) for the 0.77–31 Ma interval is consistent with the scaling rule, suggesting that the API record has been sufficiently sampled over the past 31 Ma. We thus speculate that the absence of negative correlation between changes in dipole moment and reversal frequency in the API database over the past 155 Myr may be the result of insufficient sampling prior to 31 Ma rather than the signature of an intrinsic geomagnetic feature.

## **Tithonian-Berriasian transition in the Silesian Unit, Pieniny Klippen Belt and Magura Group of nappes based on rock- and paleomagnetic analyses**

Tiiu Elbra (1), Petr Pruner (1), Šimon Kdýr (1), Petr Schnabl (1), Lada Koukliková (1), Daniela Reháková (2), Miroslav Bubík (3), Petr Skupien (4)

1) Institute of Geology of the Czech Academy of Sciences, Rozvojová 269, 16500 Prague, Czech Republic

2) Department of Geology and Palaeontology, Comenius University in Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovak Republic

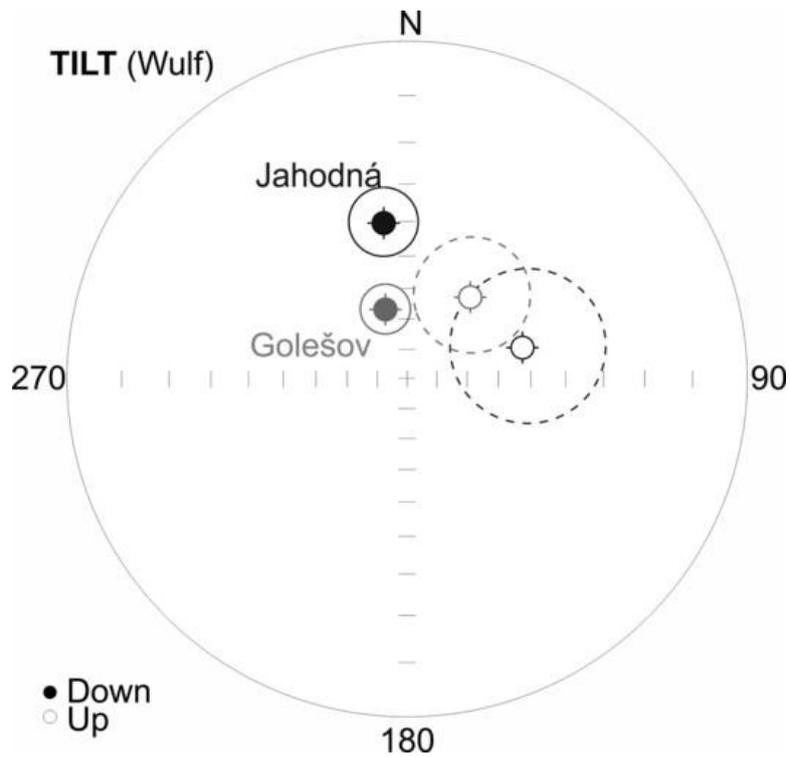
3) Czech Geological Survey, Leitnerova 22, 60 200 Brno, Czech Republic

4) Institute of Geological Engineering, VŠB-Technical University of Ostrava, 17. listopadu 15, Poruba, 708 33, Ostrava, Czech Republic

Correspondence to: elbra@gli.cas.cz

**Keywords:** Rock magnetism, Jurassic-Cretaceous boundary, Paleomagnetism, Magnetostratigraphy

The project, aiming to record and assess magnetic, geochemical and biotic changes across the Tithonian-Berriasian transition, in order to contribute to the global definition of the Jurassic–Cretaceous boundary (J-K) as well as produce new data for paleoenvironmental reconstruction on the J-K, is being carried out. Silesian Unit (CZ, PL), Pieniny Klippen Belt (SK) as well as Magura Group of nappes (CZ), are some of the key areas in this study. Studied localities are exposed along the river-cuts and in the abandoned quarries. In Silesian Unit (e.g. Golešov, Jahodná, Ropice and Karpetná sections), the slope marlstones and pebbly mudstones of Vendryně Fm. and overlying calciturbidites of Těšín Limestone Fm. are exposed. The hemipelagic limestones of the e.g. Czorsztyn and Pieniny Fms., can be found in the Pieniny Klippen Belt (e.g. Snežnica and Brodno sections); while Kurovice section (Magura Group of nappes) consists of micritic limestones and marlstones of Kurovice Fm. overlain by Tlumačov Marlstones. Sections were subjected to laboratory analysis by multiple rock- and paleomagnetic methods. Mineralogical changes were observed during thermal treatment. Paleomagnetic results indicate extensive remagnetization, with only normal polarity magnetization component, in Ropice. Primary magnetization, and presence of both normal and reversed magnetization (Fig. 1), was determined for e.g. Kurovice, Snežnica, Golešov and Jahodná. Directions of remanent magnetization suggest counter-clockwise rotation of the Silesian Unit. Our earlier data has shown stratigraphic range from the Early Tithonian magnetozone M21r to the late Early Berriasian M17r (Elbra et al., 2018; Svobodová et al., 2019) and counter-clockwise rotation in Kurovice sequence. Currently, the new magnetostratigraphy is being compiled for the other sections. IRM acquisition curves display the presence of both low (magnetite) and high coercivity fraction (either hematite or goethite) in most of the localities. Magnetite is the main carrier of the remanent magnetization. Furthermore, analyses of Hg contents and X-ray fluorescence spectrometry were done for selected sections and indicate up to higher tens of ppb variations in Hg concentrations. New magnetic results together with concise geochemical data of individual sections will be combined to determine the connections within Units as well as variations between different Units, and will be presented and discussed.



**Fig. 1:** Stereographic projection of normal and reversed polarity components (closed and open symbols, respectively) and their confidence intervals of the Golešov (gray) and Jahodná (black) sections after tilt correction.

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## Magnetism of speleothems: advances and perspectives

Eric Font (1,2), Elisa Sanchez-Moreno (3), Ana Raquel Marçalo Brás (1), Rui Leandro dos Santos Melo (1), Joana Ribeiro (1,4), Ana Sofia Reboleira (5), Paulo Fonseca (2), Ricardo Trindade (6), Eduardo Lima (7), Joshua Feinberg (8), Larry Edwards (9), Cristina Veiga-Pires (10), Claude Marcel-Hilaire (11), Luca Dimuccio (12), Lucio Cunha (12), Roger Fu (13), Benjamin Weiss (7), Alexandra Pais (14)

- 1) Department of Earth Sciences, University of Coimbra, 3030 790 Coimbra, Portugal
- 2) Instituto Dom Luís (IDL), Faculdade de Ciências, Universidade de Lisboa, 1749-026 Lisboa, Lisboa, Portugal
- 3) Departamento de Física, EPS Campus Rio Vena, Universidad de Burgos, Spain
- 4) Institute of Earth Science - Porto Pole, Rua do Campo Alegre 687, 4169-007 Porto, Portugal
- 5) Departamento de Biologia Animal, Faculdade de Ciências, Centre for Ecology, Evolution and Environmental Changes (cE3c), Universidade de Lisboa, Lisbon, Portugal
- 6) Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo, 05508-090 São Paulo, Brazil
- 7) Department of Earth, Atmospheric and Planetary Sciences Massachusetts Institute of Technology 77 Massachusetts Ave, Rm. 54-724, Cambridge, MA 02139
- 8) Institute for Rock Magnetism, University of Minnesota, Minneapolis, MN 55455
- 9) Department of Earth Sciences, University of Minnesota, Minneapolis, MN 55455
- 10) Universidade do Algarve, Faro, Portugal
- 11) GEOTOP, Université du Québec, Montreal, Quebec, Canada
- 12) University of Coimbra, Centre of Studies in Geography and Spatial Planning (CEGOT), FLUC, Department of Geography and Tourism, Coimbra, Portugal
- 13) Department of Earth and Planetary Sciences, University of Harvard, 20 Oxford Street, Cambridge, MA 02138
- 14) Department of Physics, University of Coimbra, 3030 790 Coimbra, Portugal

Correspondence to: efont@uc.pt

**Keywords:** speleothem, magnetism, paleosecular variation, climate

Speleothems are secondary mineral deposits formed in caves and are excellent recorders of variations in the Earth's magnetic field and climate during the Quaternary. Their age can be determined precisely using U-Th disequilibrium series dating, and the magnetic, geochemical and mineralogical signatures preserved in their thin laminations provide high-resolution climate- and environmental proxy time series, from sub-annual to millennial time-scales. Magnetic studies of speleothems provide two important forms of data: i) continuous and high-resolution records of short-term variations of the Earth's magnetic field (EMF), and conversely the use of paleomagnetism as a dating tool of speleothems; and ii) high-resolution records of climate variability by linking rock magnetic properties to climate and environmental forcing parameters acting on soils. However, applications on the use of speleothem magnetic properties as archives of climate change are at an embryonic stage and require a great deal of maturation before they can be comparable to traditional studies. Here we present a review of the Holocene paleosecular variation records of the Earth's magnetic field from Portuguese speleothems obtained during the last five years. We also preliminary results and future investigations in the frame of an ongoing research project (Speleothems as magnetic, environmental and paleo-fire archives; ref. PTDC/CTA-GEO/0125/2021) and a bilateral exploratory MIT-FCT project (Analyzing environmental and climate records in Portuguese speleothems using ultra-high sensitivity magnetic microscopy; ref. MIT-EXPL/ACC/0023/2021) funded by the Foundation of Sciences and Technology (FCT) of Portugal.

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## Mineral magnetism and paleomagnetism of a Holocene alluvial soil as tools for robust paleoenvironmental reconstructions

B. Georgieva (1), D. Jordanova (1), N. Jordanova (1), F. Lagroix (2), Y. Guyodo (2)

1) National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G. Bonchev str., block3, 1113 Sofia, Bulgaria

2) Institut de Physique du Globe de Paris, Université Paris VII - Paris Diderot, UMR7154, 1 rue Jussieu, 75238 Paris cedex 05, France

Correspondence to: bojurkageorgieva97@abv.bg

**Keywords:** Alluvial soil; Paleomagnetism; Archaeological age constrains; Paleoclimate; Holocene

Obtaining proxy records for the history of Holocene paleoenvironmental changes coming from diverse geographic areas is an important pre-requisite in development and testing reliable Earth system models. Advantageous combination of a sedimentary sequence with nearby well dated archeological sites gives good opportunity for establishment of reliable sedimentary age model in the absence of other dating. In our study we obtained records of paleomagnetic direction (D and I) and relative paleointensity (RPI) of the Earth's magnetic field for the last 8000 y BP from an alluvial soil situated on a flood river terrace close to the Chalcolithic mound near the village of Koprivetz (NE Bulgaria). Anisotropy of magnetic susceptibility data were obtained as well, showing two different sedimentary regimes for the upper soil and underlying alluvial clays. Humic and transitional soil horizons display clearly defined directions of  $K_{max}$ , consistent with the direction of delluvial sedimentation from the nearby slope. Lower alluvial clays possess a coherent imbricated magnetic fabric established under the orienting effect of the river flow. Variations of D, I and RPI along depth of the soil profile were correlated to the archaeomagnetic secular variation curves for Bulgaria, utilizing as tie point the age of the earliest archaeological stratigraphic horizon of the nearby Chalcolithic mound. Time records of rock magnetic parameters were utilized for paleoclimate reconstructions. The ratio of frequency dependent susceptibility to anhysteretic susceptibility ( $\chi_{fd}/\chi_{ARM}$ ) showed good resemblance to paleo-flood records from the Northern and Southern Alps (Wirth et al., 2013) and thus is considered as a proxy for paleoprecipitation. On the other hand, the ratio of isothermal remanent magnetization after 20mT alternating field demagnetization ( $IRM_{20mT}$ ) normalized to the full IRM showed good correlation with the GISP2 ice record of temperature variations in Greenland during the Holocene (Stuiver et al., 1995). The obtained results show that climate at mid-latitude SE Europe is sensitive to global and regional drivers of environmental change during the Holocene.

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**First determinations of ancient firing temperatures  
of Early Neolithic pottery from a multilevel settlement  
near Varbitsa town (Bulgaria) using mineral magnetic methods**

V. Georgieva (1), N. Jordanova (2), M. Kostadinova-Avramova (2)

1) National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences

2) National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy of Sciences

Correspondence to: neli\_jordanova@hotmail.com

**Keywords:** Neolithic pottery, mineral magnetism, firing temperatures

Evaluations of ancient firing temperature ( $T_{\text{fire}}$ ) of pottery provides important analytical data, which can be utilized as an indication of the pyrotechnological development during the human evolution. Magnetic susceptibility method for evaluation of  $T_{\text{fire}}$  (Rasmussen et al., 2012) was used as sensitive tool for obtaining  $T_{\text{fire}}$  for pottery of different historical epochs from Bulgaria (Kostadinova-Avramova et al., 2018). Data for the Neolithic period in Bulgaria, however, are lacking in the latest compilation. In this contribution, we present a first set of  $T_{\text{fire}}$  evaluations for pottery from the Neolithic multi-layered settlement in the Kenevira area, near to the town of Varbitsa. Fifteen stratigraphic layers have been documented during its archaeological research. In this contribution 40 Neolithic pottery fragments selected from the different layers of trench 1, dated by archaeomagnetism and  $^{14}\text{C}$ , were investigated. Samples selected belong to four stages of Karanovo culture (Karanovo I; Karanovo II; Karanovo II-III; Karanovo III). Pottery shards have different color (light brown, brown, reddish-brown, gray-brown, dark gray) and wall thickness. When heated up to 500 °C, the colors of the samples begin changing towards a beige or reddish-brown but complete homogeneity occurs above 800 °C, when they become intensely orange-red colored. Mass-specific magnetic susceptibility ( $\chi$ ) of pottery shards vary strongly in the range  $(14 - 1643) \cdot 10^{-8} \text{m}^3/\text{kg}$ . The highest variability is observed for pieces from the oldest periods (Karanovo I and II), while for pottery from more recent ones  $\chi$  has lower dispersion. The initial biscuit structure (where exists) disappears upon heating above 600 °C. For most samples  $\chi$  increases smoothly to temperatures of about 600 – 900 °C, which is likely due to firing atmospheres differences. Then  $\chi$  drops sharply and often a new increase after 900 °C is observed. The estimated firing temperatures vary between 710 °C and 950 °C. Considering the age of the respective layer from which pottery samples come, a decreasing  $T_{\text{fire}}$  tendency from more ancient to more recent time is observed. Temperatures above 820 °C are detected only for the older samples (Karanovo I and Karanovo II), while the younger pottery fragments (Karanovo II-III and Karanovo III) show lower  $T_{\text{fire}}$  temperatures ( $< 820$  °C). The highest  $T_{\text{fire}}$  show samples having low  $\chi$  values before the laboratory re-heating. Additional rock-magnetic analyses will be done to refine the magnetic mineralogy of various  $\chi$  groups.

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## **Influence of data filters on the position and precision of paleomagnetic poles: What is the optimal sampling strategy?**

D. Gerritsen, B. Vaes, D.J.J. van Hinsbergen

Utrecht University, Utrecht, The Netherlands

Correspondence to: gerritsendieke@gmail.com

**Keywords:** Paleomagnetic poles, sampling strategy

To determine a paleopole, the paleomagnetic community commonly applies a loosely defined set of quantitative data filters that were established for studies of geomagnetic field behavior. These filters require costly and time-consuming sampling procedures, but whether they improve the precision and influence the position of paleopoles has not yet been systematically analyzed. In this study, we performed a series of experiments on four datasets which consist of 73–125 lava sites with 6–7 samples per lava. The datasets are from different regions and ages, and are large enough to represent paleosecular variation, yet include demonstrably unreliable paleomagnetic directions. We show that the systematic application of data filters based on within-site scatter (a maximum angular deviation filter on individual directions, a k-cutoff, a minimum number of samples per site, and eliminating the farthest outliers per site) cannot identify unreliable directions. We find instead that excluding unreliable directions relies on the subjective interpretation of the expert, highlighting the importance of making all data available following the FAIR principles. In addition, data filters that decrease the number of sites even have an adverse effect; they decrease the precision of the paleopole. Between-site scatter often outweighs within-site scatter, and when collecting paleomagnetic poles, the extra efforts put into collecting multiple samples per site are more effectively spent on collecting more single-sample sites.

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## **Deciphering the evolution of the South Atlantic Anomaly over the last 2000 years: New archaeointensities from central South America**

M. Gómez Paccard (1), F. J. Pavón-Carrasco (2), A. Palencia-Ortas (3), A. Chauvin (4),  
M. Rivero-Montero (1), Archaeological team

1) Instituto de Geociencias IGEO (CSIC-UCM), Spanish National Research Council, c/ del Doctor Severo Ochoa 7, Edificio Entrepabellones 7 y 8, 28040, Madrid, Spain.

2) Dpto. de Física de la Tierra y Astrofísica, Universidad Complutense de Madrid, Avd. Complutense s/n, 28040-Madrid, Spain.

3) Dpto. de Ingeniería Eléctrica, Electrónica, Automática y Física Aplicada, E.T.S Ingeniería y diseño industrial, Universidad Politécnica de Madrid, Spain.

4) Univ Rennes, CNRS, Géosciences-Rennes - UMR 6118, F-35000, Rennes, France.

Correspondence to: mgomezpaccard@csic.es

**Keywords:** Archaeomagnetism, Archaeointensity, South America, SAA

A good characterization of geomagnetic field strength changes in the Southern Hemisphere is crucial to disentangle the long-term evolution of the South Atlantic Anomaly, one of the most important geomagnetic features observed on the Earth's surface nowadays. However, up to now the number of high-quality archaeointensities available for this region is still very low and, hence, a considerable grade of uncertainty surrounds geomagnetic field intensity reconstructions from this hemisphere. In particular for South America, and despite recent efforts, the number of high-quality absolute archaeointensities remains low, data are concentrated in the last 1000 years and the majority of available results do not meet modern standard criteria of quality (Poletti et al., 2016; Goguitchaichvili et al., 2019; Gómez-Paccard et al., 2019). Here, we present 39 new high-quality archaeointensities from central South America obtained from Thellier and Thellier experiments including TRM anisotropy and cooling rate corrections. The new data reveal the presence of relatively low and steady intensities around 40  $\mu\text{T}$  in central South America between 200 and 600 AD, as well as two differentiated intensity bumps, the first one around 950 and the second around 1500 AD, just before the rapid decay of the geomagnetic field strength associated to the strengthening of the South Atlantic Anomaly over this continent. Together with previous archaeointensities from South America the new data are weighted and used to present a first regional archaeointensity model for this region covering the last 2000 years. The new model is presented and discussed focusing on the next challenges for obtaining reliable geomagnetic field reconstruction in South America.

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**Geoelectric, magnetic susceptibility, and geochemical survey  
as a tool to clarify the origin of Bronze Age water reservoirs  
at the Štěpánov hillfort, Czechia**

Hana Grison (1), Radek Klanica Radek (1), Šárka Stejskalová (1), Jindřich Šteffl (2)

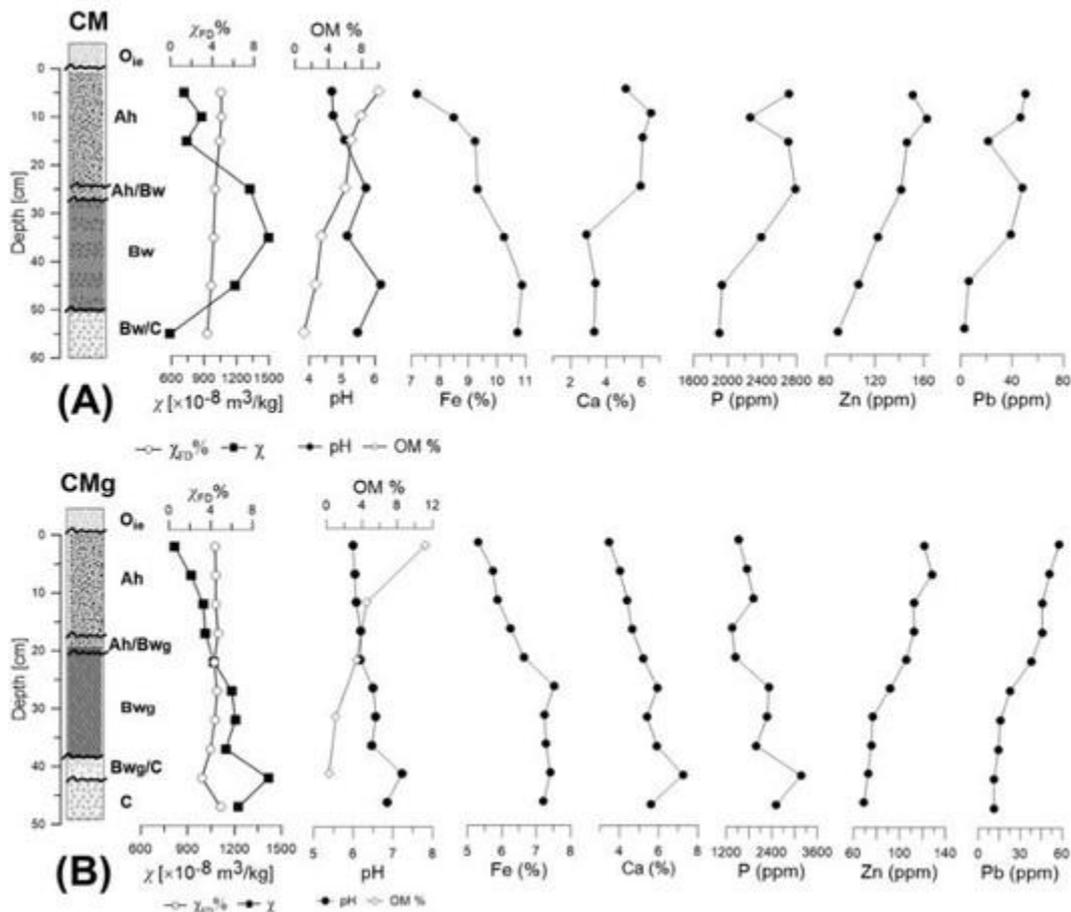
1) Institute of Geophysics ASCR, Prague, Czech Republic

2) Regional Museum in Teplice, Teplice, Czech Republic

Correspondence to: grison@ig.cas.cz

**Keywords:** Soil magnetism, basalts, electrical resistance tomography, ERT, archaeology, waterlogging

Geophysical prospecting methods can reveal structures and objects connected with past settlement in a noninvasive manner and thus contribute significantly to understanding a fortified settlement's function. It is challenging to discriminate properly between geogenic and anthropogenically influenced soil features. In highly magnetic soil that is locally influenced by water, this is not straightforward and more detailed study is needed. We propose to address this challenge by combined measurements of electrical resistivity tomography, magnetic susceptibility, and elements content on vertical soil profiles. Pedological description is completed by examining the content of soil organic matter (OM) and active soil reaction. The combination of ERT, magnetic, and geochemical analyses can differentiate the origins of water reservoirs at the hillfort. The deep subsoil of the site is generally formed by a weathered layer that gradually turns into solid bedrock. The ERT measurement helped to identify two types of water reservoirs. The anthropogenic water reservoirs show lower resistivity than does the natural one, they have greater thickness of the water-saturated layer, and they are more sharply demarcated from their surroundings. The natural water reservoir is less thick, and the water-saturated zone extends outside the surface manifestation of the reservoir. Soils in the vicinity of the three WRs reflect physicochemical mineral changes by magnetic susceptibility ( $\chi$ ), its frequency dependence parameters ( $\chi_{FD}$ , and  $\chi_{FD\%}$ ), and differences in element concentrations. The strongly magnetic Cambisol (CM) and Cambisol with gleying features (CMg) at the Štěpánov hillfort reveal the best links between  $\chi_F$ ,  $\chi_{FD}$ , and concentrations of the elements Fe, Mn, Ti, Sr, and Ca (Fig.1). The most enriched elements in soil were Pb, S, K, Rb, Si, and Zr compared to parent rock. Stagnant water influences soil features, and drastically decreases concentration of ferrimagnetic minerals. In our study, magnetic susceptibility in Stagnosols show significant correlation with Ti, Al, Ca, Sr, and Cr. Settlement activities on the top part of the acropolis caused increase of all magnetic parameters and concentrations of elements such as Zn, Mn, Ca, K, and P. Increased concentrations of elements Zn, Ca, and P can be taken as proof of active past human activity. Recent human activities are reflected by an increase of Pb and S in the topsoil horizon rich in humus. The results of this study are important for the applicability of magnetic susceptibility as possible proxy approach for the identification of past settlement in highly magnetic areas and in areas affected by presence of water.



**Fig. 1:** Drawing of typical Cambisol (CM), Cambisol with gleyic features (CMg) profile and vertical distribution of selected magnetic and geochemical parameters. Magnetic susceptibility ( $\chi$ ), frequency-dependent magnetic susceptibility ( $\chi_{FD}\%$ ), soil reaction (pH), content of soil organic matter (OM), and concentrations of Fe, Ca, P, Zn, and Pb.

This work was supported by the INTER-EXCELLENCE program of the Ministry of Education, Youth and Sports of the Czech Republic (MEYS), grant No. LTC19029.

**Searching for a lost Achaemenid Palace - Magnetometer prospection,  
soil magnetism and pXRF analysis in Gumbati (Georgia)  
to decode a magnetic "ghost feature"**

Sandra E. Hahn, Michaela Schauer, Jörg W.E. Fassbinder

Ludwig-Maximilians-University, Munich, Germany

Correspondence to: sandra.hahn@geophysik.uni-muenchen.de

**Keywords:** archaeological prospection, magnetometer survey, soil magnetism, archaeo-geophysical interpretation

The survey with portable magnetometers is an indispensable tool to map the differences in magnetic properties of the subsurface. In archaeological prospection, grids with a data point separation of 25 cm x 25 cm are used to find unknown archaeological sites or investigate known ones for more information on the yet unearthed features. Modern portable magnetometers register differences in the pT-range, enabling the prospector to map even the smallest differences in magnetisation, magnetic susceptibility and content of magnetic minerals of the buried archaeological features and the surrounding soil and geology. Thereby, a notable magnetic contrast is crucial for the visibility of archaeological features in the resulting magnetogram. The site of Gumbati in the east of Georgia was already partly excavated in 1994 and surfaced remains of an Achaemenid monumental mudbrick building with 2 m thick walls from the 5th century BC (Knauß, 2006). Starting 2018, one of the first aims of the magnetometer prospection was to rediscover the old excavation besides the large-area investigation of the site. The results revealed a poorly preserved site, adversely affected by deep ploughing and contamination with metal pieces and the tracing of the building complex was inconclusive. Only an ambiguous linear feature sparked the interest of the archaeologists. The presence of an anomalous body, which was suspected to maybe be a mudbrick wall, was also suggested by results of the electromagnetic induction (EMI) and the electrical resistance tomography (ERT) surveys (Thiesson et al. 2020). However, the excavations in 2019 revealed no archaeological findings or any other kind of findings at the anomalies location explaining the source of the anomaly. Another example of a "ghost feature", which is an anomaly in geophysical maps which are not detectable with the naked eye in archeological excavations and investigations. To demystify this feature, we collected soil samples along four vertical profiles in 10 cm increments in the open trenches around the supposed location of the anomaly to unravel the nature of the anomaly. We studied the samples' magnetic properties via hysteresis, thermomagnetic and susceptibility measurements accompanied by pXRF measurements to identify variations in magnetic mineralogy and magnetic properties. The focus lies on the results of the susceptibility measurements in-situ and in the laboratory as well as a subsequent modeling of the data via artificial magnetograms to find a plausible cause for this „ghost feature“. Recently, with new access to old satellite images recorded during the old excavation in 1994, we were finally able to conclude that this „ghost feature“ doesn't belong to the Achaemenid building complex. Unfortunately, this also concludes, that the building complex is not preserved in a state detectable by magnetometer prospection at its original location.

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## **Paleo[X].org: an online toolset for paleomagnetism, paleoclimatology, and paleogeography**

D. van Hinsbergen, B. Vaes, L. Boschman

Department of Earth Sciences, Utrecht University, Princetonlaan 8A, NL-3584 Utrecht, The Netherlands

Correspondence to: [d.j.j.vanhinsbergen@uu.nl](mailto:d.j.j.vanhinsbergen@uu.nl)

**Keywords:** Paleomagnetism, APWP, Paleolatitude, Paleogeography, Paleotemperature

Paleomagnetism provides the key quantitative constraint on plate tectonic and paleogeographic reconstructions relative to the Earth's spin axis and is thus provides a cornerstone boundary condition for the analysis of paleoclimatology, paleoceanography, and paleobiology. However, paleomagnetic data are provided in a myriad of different formats and finding where a modern sampling site is in paleogeographic reconstructions, or which reference frame to select in published reconstructions, is often challenging for the non-specialist.

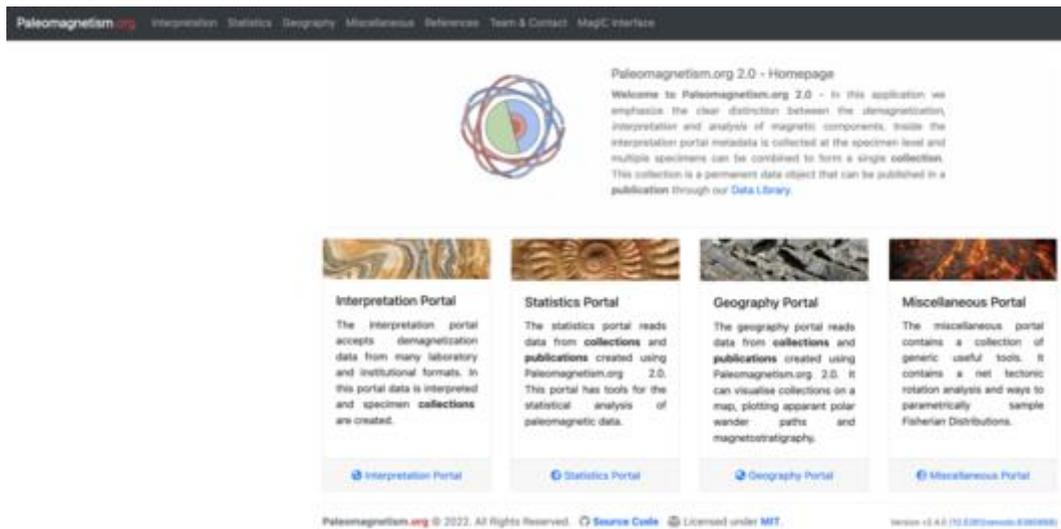
To overcome these problems, we have developed, and are developing a series of easy-access and free online tools for paleomagnetic data sharing and analysis, and for reaching out to communities who need paleogeographic input. These web tools include that already available [Paleomagnetism.org](http://Paleomagnetism.org) and [Paleolatitude.org](http://Paleolatitude.org), and tools under development including [Paleotemperature.org](http://Paleotemperature.org), [Paleogeography.org](http://Paleogeography.org), and [APWP-online.org](http://APWP-online.org).

[Paleomagnetism.org](http://Paleomagnetism.org) (version 1.0 launched in 2016, version 2.0 in 2020) provides a platform for interpretation of paleomagnetic data (Fig. 1). Data formats from a tens of paleomagnetic laboratories are accepted, facilitating data sharing between labs, and interpreted data can easily be uploaded into the MagIC database. The tool further allows advanced statistical data treatment, standard field tests, Net Tectonic Rotation analysis, and parametric sampling tools. In addition, the tool is interfaced with GPlates plate reconstructions dataformats so kinematic reconstructions can be compared to paleomagnetic data.

The newly developed [APWP-online.org](http://APWP-online.org) tool will be an addition to [Paleomagnetism.org](http://Paleomagnetism.org). The tool will include calculators of declination or inclination differences of a given paleomagnetic locality relative to a custom-chosen reference plate (standard plates, or custom plates defined in GPlates format). In addition, the web tool will include a database where authors may upload new poles from stable plate interiors that will be included in upgrades of the global APWP in new versions of the tools.

[Paleolatitude.org](http://Paleolatitude.org) (version 1.0 launched in 2015, version 1.1 ) allows calculating the paleolatitude of a given coordinate at a given time in three different published paleomagnetic reference frames. In the fall of 2022, there will be an update of the site using the new APWP of Vaes et al (presented at this conference). This version will also include detailed reconstructions of orogenic belts, to make the tool better available for paleontologists.

[Paleotemperature.org](http://Paleotemperature.org) will be a new tool, available in the fall of 2022, in which paleolatitudes through time will be coupled to paleotemperature and polar amplification records. This tool will allow to compute the temperature that a given location on the modern Earth has experienced during the last ~330 million years. When interfaced with another tool that we develop ([Paleogeography.org](http://Paleogeography.org)) this will allow to map out 'anomalies' in paleotemperature through time that may be used to improve paleoclimate reconstructions. In addition, the tool may provide boundary conditions to interpret paleobiology.



**Fig. 1:** Paleomagnetism.org web page.

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**Fabric of pyrrhotite mineralization in contact area between Neo-Proterozoic slates and Variscan granitoids revealed by the anisotropy of out-of-phase magnetic susceptibility (Central Bohemian Massif)**

František Hrouda (1), Jan Franěk (2), Jaromír Hanák (3), Marta Chlupáčová (4), Ondřej Švagera (2)

1) Agico Inc., Brno, Czech Republic

2) Czech Geological Survey, Prague, Czech Republic

3) Koretina 370/47, Lelekovice, Czech Republic

4) Boháčova 866/4, Praha, Czech Republic

Correspondence to: hrouda@agico.cz

**Keywords:** out-of-phase susceptibility anisotropy, pyrrhotite fabric

A detail study was made in the *Josef Gallery* at Mokrsko, where a contact between Neo-Proterozoic ortho-slates of the Jílové Belt and Variscan granitoids of the Central Bohemian Plutonic Complex is well exposed. The susceptibility carriers of the Barrandian Proterozoic and Sázava tonalite outside the *Josef Gallery* are paramagnetic mafic silicates and magnetite, while pyrrhotite was identified as important carrier of magnetism in the *Josef Gallery*. As the out-of-phase susceptibility is virtually zero in both paramagnetic minerals and magnetite and conspicuously non-zero in pyrrhotite, the anisotropy of out-of-phase magnetic susceptibility (opAMS) was used to investigate the fabric of pyrrhotite. In rocks of the Jílové Belt within *Josef Gallery*, pyrrhotite shows a conspicuous preferred orientation by crystal lattice and the opAMS foliations defined by the pyrrhotite basal planes are very steep and parallel to mesoscopic cleavage. In addition, the opAMS lineation is sub-horizontal, resulting from a very faint fan of pyrrhotite basal planes, and being parallel to the stretching lineation. In the granitoids (granodiorite to tonalite), in which the dominant AMS carrier is pyrrhotite, the opAMS foliations are also very steep, but approximately perpendicular to the cleavage and opAMS foliations in slates of the Jílové Belt. Their orientations correspond to those of frequent E-W subvertical quartz micro-dykes in tonalite that are parallel to ore veins. Also in these rocks, the pyrrhotite basal planes create a very faint fan, but its axis is very steep to vertical. Even though pyrrhotite is evidently secondary in the granitoids of the Central Bohemian Plutonic Complex, it displays a conspicuous preferred orientation by crystal lattice. This find opens numerous questions concerning the pyrrhotite mineralization in the region investigated and its time relationship to deformation phases identified by field structural research.

**Paleomagnetic study from Apan-Tecocomulco, Hidalgo, Mexico:  
Evidence of a geomagnetic excursion record**

Hector Ibarra-Ortega, Harald Böhnel, Alejandro Rodríguez-Trejo

Centro de Geociencias – Universidad Nacional Autónoma de México, Campus Juriquilla, Mexico

Correspondence to: hboehnel@geociencias.unam.mx

The earth's magnetic field show variations on their direction, magnitude and polarity over different time scales, including the geomagnetic excursions. Those events occur over short periods of time (geologically). In Mexico, due to its intense volcanic activity over the last 20 Ma, present a great large collection of different lava flows and volcanic structures. On the last 20 years, a big number of radio metrical dates and geochronology studies had been performed along the Mexican territory. It allows to the paleomagnetist to identify different potential sites to find a geomagnetic excursion. However, it represents a hard duty to find geomagnetic excursions in different volcanic structures, and corelate them with a precise radio metrical date. In this work, we present paleomagnetic and rock magnetism results from five volcanic units, collected on the Apan-Tecocomulco volcanic field, Hidalgo, Mexico, with ages ranging from 190 ka to 650 Ka (Garcia-Tovar et al, 2015). According to the geochronology and directional results, one of the lava flows with an age ca. 540 Ka, could correspond to the West Eifel 4 (579 Ka) or West Eifel 5 (555 Ka) event. Meanwhile, the other lava flows show a normal polarity. The evidence of a geomagnetic excursion record on central Mexico, allow out a better understanding of the nature of those geomagnetic events, in this work the precise dating of the units and short time between eruptions, can show some valuable information about timing on geomagnetic excursions.

## Evaluation of anthropogenic pollution degree at children's playgrounds in the city of Sofia using mineral magnetism

D. Ishlyamski, B. Georgieva, N. Jordanova

National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy of Sciences

Correspondence to: danielishlyamski95@abv.bg

**Keywords:** urban settled dust, environmental magnetism, anthropogenic pollution

Urban particulate matter (PM) pollution causes important injuries to human's health and especially to children who are more vulnerable to dust ingestion during outdoor activities. Therefore, settled dust at children's playgrounds, parks and kindergartens warrants specific attention and research. Magnetic study on a collection of settled dust material from 13 playgrounds located in the city of Sofia and several sub-urban areas in its vicinity had been carried out. The major goal of our study was to evaluate the degree of anthropogenic pollution and the quality of the environment at the urban playgrounds during different seasons (winter, summer, autumn). A set of rock-magnetic parameters (magnetic susceptibility, isothermal and anhysteretic remanence) was obtained for the dust collection comprising 51 samples. Identification of magnetic minerals was carried out by thermomagnetic analysis of high-temperature behavior of magnetic susceptibility and composite isothermal remanence thermal demagnetization. The magnetic data suggest that the main magnetic minerals are magnetite, maghemite and titanomagnetite. Bulk dust materials was divided in fine ( $d < 1$  mm) and coarse ( $d > 1$  mm) fractions and their magnetic parameters mentioned above were determined. The obtained mineral magnetic results are discussed in relation to the degree of anthropogenic pollution caused by local (point) and areal (distant) sources, related to the atmospheric air circulation in the city and the particulate matter (PM) distribution. Magnetic susceptibility of the fine dust fraction from locations, sampled in the autumn and winter is higher than the susceptibility of the coarse fraction. Contrary, magnetic susceptibility of the coarse fraction of the playground dust sampled in summer is higher than that of the fine fraction. It is concluded that fine-grained PM pollution predominates during the autumn-winter seasons, while during the summer local sources mostly from the automobile traffic cause dust pollution at playgrounds. Scanning electron microscopy observations on magnetic extracts from playground dusts show abundant anthropogenic particles (both of irregular shape and spherules). All anthropogenic particles are strongly enhanced in iron oxides and other chemical elements, like Pb, Zn and Sb.

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**Loess-paleosol sequence from central north Bulgaria as a unique detailed archive of the Middle – Late Pleistocene environmental change in SE Europe**

D. Jordanova (1), N. Jordanova (1), C. Laag (2), F. Lacroix (2), B. Georgieva (1), D. Ishlyamski (1), Y. Guyodo (2)

1) National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences, Acad. G. Bonchev str., block3, 1113 Sofia, Bulgaria

2) Institut de Physique du Globe de Paris, Université Paris VII - Paris Diderot, UMR7154, 1 rue Jussieu, 75238 Paris cedex 05, France

Correspondence to: diana\_jordanova77@abv.bg

**Keywords:** Loess, Paleosols, Environmental magnetism, Lower Danube, Tephra

Loess – paleosol sequences (LPSs) from lower Danube area are sensitive recorders of millennial timescale climate variability during the Pleistocene. Environmental magnetism studies on continuously sampled profiles improve our understanding of the processes and interactions between dust transport, sedimentation, and soil formation affected by climate, vegetation and time. Herein, we present results from mineral and rock magnetic studies of a 27 m long LPS sampled from the Suchia Kladenetz open pit quarry near the city of Pleven (central North Bulgaria). Continuous 2 cm resolution sampling allows for obtaining a detailed record of changing paleoenvironmental conditions during the last 800 ka. Systematic contrast between strongly magnetic paleosols and weakly magnetic loess units is punctuated by several sharp maxima associated with the visible 20 cm thick tephra layer in the second loess unit (L2) as well as four cryptotephra in older units. Magnetic mineralogy of the remanence-carrying magnetic fraction shows an increasing hematite content towards the top of the sequence revealing the effect of climate aridization. The content of pedogenic maghemite is enhanced in the second and third paleosols (developed during marine oxygen isotope stages 7 and 9 respectively) suggesting changed seasonality of precipitation, as compared to magnetite-dominated younger first paleosol and Holocene soil. Older paleosols in the Pleven sequence, correlated to MIS 13-15 and MIS 17-19 are characterized by low magnetic susceptibility enhancement. Cryptotephra layers are particularly well expressed by enhanced values of the anhysteretic remanence. Depth variations of the ratio of saturation isothermal remanence to magnetic susceptibility ( $SIRM/\chi$ ) closely follow changes in coarse silt content and thus, it is considered as a proxy for wind strength. Scanning electron microscopy observations on single grains from (crypto)tephra layers revealed the presence of volcanic ash particles in the sand grain size range (50 – 250 microns). Thus, complex interplay between variations in eolian dust sources (including ashes from volcanic eruptions) and climate dynamics are encrypted in the variations in mineralogy and grain size of the iron oxides.

This study is financially supported by Bulgarian National Science Fund through project No KP-06-N34/2.

## **Fire record in archaeological clay remains and soils – mechanisms and expression through mineral and rock magnetism**

Neli Jordanova

National Institute of Geophysics, Geodesy and Geography, Bulgarian Academy of Sciences

Correspondence to: neli\_jordanova@hotmail.com

Fire is recognized as a global phenomenon and wildfires play an important role in shaping Earth's climate. High temperatures are reached when vegetation and soil burn down during natural fires and considerably more profound effects result from controlled use of fire during human's evolution. Since iron and iron-containing mineral phases are abundant at the Earth's surface, their behavior and transformation paths during firing significantly influence materials' properties. Mineral magnetism is a sensitive and precise technique for evaluating the concentration, grain size and type of iron oxides in soil, sediments, rocks, dust, etc. In this overview contribution, the major pathways of thermal transformations of various iron (oxy)hydroxides present in soils/clays are summarized and compared. Special attention is paid to the important role of firing atmosphere on the final thermal transformation product of different Fe-containing minerals. Hematite is the ultimate transformation product during firing in oxidizing atmosphere, while reducing conditions systematically lead to magnetite's production. Examples of magnetic signature of natural soils affected by severe or milder wildfires are presented. Furthermore, special consideration is given to processes occurring during clay firing in different archaeological settings – open settlement fires, bonfires, kiln firing of pottery, etc. Mineral magnetic signature most commonly resulting from such settings is demonstrated by various case studies. Therefore, rock magnetic parameters obtained from archeological fired structures store important information about the environment and possible processes which lead to the appearance of certain set of iron-containing minerals and can be utilized for recovering these ancient processes. An important technological parameter in pottery production – ancient firing temperature – can be successfully recovered by magnetic susceptibility method. Application of the method to various settings and possible applications of the information obtained will be demonstrated by selected case studies.

**Palaeoenvironmental changes and anthropogenic impact  
recorded in floodplain sediments: A case study  
from the lower Morava River Basin (Czech Republic)**

J. Kadlec (1), I. Světlík (2), M. Rybníček (3), T. Kolář (3), E. Petrovský (1), H. Grison (1)

1) Institute of Geophysics CAS, Boční II/1401, 14100 Prague 4, Czech Republic

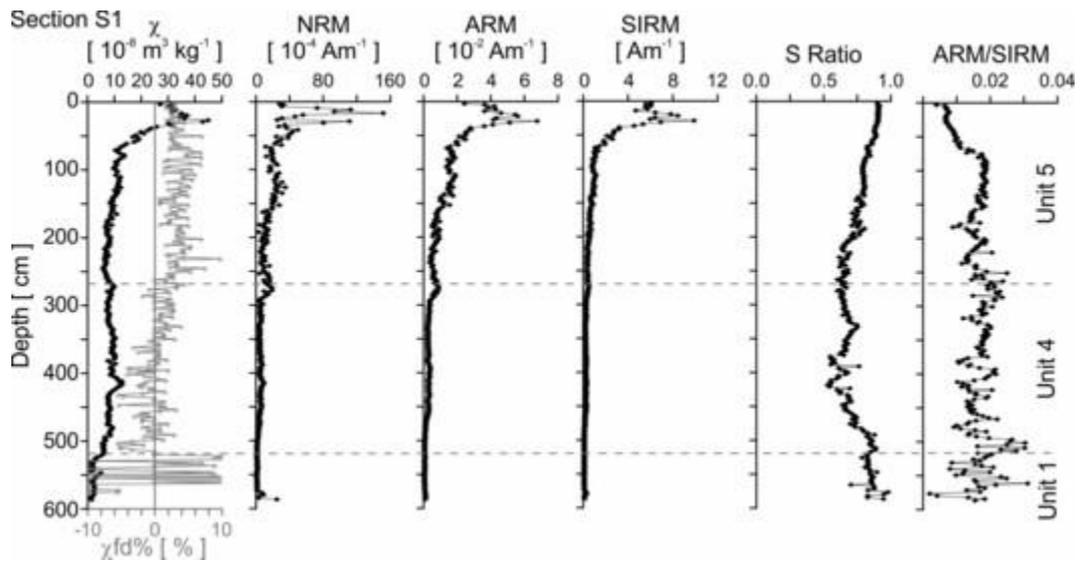
2) Nuclear Physics Institute CAS, CRL Radiocarbon Laboratory, Na Truhlářce 39/64, 18086 Prague 6, Czech Republic

3) Department of Wood Science and Wood Technology, Faculty of Forestry and Wood Technology, Mendel University in Brno, 61300 Brno, Czech Republic

Correspondence to: edp@ig.cas.cz

**Keywords:** flood frequency, soil erosion, human activities, magnetic minerals, dating

The Morava River catchment in the Czech Republic serves as sedimentary archive reflecting various natural and man-made processes, and was studied by several authors from the point of view of flood frequency, anthropogenic contamination, or alluvial history. However, more consistent and detailed information on the effect of human activities, namely in terms of land use and river regulation, is missing. The aim of this study is to reconstruct the palaeoenvironmental and anthropogenic processes affecting the floodplain sediments in this area, focusing on the last few hundreds of years. Alluvial sediments from river banks and cores down were collected in the Strážnické pomoraví area from sites both inside and outside dams constructed to avoid flooding. Magnetic parameters, reflecting the composition and grain-size distribution of iron oxides, which serve as fingerprints of lithogenic vs. pedogenic vs. anthropogenic origin, are complemented by the radiocarbon and dendrochronological dating. In addition, deposition age was estimated using the  $^{137}\text{Cs}$  activity and persistent organic pollutant content. Our results reveal continuous increase of ferrimagnetic mineral (magnetite) input to the floodplain, suggesting increased soil erosion in the catchment. Significantly different pattern was observed inside and outside the flood dykes. The erosion accelerated since the 1950s due to incorrect land use and introduction of modern agriculture techniques. Finally, the industrial pollution significantly contributes to the magnetic enhancement of the topmost 50 cm of the floodplain sequences. Although the results represent local case study, they have more general validity in the sense that record of palaeoenvironmental changes and human activities in floodplain sediments may not be well preserved in all the strata and also their spatial distribution of individual markers may show significant variability.



**Fig. 1:** Magnetic mineral characteristics along Section S1.  $\chi$  – low-field mass-specific magnetic susceptibility,  $\chi_{fd}\%$  – frequency-dependent susceptibility (anomalous values out of range not shown), NRM – natural remanent magnetization, ARM – anhysteretic remanent magnetization, SIRM – saturation isothermal remanent magnetization.

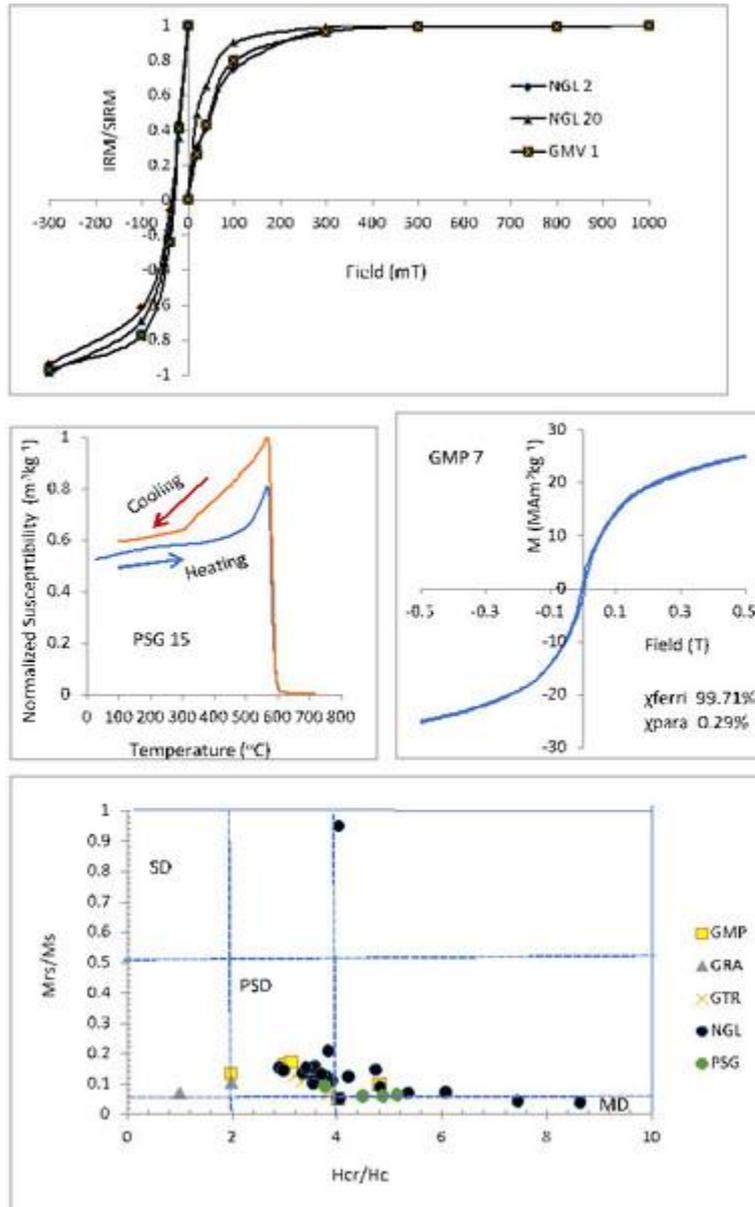
**Studies of magnetic and geochemical characteristics of lateritic soil  
in parts of Mambilla Plateau, Taraba State, NE Nigeria**

Maxwell O. Kanu (1), Osita C. Meludu (2), Nathani Basavaiah (3)

- 1) Taraba State University, Jalingo
  - 2) Modibbo Adama University of Technology, Yola
  - 3) Indian Institute of Geomagnetism, Mumbai
- Correspondence to: maxiexpress007@gmail.com

**Keywords:** magnetic susceptibility; geochemical; pollution; laterite; Mambilla plateau

The present study is aimed at providing data on the magnetic and geochemical properties of a lateritic soil as well as assesses possible anthropogenic influence on the soil. The magnetic properties which determines the concentration (e.g. magnetic susceptibility, anhysteretic and saturation isothermal remanent magnetizations), size of grains (e.g. hysteresis parameters) and mineralogy (e.g. thermomagnetic curves) were determined. Results obtained show high values in the magnetic concentration dependent properties as it indicates that the laterite soil is dominated by ferrimagnetic mineral. The mean values of magnetic susceptibility varied in the following order: motor park ( $1007.2 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ) > mechanic village ( $986.26 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ) > Primary school ( $774.82 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ) > farm land ( $773.93 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ) > tarred road ( $697.77 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ) > residential area ( $642.11 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ) > natural grazing land ( $264.24 \times 10^{-8} \text{ m}^3\text{kg}^{-1}$ ). The frequency dependent susceptibility data give evidence of the dominance of superparamagnetic grain size. The magnetic minerals in the soil is found to be dominated by low coercivity, soft magnetic fraction, basically magnetite with Curie-point temperature of  $\sim 580^\circ\text{C}$ . Information revealed from the Day plot and hysteresis parameters indicates that the magnetite is of the pseudo-single domain/ multi-domain origin. The XRF analysis revealed Al, Si, P, Ti, Fe, Zn, Br, Zr, Sn, Mg, Pb, Th, and U to exceed the geochemical background values. Strong positive correlation was seen to exist between the magnetic concentration indicating parameters ( $\chi_{lf}$ , SIRM and  $\chi_{ARM}$ ) and Ti, V, Cr, Mn, Fe, Ni, Cu, As and Zr. The level of contamination of the soil assessed using the enrichment factor, pollution load and geo-accumulation indices also show strong positive correlation with  $\chi_{lf}$  and SIRM. These strong associations of geochemical parameters and pollution indices with magnetic parameters suggest the possibility of magnetic parameters to serve as proxy for metal concentration in laterite soils. Two major sources of metal concentration in the Mambilla Plateau have been identified from principal component and cluster analyses to be from both crustal and anthropogenic sources.



**Fig. 1:** Magnetic properties of selected soil samples

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## Paleomagnetic and rock magnetic investigations of cave sediments in Lipiška Jama (Classical Karst, Slovenia)

Š. Kdýr (1), N. Zupan Hajna (2), A. Švara (2), P. Pruner (3), P. Bosák (3)

1) Institute of Geology of the Czech Academy of Sciences

2) Karst Research Institute ZRC SAZU

3) Institute of Geology of the Czech Academy of Sciences, Karst Research Institute ZRC SAZU

Correspondence to: kdyr@gli.cas.cz

**Keywords:** paleomagnetism; cave sediments; dating; rock magnetism

Cave sediments from the Lipiška Jama Cave, which is located on the south edge of the Kras Plateau, were the subject of the study. Lipiška Jama is a 1,400 m long, 20 degrees inclined to the SSW with a recent epiphreatic and vadose regime. The aim of this study was the paleomagnetic research of allogenic and flowstone sediments. We sampled three allogenic sedimentary profiles in distinctly developed cave levels (bottom, middle, top). Their thickness covers from 2 to 3 m (the bottom level – 2.08 m, the middle level – 3 m, the top level – 2.54 m). Except for the bottom level profile, disturbed with slides and slumps, all profiles were sampled with high resolution (Zupan-Hajna et al. 2008). Rock magnetic methods, such as the acquisition of isothermal remanent magnetization, S-ratio, anisotropy of magnetic susceptibility (AMS), etc., were implemented for magnetomineralogy characterization. Magnetic susceptibility shows a wide variation of values in all three profiles (374 – 1488 SI x 10<sup>-6</sup> in the bottom profile, 86 – 4,288 SI x 10<sup>-6</sup> in the middle profile, and 242 – 1,442 SI x 10<sup>-6</sup> in the top profile). A low coercivity mineral (e.g. magnetite) is identified as the main carrier of magnetization. The AMS shows dominantly oblate fabric, which corresponds to fine-grain sedimentation. Alternating field demagnetization was applied to determine characteristic remanent magnetization (ChRM). Primary magnetization, and the presence of both normal (N) and reverse (R) polarity samples, were determined. The profile in the bottom cave level, extensively influenced by slumps, displays a chaotic distribution of ChRM components. The profile in the middle cave level reveals R and N polarity zone within the allogenic sediment with the antipodal position of their mean directions, as well as basal flowstone with R polarity. The highest positioned profile reveals mainly R polarity and occasionally N polarity samples. Although the homogenous non-laminated clay forms this sedimentary sequence, AMS parameters reveal some samples suspected of slumps behaviour. The presence of R polarity zones within two studied profiles in Lipiška Jama suggests at least Matuyama's chron age. The result will be compared to Geomagnetic Polarity Time Scale (Ogg 2020) and correlated with other sections within the studied area of the Classical Karst.

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**Assessing the volume of defensive structures  
for architectural energetics analysis  
using 3D electrical resistivity tomography**

Radek Klanica (1), Hana Grison (1), Jindřich Šteffl (2), Roman Beránek (1)

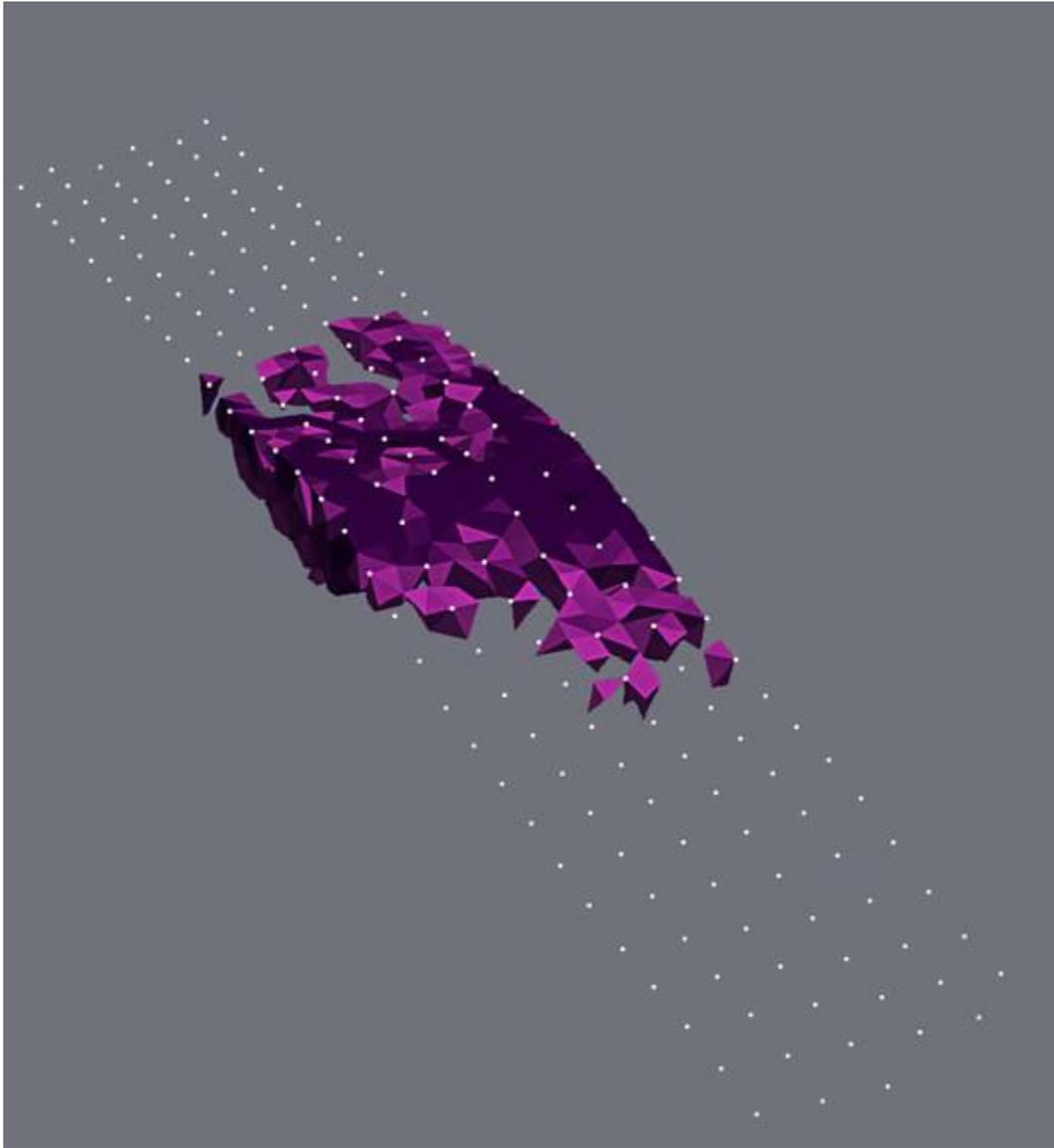
1) Institute of Geophysics ASCR, Prague, Czech Republic

2) Regional Museum in Teplice, Teplice, Czech Republic

Correspondence to: rk@ig.cas.cz

**Keywords:** electrical resistivity tomography, archaeological prospection, geophysics, hillfort, volume

Architectural energetics is a methodology that translates architectural objects into a quantitative time-labor equivalent, from which information about past societies, labor organizations, or political relations can be inferred. Preceding such study, the volume of every architectural structure must be determined. This is usually done by in-situ measurements and computing of volume by mathematical formulae or using photogrammetry based on unmanned aerial vehicles (UAV) processed into digital surface model. However, both of these methods are impracticable in the case of buried or semi-buried monuments where the only remaining option is direct excavation. Hence, we introduce a new method for the determination of volumetric information based on the electrical resistivity tomography (ERT) geophysical method. ERT can characterize the subsurface distribution of electrical resistivity in lateral and vertical directions and distinguish various archaeological features from the surrounding environment. We conducted our study at defensive lines (ramparts/ditches) within two hillforts of different ages, constructed from different building materials, in the Czech Republic. ERT surveys performed in 3D can differentiate ramparts/ditches in detail from the surrounding environment based on resistivity. Compared to previous excavations, the 3D inversion results show that ERT can obtain meaningful volumes based on the chosen resistivity threshold for both ramparts and ditches. The best results were achieved on homogeneous semi-buried ramparts and the ditch. ERT was able to access same volumetric information as obtained by mathematical formulae in case of very heterogeneous rampart. ERT can be performed at a fraction of the cost of direct excavation. This method also leaves an intact site for future generations. The results suggest that same methodology for obtaining of volume should be applicable also in other situations including different archaeological monuments or archaeological/pedological layers.



**Fig. 1:** Extracted resistivity structure of the rampart from hillfort Hradiš'any when the threshold of  $3162 \Omega\text{m}$  was applied. The white dots represent the individual positions of the electrodes.

This work was supported by the INTER-EXCELLENCE program of the Ministry of Education, Youth and Sport of the Czech Republic (MEYS), grant no. LTC19029.

## **Impact craters have their magnetizations reduced by impact plasma shielding**

Gunther Kletetschka (1), Marian Takac (2), Kurosh Karimi (2), Radana Kavkova (2), Hakan Ucar (2)

1) Faculty of Science, Charles University, Albertov 6, Prague, Czech Republic, Geophysical Institute, University of Alaska Fairbanks, 903 N Koyukuk Drive, Fairbanks, AK, USA, and Institute of Geology, Academy of Sciences, Prague, Czech Republic

2) Faculty of Science, Charles University, Albertov 6, Prague, Czech Republic

Correspondence to: kletetschka@gmail.com

**Keywords:** Impact cratering, Magnetic remanence, Magnetic anomalies, shock detection, Acraman and Santa Fe craters

The shock exposure of both the Santa Fe's impact structure in New Mexico and Acraman impact crater in south Australia is evidenced by shatter cones. We detected a magnetic mechanism revealing a plasma's presence during the impact processes. Rocks before the impacts were once magnetized by a geomagnetic field. An observed remanent magnetization of the shocked rocks was more than an order of magnitude lower than rocks formed in the presence of geomagnetic field. It was suggested that the impact generated plasma can generate magnetic shielding during the time scale that is comparable to the time when shock wave propagate through the rocks under the impact crater (Kletetschka et al, 2021). The incoming shock wave destabilizes the magnetic grains, so they are in a superparamagnetic-like state during the shock's exposure. The shielding of the ambient magnetic field prevents alignment of the magnetic vectors, leaving the individual magnetized grains in random orientations, and thus significantly lowering the overall magnetic intensity. Our data not only clarify how an impact process allows for a reduction of magnetic remanence but also inspire a new direction of effort to study impact sites, using paleointensity reduction as a new impact proxy.

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## Greigite in the changing seas of Central Eurasia

W. Krijgsman, M.J. Dekkers, D.V. Palcu

Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, The Netherlands

Correspondence to: W.Krijgsman@uu.nl

**Keywords:** Paratethys, paleomagnetism, magnetostratigraphy, iron sulphides

During the Oligocene-Miocene times a large waterbody known as Paratethys covered a big part of Central Eurasia. During its history this aquatic realm experienced diverse paleogeographic configurations that were reflected in diverse aquatic chemistries in the sub-basins of Paratethys that ranged from evaporitic, hypersaline, normal marine, brackish semi-marine or lacustrine to fresh-water environments.

We identify and date the major paleogeographic phases, controlled by the functioning marine gateways and document the specific environmental changes and that correspond to restriction events that created brackish “lake-seas” or connection events, that allow exchange between seas with negative and positive hydrological budgets and propose a paleoenvironmental chronology for the Paratethys.

Next we discuss the rock magnetic changes that are observed when changing from open marine seas, via restricted brackish-water basins, to isolated lake environments. We identify three types of greigite: 1) primary biomagnetic components, 2) early diagenetic components and 3) late diagenetic overprints. We show that greigite-based magnetostratigraphy on the first two components can be extremely useful to date these paleoenvironmental changes and to correlate them to the global climate and sea-level records. Finally, we combine the conservation of water and salt mass with strait-exchange theory to quantitatively link freshwater surface forcing and gateway dimensions to the observed paleoenvironmental changes.

**Mag-Instruments**  
**New research tools for paleo-, rock, and environmental magnetism**

P. Kryczka, S.C. Roud

Mag-Instruments UG, Munich, Germany

Correspondence to: [info@mag-instruments.com](mailto:info@mag-instruments.com)

**Keywords:** magnetometer, instrumentation, spinning magnetometry, paleomagnetism, paleointensity

Mag-Instruments is a young company developing state-of-the-art solutions for magnetic measurements by combining expertise in geophysics, robotics, and mechatronics. Here we will introduce our latest developments oriented towards research in paleo-, rock and environmental magnetism: the Triaxe 2.0 for fully integrated full-vector magnetic measurements during thermal demagnetization and a new generation of ultra-sensitive spinning magnetometers. The Triaxe 2.0 is a three-in-one tabletop device combining a three-axis vibrating-sample magnetometer (VSM) with a dynamic range of  $10^{-8}$ -1 Am<sup>2</sup>, thermal demagnetization up to 800°C and 3D Helmholtz coils to impart thermomagnetic remanence in homogenous fields up to 1.7 mT. Precise feedback control of sample temperature and feed-forward control of the applied magnetic field together with automatic measurement sequences facilitate user-friendly, rapid paleomagnetic measurements and make the Triaxe particularly useful for absolute paleointensity experiments. Apart from explaining the instruments capabilities we will present experimental data to demonstrate applications in paleomagnetism. We will also report on current developments bringing together spinning magnetometry and state-of-the-art sensing technologies to deliver a low-maintenance, affordable alternative for SQUID based cryogenic rock magnetometers. The instrument will bring the ultra-low level magnetic measurements into regular laboratories, which previously could not afford instrumentation at this sensitivity level.

## Analog modelling: shear strain-AMS relationship

V.K. Kusbach, Z. Roxerová, M. Machek

Institute of Geophysics of the Czech Academy of Sciences, Prague, Czechia

Correspondence to: kusbach@ig.cas.cz

**Keywords:** simple shear, AMS, deformation, microstructure, localization

Structural pattern recorded within shear zones has long been a subject of intense research in geology. The mechanisms of deformation during the evolution of shear zones depends both on the character of lithology such as mineralogical composition, grain size, etc. and the physical conditions such as pressure and temperature, strain rate, presence of fluid, etc. The development of shear zones has been also studied by many numerical and analogue experiments. Analogue modelling techniques provide a powerful and important tool for the spatial and temporal investigation of various tectonic processes. The great advantage is its potential to incorporate models of complicated rheologies of natural rocks. However, rock analogue materials used usually in laboratory experiments of ductile shear zones are typically homogeneous and isotropic. In order to maintain the material complexity and to effectively realize the deformation localization coupled with an easy handling with the material, we have been working on experimental modelling using the plaster of Paris. The used analogue material displays a peculiar strain-rate dependent rheology (thixotropy) and is capable to well-reproduce the strain localization up to brittle failure corresponding thus to natural rocks. This approach enabled us to describe the internal fabric pattern thanks to obtained AMS from dispersed magnetic particles and coloured layers. We explore the space and time relationships between the finite strain, deformation structures and the AMS. By changing experimental strain rate, we are able to model not only ductile to brittle behaviour of the shear zones, but also observe the AMS evolution with the localization of strain. A correlation is observed between the strain rate and the width of the shear zone identified from the reoriented magnetic fabric. The AMS shape parameter  $T$  from the edge of the shear zone to its core reveals an interesting development. AMS ellipsoid changes from background primary fabric to more prolate shapes in shear zone margins and then back to more neutral shapes in core of the shear zone. This gradual development is probably connected with transposition of strong initial fabric, its gradual reorientation and superposition of newly formed synkinematic conjugate subfabrics and anastomosing shears in the middle of the shear zone. Our experiments suggest that the AMS-strain relationship is not straightforward and that localization and partitioning of deformation on microscale is most important for interpretation of AMS in deformation zones and flow gradients recorded in natural rocks. Therefore, the proper interpretation of an AMS fabric (not only from shear zones) requires additional structural information to be correctly interpreted.

**Changing sediment supply during Glacial-Interglacial intervals  
in the North Atlantic revealed by particle size characterization  
and environmental magnetism**

Stephanie Leone

University of São Paulo, São Paulo, Brazil

Correspondence to: stephanie-leone@outlook.com

**Keywords:** Pliocene, intensification of the Northern Hemisphere Glaciation, DSDP Leg 94 Hole 611A, environmental magnetism, particle size characterization

Since the late Miocene, Earth's Northern Hemisphere experienced sustained cooling that culminated with glaciation episodes (ice-ages). The Pliocene-Pleistocene transition is characterized by an abundance of Ice-Rafted Debris (IRD) indicating the intensification of the Northern Hemisphere Glaciation (iNGH). One of the regions affected in this epoch by IRD is Gardar Drift, where the DSDP Leg 94 Hole 611A is located. This region received sediments from different sources, like Greenland and Iceland. We analyzed physical and magnetic grain size variations for characterization of distinct sediment sources during ~2.7 to 2.5 Ma. Our work shows a higher sand input with coarser magnetic grain size in the glacial periods and vice-versa. Sediments in most parts of the studied core are basaltic in origin, while more non-basaltic sediments are deposited in the glacial periods, with some presence of IRD. The substantial deep water current variations explain the difference in ferrimagnetic fraction during glacial and interglacial periods, i.e., a decrease in North Atlantic Deep Water (NADW) and water masses associated with glacial times are associated with an increase in IRD deposition and higher concentration of coarse-grained magnetite particles.

## **Magnetic biomonitoring of traffic-related particulate matter deposition: The effect of the earth-berm noise barriers along a motorway**

S. Letaief, P. Camps, D. Bosch, T. Poidras, P. Nicol, O. Bruguier

Géosciences Montpellier, University of Montpellier and CNRS, Montpellier, France.

Correspondence to: sarah.letaief@umontpellier.fr

**Keywords:** traffic-related PM, motorway, environmental magnetism, geochemistry, modeling.

This study takes part to a broader project focusing on the role of three hedgerows on air quality from a test site located along a 12-lanes motorway east to Montpellier city, France. The noise control is achieved with two configurations, three berms having a basic design, the fourth located windward to the traffic being roofed with a precast concrete wall. A current direct measurement of traffic-related particulate matter concentrations is performed by the regional air agency, Atmo-Occitanie by means of a network of 14 dust  $\mu$ -sensors. We propose to complete this monitoring with magnetic and geochemical analyses in order to characterize PM depositions and their accumulations on plant leaves, soils and low-cost artificial filters. Results from X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) analyses confirm that PM deposition on study area have mainly a traffic origin. Investigations of their sources reveal that they are derived from combustion residues, break, vehicles and highway equipment wears. These trace metals are often directly associated to magnetic particles formed during combustion processes. That is why magnetic PM can be used as a proxy for air pollution if only combined occurrence with other pollutant is proved. To this end, relative variation of isothermal remanent magnetization (IRM) was correlated with trace metals concentrations. Basically, two filter campaigns during 90 days each and an annual sampling of soil and leaves from endemic Mediterranean species such as: *Ciste Monspeliensis*, *Acer Monspessulanum*, *Quercus Ilex*, *Coronilla Valentina*, *Acer Platanoides* and *Cercis Siliquastrum* have been conducted in 2019. Results obtained from the analysis of the accumulation surfaces are in line with the  $\mu$ -sensors measurements. Maximum relative variation of IRM are detected downstream of the berm wall combination while no significant deposition is observed on both sides of the basic berms. Because the carriageways are located in the lee of the former, this observation seems to be counterintuitive. For that reason and to complement magnetic analysis, a computational fluid dynamics modeling based on the Reynold-Averaged Navier-Stokes (RANS) equations with the standard k- $\epsilon$  turbulence approach was performed and predicts as well, a recirculated pollution downstream to the berm wall combination, whereas the free-wall berm geometry does not alter air pollution transport and dispersion.

**Is the magnetic characterization of traffic-related PM sources able to determine the contribution of each source in the total magnetic signal released by traffic?**

Sarah Letaïef (1), Claire Carvallo (2), Christine Franke (3), Aude Isambert (4), Pierre Camps (1), Patrick Nicol (1)

1) Géosciences Montpellier, University of Montpellier and CNRS, Montpellier, France

2) IMPMC, Sorbonne University, Paris, France

3) MINES-ParisTech, Fontainebleau, France

4) IPG-Paris, France

Correspondence to: sarah.letaief@umontpellier.fr

**Keywords:** Environmental Magnetism, Traffic Pollution, Machine Learning.

The interest of the environmental magnetism to air quality monitoring has greatly increased during the last decades. Correlations between the chemical compositions and various magnetic parameters have been already established, for instance, between Saturated Isothermal Remanent Magnetization (SIRM) parameter measured on plant leaves with the traffic-related Pb concentrations despite that leaded fuel has been forbidden in Europe since 2000 (Maher et al., 2008); or, between magnetic signature and element content from the atmospheric dust accumulations observed by microscopy and magnetically on plant leaves (Castanheiro et al., 2020). In addition, a recent study compared the  $IRM_{1000mT}$  relative changes values with a numerical modelling for  $PM_{2.5}$  and  $PM_{10}$  dispersions along a motorway (Letaïef et al., 2020), where the PM concentration trends forecasted by the model explain very well the magnetic measurements made on field. This magnetic method seems to be precise enough to be able to detect small variations at small-scale, street-level, whatever the accumulative surface used (plant leaves or PM filter-collected; Letaïef et al., 2022 submitted). However, a question remains: what are we truly measuring with this magnetic monitoring technique, especially when we assume that not all the pollutants are magnetics? For this purpose, different type of traffic-related PM sources and sensors such as: combustion residues, brake pads, tires, street canyon dust, and passive filters or plant leaves were collected and magnetic properties were analyzed. We measured susceptibility against temperature curves, hysteresis loops, FORCs diagrams and IRM acquisition curves. We found that source fingerprints are well highlighted by combining the different approaches that covers environmental magnetism. By comparing the magnetic source fingerprints with those measured on sensors, this study will help determining the contribution of each source in the total magnetic signal measured or at least establishing the main traffic source. In that way, data from the different magnetic approaches were reduced into 1 or 2 characteristic parameters. These parameters and additional data as XRF and MEB analyses were then used as input settings for a machine learning protocol. These results will allow us to assess whether magnetic measurements can be brought to such a degree of confidence that they could be useful for citizens and public policies.

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## Relevance of quantitative microstructural analysis for AMS interpretation

M. Machek (1), Z. Roxerová (1), V.K. Kusbach (1), P. Závada (1), P.F. Silva (2), M. Racek (3)

1) Institute of Geophysics of the Czech Academy of Sciences, Prague, Czechia

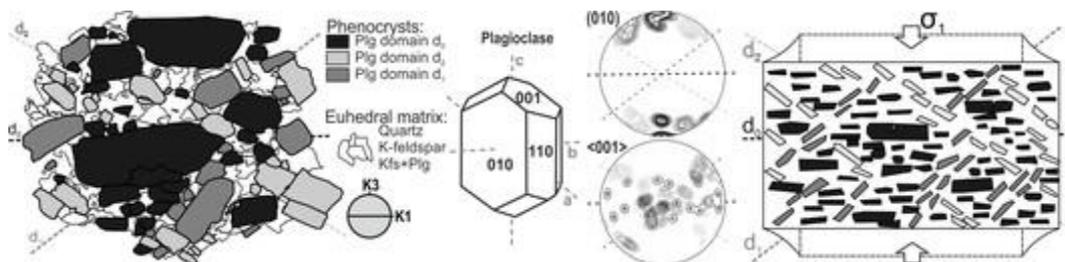
2) Instituto Dom Luiz (IDL - Univ. Lisboa), Lisbon, Portugal

3) Charles University Prague, Institute of Petrology and Structural Geology, Prague, Czechia

Correspondence to: mates@ig.cas.cz

**Keywords:** AMS, microstructure, deformation,

Anisotropy of magnetic susceptibility (AMS) as a dimensionless material parameter indicates the degree of magnetization of a sample in response to an applied magnetic field in different directions. AMS measurements reflect an integrated magnetic signal of crystallographic and shape preferred orientation of all mineral grains forming the rock. Rock microstructures are a consequence of superpositions of a wide variety of processes, such as sedimentation, diagenesis, magma flow, deformation and metamorphism. These processes give origin to individual subfabrics, which form the microstructure during rock evolution. Consequently, the microstructure of a rock is often a complex combination of distinct microstructural features of diverse origins, orientations and strengths. Therefore, it is not only important to evaluate the contributions of the main susceptibility carriers to the anisotropy, but identify also the processes responsible for the AMS development and eventual superpositions of corresponding fabrics. On the example of two different rock types with different rock fabric origin we demonstrate the relevance of microstructural analysis for the AMS and its successful geological interpretation. In concentrically expanded Castle Crag pluton (CA, USA) the flow of dense crystal mush accommodated by self-organized slip of crystals was identified. The pluton structure was interpreted to be a result of compaction, melt segregation, cumulate formation and subsolidus overprint caused by the intrusion of trondhjemite magma in the core of the pluton. All these processes are by corresponding textures connected with the AMS and explained based on microstructural observation by crystal mush deformation process. The study of small-scale shear zone in marble (Ossa-Morena Zone, Portugal) showed that the localization of deformation at conditions of dislocation creep leads to the contemporaneous evolution of two microstructural subfabrics. The combination of their respective magnetic signals results in discordant orientation of AMS and local macroscopic fabric and also influences the shape and strength of magnetic anisotropy. The AMS in the shear zone corresponds to the magnitude and character of deformation only indirectly and it rather reflects the proportion and orientation between subfabrics originating from localization of deformation. The successful interpretation of magnetic signal was possible in both studies only using methods of quantitative microstructural analysis, which enabled us to reveal the mechanism of rock fabric formation.



**Fig. 1:** From left to right, the Castle Crag pluton granodiorite microstructure, ideal shape of plagioclase phenocryst, corresponding crystallographic preferred orientation of plagioclase phenocrysts and schematic sketch of the microstructure origin.

## Identification of technogenic magnetic particles from different pollution sources by magnetic proxies

Tadeusz Magiera (1), Beata Górka-Kostrubiec (2), Marzena Rachwał (1), Tadeusz Szumiata (3)

1) Institute of Environmental Engineering, Polish Academy of Sciences, Zabrze, Poland

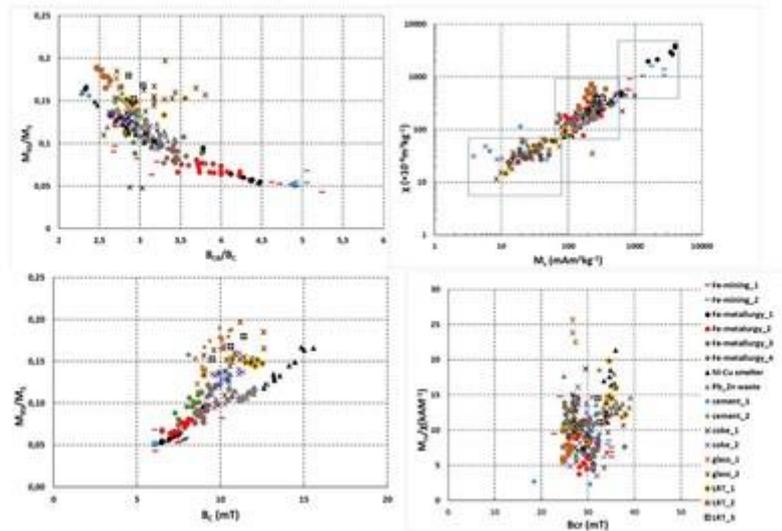
2) Institute of Geophysics, Polish Academy of Sciences, Ks. Janusza 64, 01-452 Warsaw, Poland

3) Department of Physics, University of Technology and Humanities in Radom, Poland

Correspondence to: tadeusz.magiera@ipis.zabrze.pl

**Keywords:** technogenic magnetic particles, Mössbauer spectrometry, hysteresis parameters, soil pollution

The subject of the study were technogenic magnetic particles (TMPs), defined as “magnetite-like” phases, formed during wide variety of high temperature technological processes, which are emitted to the atmosphere and deposited to the soil in the vicinity of the emitters (Magiera et al., 2011). The aim of our study was to characterize the TMPs from different industrial sources by means of magnetic parameters and Mössbauer spectra to identify parameters that are indicative and discriminative enough to be potentially used as indicators of the source of soil pollution. Topsoil samples were collected in the vicinity of different pollution sources (iron and steelworks, iron mines, coking plants, Ni-Cu and Pb-Zn smelters, cement plants, glass works and areas influenced by long-range transport) located in 3 European countries (Poland, Norway and Czech Republic). TMPs derived from different emission sources (formed in different conditions) are “magnetite-like” particles with low stoichiometry and therefore they can be easily discriminated from the stoichiometric geogenic magnetite, which is MD magnetite. In Mössbauer spectra TMPs are manifested by much lower  $P(B)/P(A)$  ratio than theoretical 2.0, which is typically indicated for stoichiometric magnetite. In the case of TMPs collected from the topsoil from the vicinity of steel and ironworks, the ratio of  $P(B)/P(A)$ , which represents the degree of stoichiometry, was usually less than 1.3, whereas allogenic magnetic particles, related to the iron mining activity, exhibited higher stoichiometry with  $P(B)/P(A)$  ratio between 1.3 and 1.6 (Magiera et al., 2021). Soil samples collected around iron and steelworks and iron-ore processing plants have the highest  $\chi$  values and very low values of frequency dependence of magnetic susceptibility ( $\chi_{fd}\%$ ), usually less than 2.0%, suggests that the content of superparamagnetic grains is negligible. All the investigated particles typical for iron metallurgy and iron mining exhibited the  $Mrs/Ms$  ratio of less than 0.15 and  $Bcr/Bc$  ratio from 2.5 to 6.0 and  $Mrs/\chi$  ratio from 3.5 to 15. On the Day diagram they are grouped close to the MD/PSD border or in the area around PSD. TMPs from long-range transport and glass production exhibited the considerable admixture of SD particles. Mössbauer spectroscopic analysis revealed the surface oxidation/magnetization that was especially intensively observed in samples collected in the vicinity of old plants operating 180 years. The effect of low stoichiometry and surface oxidation (noticeable also in TMPs from long-range transport) can influence the position of TMPs on the Day diagram shifting them toward the area for finer PSD grains, whereas the core particles are probably the MD fraction (Roberts et al., 2018). The mean values of the hyperfine sextet field for the A and B positions of iron in the studied magnetic concentrates suggested that octahedral sites are more sensitive to various defects of the magnetite crystal structure in TMPs.



**Fig. 1:** Magnetic ratios:  $B_{cr}/B_c$  vs.  $M_{rs}/M_s$  (upper left); magnetic susceptibility ( $\chi$ ) vs. saturation magnetization ( $M_s$ ) (upper right); coercivity ( $B_c$ ) vs. magnetization ratio  $M_{rs}/M_s$  (lower left); coercivity remanence ( $B_{cr}$ ) vs. ratio of  $M_{rs}/\chi$  (lower right).

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## ISO 21226: 2019 - "Soil quality - Guideline for the screening of soil polluted with toxic elements using soil magnetometry"

Tadeusz Magiera

Institute of Environmental Engineering, Polish Academy of Sciences, Zabrze, Poland

Correspondence to: tadeusz.magiera@ipispan.edu.pl

**Keywords:** magnetic susceptibility, soil pollution, soil mapping, ISO standard

ISO 21226 is the world's first standardized method that uses soil magnetometry in environmental analyzes. For this purpose, a standard procedure, protocols and guidelines for the using soil magnetometry as a screening method were developed. There has been described the procedure of pre-screening to support the implementation of the two-stage optimized geophysical/geochemical method of measuring the spatial distribution of trace elements pollution from the dry and wet deposition, for further delineation of potentially polluted areas, in order to set up adequate management and control systems. The method provides data on the volume-specific magnetic susceptibility ( $\kappa$ ), which reflects cumulative anthropogenic pollution of soil with trace elements, expressed as a Pollution Load Index (PLI). The method is intended to serve as a screening and early warning system to be applied at any scale, from local to large regional one, also for the investigation of a long-range airborne transport. The application of this screening method alone does not allow determining the kind and concentrations of specific trace elements in soils. To carry out a more precise survey soil magnetometry as the screening geophysical "in situ" measurement technique (the 1st stage) has to be integrated with the classical geochemical methods (the 2nd stage) as the optimized procedure. The results of measurements are used for preparing the maps of magnetic susceptibility of soils in the area of interest. Specifically, on the basis of geophysical methods used for screening, a relevant dense geochemical monitoring network can be applied exactly in the areas of diagnosed elevated risk, thus reducing the number of samples and chemical analyses required in potentially "less-polluted" areas. From these maps, the areas of elevated and high magnetic susceptibility, indicating potentially high PLI, can be precisely delineated for further identification of pollutants by geochemical methods, using targeted sampling. In rare cases, some soils are developed on bedrock exhibiting geogenically high magnetism, which can cause false-positive results. This influence can, however, be easily indicated by measurements of magnetic susceptibility along vertical soil profiles. In general, the topsoil magnetic susceptibility values can be classified:

- in the range within 0 to  $30 \times 10^{-5}$  SI magnetic units, considered to indicate low probability of pollution (only single control samples should be collected);
- in the range within  $30 \times$  to  $70 \times 10^{-5}$  SI magnetic units, indicating moderate probability of pollution (some control samples are required);
- in the range within  $70 \times$  to  $100 \times 10^{-5}$  SI magnetic units, indicating high probability of pollution (regular geochemical sampling);
- $>100 \times 10^{-5}$  SI magnetic units, indicating that at least one element concentration is above the threshold value) high pollution with trace elements (the intense targeted sampling is required).

**Global insights into the behaviour of the Earth's magnetic field  
during 700–900 ka: Results from a new spherical harmonic field model**

A. Nasser Mahgoub, M. Korte, S. Panovska

Helmholtz Zentrum Potsdam. Deutsches GeoForschung Zentrum GFZ, D-14473 Potsdam, Germany

Correspondence to: [ahmedn@gfz-potsdam.de](mailto:ahmedn@gfz-potsdam.de)

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**Perspectives on magnetic research of sediments  
of Northern Velebit deep caves, Dinaric karst, Croatia**

Maja Marinić (1), Dalibor Paar (1), Stanislav Frančičković-Bilinski (2)

1) Faculty of Science, University of Zagreb, Croatia

2) Ruđer Bošković Institute, Zagreb, Croatia

Correspondence to: dpaar@phy.hr

**Keywords:** magnetic research, Dinaric karst, deep caves, Croatia

Caves formed in karst terrains are often trapping big amounts of different kinds of sediments. Cave sediments can be very useful for the determination of conditions and processes that were present at the time of their deposition. They are usually well preserved so they can give us a lot of information about changing of the conditions over a long period (sometimes even over a few million years). One of the key methods that can provide us with a deeper insight into the complex karst systems is magnetic susceptibility, which shows the magnetism of measured material. Magnetic susceptibility measuring allows recognition of iron-rich minerals (together with their concentration and volume), classification of different types of materials and a better understanding of tectonic events. This is also particularly important in the context of exploration of karst waters that are important from the aspect of vulnerable karst ecosystems and strategic reserves of drinking water. In this research, two caves were chosen for sediment analysis. Both caves are located in the northern part of Velebit mountain, named Nedam and Ledena jama. Nedam is Croatia's fourth deepest pit with a depth of 1021 m. Ledena jama, is 536 m deep pit that is significant by the perennial ice between depths of 50 and 160 m, and is located in a paleoglacier valley. Nedam is located on steeper and more inaccessible karst terrain. The entrances are at different altitudes – at 1420 m for Nedam, and at 1235 m for Ledena jama. That altitude difference and different terrain morphology (paleoglacier valley vs. steep karst), suggest that interesting differences in the sediments studied may be present. Sediment samples were taken at 50 m depth in Ledena jama, and at 100 m depth in Nedam. Preliminary magnetic measurements were performed using the SM30 instrument (ZH instruments). The additional analyzes made on the sediment samples were the determination of mineralogical composition – identification of clay minerals by X-ray diffraction analysis, separation of light and heavy mineral fraction, and observing under the microscope. Magnetic research provides complementary data to these methods. From this analyzes, we can deduce the province of the sediments, and some conditions that were present during their deposition and terrain formation. The mineral composition of the samples from both pits was compared. This work was done in collaboration with Northern Velebit National Park, Krasno (project Exploration of the deep pits of the Northern Velebit National Park), Department of Geology, Faculty of Science, University of Zagreb and Speleological Society Velebit, Zagreb.

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**Increased weathering and anoxic conditions  
in the late Norian-early Rhaetian interval  
from rock magnetism and geochemistry  
of Pignola-Abriola (Italy) and Kiritihere (New Zealand) sections**

M. Maron (1), T. Onoue (2), S. Satolli (1), K. Soda (3), H. Sato (2), G. Muttoni (4), M. Rigo (5)

1) Department of Engineering and Geology, University "G. D'Annunzio" of Chieti-Pescara

2) Department of Earth and Planetary Sciences, Kyushu University

3) Center for Advanced Marine Core Research, Kochi University

4) Department of Earth Sciences "Ardito Desio", University of Milano

5) Department of Geosciences, University of Padova

Correspondence to: [matteo.maron@unich.it](mailto:matteo.maron@unich.it)

**Keywords:** Upper Triassic, rock magnetism, paleoclimate, geochemistry

The late Norian-early Rhaetian (Late Triassic) interval is characterized by a major biotic turnover that involved both marine and terrestrial fauna (conodonts, ammonoids, bivalves and theropods), which seems to be linked to a climate perturbation that began in the Sevatian (upper Norian, ca. 216 Ma) and persisted up to the Rhaetian (ca. 206 Ma). In order to obtain information about the climatic perturbation occurred across the Norian/Rhaetian boundary (NRB), we applied a rock magnetic investigation to the Upper Triassic marine section of Pignola-Abriola (Lagonegro Basin, Italy; candidate GSSP for the Rhaetian Stage) and of Kiritihere (North Island, New Zealand). Both these sections have been broadly investigated by biostratigraphic and chemostratigraphic studies. We have thus compared the rock magnetic analyses (ARM, IRM, magnetic susceptibility, hysteresis loops) with the geochemical data from Pignola-Abriola and Kiritihere, obtaining a new insight about the paleoclimatic conditions across the Norian/Rhaetian boundary. Both rock magnetic and geochemical data revealed two phases of increasing weathering in the Sevatian and across the Norian/Rhaetian boundary. A relevant  $\delta^{13}\text{C}_{\text{org}}$  perturbation occurred in concomitance to the Norian-Rhaetian biotic crisis, leading to a negative carbon isotope excursion at the NRB, marked by the disappearance of monotid bivalves and close to the first appearance of conodont *Misikella posthernsteini*, suggested biomarker for the base of the Rhaetian.

## Magnetic and mercury fingerprint of burnt soils from Portugal

Rui Melo (1), Eric Font (1,2), Joana Ribeiro (1,3)

1) Department of Earth Sciences, University of Coimbra, 3030 790 Coimbra, Portugal

2) Instituto Dom Luís (IDL), Faculdade de Ciências, Universidade de Lisboa, 1749-026 Lisboa, Lisboa, Portugal

3) Institute of Earth Science - Porto Pole, Rua do Campo Alegre 687, 4169-007 Porto, Portugal

Correspondence to: ruileandromelo@gmail.com

**Keywords:** soils, forest fire, magnetite, mercury, Portugal.

Forest fire is a well-known process that leads to the formation of new magnetic minerals in soils (Clement et al., 2011; Jordanova et al., 2016; Till et al., 2021), charred organic particles (Belcher et al., 2018), as well as the remobilization of mercury (Hg) resulting from anthropogenic and natural (volcanic) sources (Witt et al., 2009). However, the origin of the magnetic enhancement, organic and/or lithogenic, as well as the fate of the Hg emitted in the atmosphere is still poorly studied. Here, we studied non-burnt and burnt soils and the underlying meso-cenozoic sedimentary cover from Pedrogão Grande (Portugal). The forest fire of Pedrogão Grande started on June 17, 2017, in the district of Leiria, causing 66 fatalities and 254 injured people. We measured the magnetic properties of the soil samples, namely the magnetic susceptibility and the analysis of isothermal remanent magnetization curves. We also measured the Hg content by atomic absorption spectrometry and conducted scanning electron microscopic observation of the burnt vegetal cover. The results show that the enhanced magnetization and magnetic susceptibility of burnt soils is due to higher content of lithogenic titanomagnetite, probably supplied by dust lately deposited onto organic particles. The Hg content is higher in the burnt soils than in the underlying sedimentary cover, but still need to be normalized by TOC in the future to truly reflect the fixation or the evaporation of Hg originally contained in the organic matter.

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**Peak ring magnetism of the Chicxulub Impact Crater derived  
from rock and mineral magnetic properties  
of the IODP-ICDP drill core M0077A**

Bruno Daniel Leite Mendes (1), Agnes Kontny (1), Bonny W. M. Kuipers (2), Mark J. Dekkers (2)

1) Karlsruhe Institute of Technology, Germany

2) Utrecht University, The Netherlands

Correspondence to: bruno.mendes@kit.edu

**Keywords:** Chicxulub, Peak Ring, Magnetite, Magnetism, Thermal Annealing

The Chicxulub impact event at approx. 66 Ma left in its wake the only complex crater on earth with a preserved peak ring, a concentric ring around halfway between the rim and center of the crater. This structure formed by the interaction of the outward collapsing central uplift and inward collapsing transient wall, and is characterized by a well-developed magnetic anomaly low. The magneto-mineralogical origin of this anomaly is poorly constrained and impact-generated melt versus hydrothermal activity models are discussed. The IODP-ICDP Expedition 364 drill core M0077A revealed that the peak ring consists of uplifted basement granitoid rocks of Variscan age overlain by a 130m thick impact melt and suevite layer. Pre- and post-impact hydrothermal systems affected this basement with maximum temperatures up to 450°C. The main goal of our study is to investigate the effects of heat on shocked (Ti-) magnetite, the most important magnetic mineral in the shocked granitoid basement and impact lithologies from drill core M0077A. We used microscopy, mineral chemistry, temperature-dependent magnetic susceptibility and hysteresis properties, to characterize the magnetic mineralogy related to pre-, syn- and post-impact processes. We have identified three main magnetic carriers in the peak ring: (1) Pure, stoichiometric shocked magnetite in the granitoid basement which has a significantly decreased magnetic susceptibility; (2) Cation substituted magnetite in the melt rocks with varying compositions and varying degrees of cation disorder, which carries a marked induced and remnant magnetization; (3) Small hydrothermally formed pure magnetite, which plays a subordinate role for the magnetization of the rocks. In the basement, the shock from the impact induced lattice defects and fractures in magnetite, which are responsible for a demagnetization and decrease in magnetic susceptibility. Here, pure magnetite is partially oxidized to hematite (martite) by a pre-impact Permian hydrothermal event, which is locally retransformed to magnetite close to lithological contacts with high temperature impact melt rocks. This retransformation creates small magnetic grains, susceptible to oxidation. Susceptibility in the basement is about one order of magnitude lower when compared with other Variscan granites exposed to similar Permian hydrothermal alteration. Furthermore, either the temperature reached by the hydrothermal system was too low or the fluids not reducing enough for martite to retransform to magnetite elsewhere in the basement, away from the contacts with the impact melt. Temperature was also too low to anneal the lattice defects in the shocked magnetite, which we found to occur above 540 °C. The presence of shocked magnetite in the granitoid basement well explains the magnetic anomaly low.

## Man-made pollution assessment in Lviv (Ukraine) by soil magnetic analyzes

Oleksandr Menshov (1), Oleksandr Kruglov (2), Roman Kuderavets (3), Olena Andreeva (1)

1) Taras Shevchenko National University of Kyiv

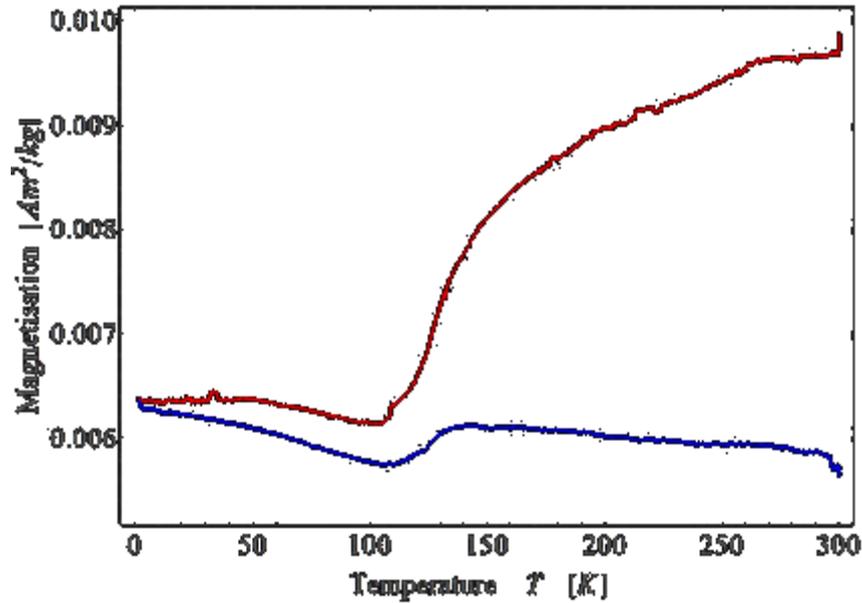
2) Institute for Soil Science and Agrochemistry Research n. a. O.N. Sokolovskiy

3) Carpathian Branch of Subbotin Institute of Geophysics of the NAS of Ukraine

Correspondence to: menshov.o@ukr.net

**Keywords:** soil magnetism, pollution, magnetic susceptibility, magnetic minerals

Soil magnetic measurements are used increasingly to estimate the impact of airborne, combustion-related particulate matter pollution in urbanized areas and big agglomerations (Declercq et al., 2019). The study of the soil magnetism in Ukraine includes several fields of the application: soil and air pollution assessment, oil and gas prospecting, agricultural lands mapping, archaeology, and landslides monitoring. In this study, we focused on the pollution assessment in the Western part of Ukraine. Previously, we performed the magnetic and mineralogy analyzes of the soil and dust from the semi-urban area of Truskavets which is mineral-water resort of Ukraine (Menshov et al., 2016). Now, we obtained new magnetic data from Lviv as a main agglomeration in the West of Ukraine. Magnetic studies included field measurements of the volume magnetic susceptibility  $\kappa$ , and soil sampling. The sampling was performed at the natural and polluted areas. The Lychakiv cemetery was selected as the area for the natural soil studies. Haplic Gleysols Dystric and Umbric Albeluvisols Abruptic (in WRB soil classification) were predominance natural soil. Such soils are characterized as slightly magnetic in Ukraine. The urban polluted soil was studied at several areas of observation in Lviv. We attracted both measurements along the cross-section and under the areal spatial investigation. At the laboratory, we measured and calculated mass-specific magnetic susceptibility  $\chi$ , its frequency dependence  $\chi_{fd}$ , isothermal remanent (IRM) and anhysteretic magnetization (ARM). The hysteresis loops and thermomagnetic studies under low (up to several Kelvins) and high temperature were applied. The results show low values of the magnetic susceptibility for natural not polluted soil ( $10\text{-}30 \times 10^{-8} \text{ m}^3/\text{kg}$ ). At the same time, we detected rapid growing of  $\chi$  up to  $100\text{-}500 \times 10^{-8} \text{ m}^3/\text{kg}$  at the hot spots with the high impact of the road traffic, railway, and regional industry, Near the railway bridge  $\chi=483\text{-}531 \times 10^{-8} \text{ m}^3/\text{kg}$ . Near the cultural center “Forum”  $\chi=143\text{-}160 \times 10^{-8} \text{ m}^3/\text{kg}$ . Near the Jewish park  $\chi=124\text{-}137 \times 10^{-8} \text{ m}^3/\text{kg}$  at the road, but decreases up to  $40\text{-}50 \times 10^{-8} \text{ m}^3/\text{kg}$  when moving inside the park zone. The results of the thermomagnetic analyzes (Fig. 1) confirmed the presence of the magnetite-like phase with Verwey transition near  $-150 \text{ }^\circ\text{C}$  (123.15 K). In addition, we detected small changes near 30 K, which may be the evidence of the presence of pyrrhotite according to the Besnus transition. Monoclinic pyrrhotite ( $\text{Fe}_7\text{S}_8$ ) goes through the Besnus transition at  $\sim 30\text{-}34 \text{ K}$ , which is used widely to diagnose its presence in bulk samples (Rochette et al., 2011). Both magnetite and pyrrhotite are from the man-made origin according to the multidomain (MD) state.



**Fig. 1:** Low-temperature dependence of the saturation remanent magnetization.

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## What is really rotating in the northeastern Caribbean plate?

L. Montheil (1), M. Philippon (2), D. Van Hinsbergen (3), P. Camps (1), J.-J. Cornée (1), T. Poidras (1),  
B. Vaes (3), P. Münch (1)

1) Géosciences Montpellier, Université de Montpellier, CNRS, Montpellier, France

2) Université des Antilles, Pointe-à-Pitre, France

3) Department of Earth Sciences, Utrecht University, The Netherlands

Correspondence to: leny.montheil@etu.umontpellier.fr

**Keywords:** Paleo-rotation, Intra-plate kinematics, Caribbean plate, subduction

Paleo-rotations are estimated from the mean declination or mean virtual geomagnetic pole (VGP) of a given paleomagnetic dataset, by comparing it to the reference direction or pole predicted by an apparent polar wander path (APWP). It was recently shown, however, that the current statistical framework for determining paleorotations has several shortcomings. About half of the poles behind the global APWP is statistically different from the APWP itself. Moreover, the estimated paleorotation may depend on subjective choices related to the number of paleopoles used in the computation of the reference pole, the size of the chosen time window from which poles were included. Overall, this may preclude the robust determination of geologically meaningful relative vertical-axis rotations of tectonic blocks of  $<20^\circ$  in deformed regions. This thus raises the question of how paleorotations can reliably be determined using paleomagnetic data.

Here, we use a large paleomagnetic dataset obtained from lavas, plutonic rocks, clastic sediments and limestones, sampled on 6 islands of the northeastern Caribbean region (Puerto Rico, British Virgin Islands, Anguilla, Saint-Martin, Antigua and Martinique) to illustrate a new approach to estimate paleorotations. The objective of this method is to obtain robust paleo-rotation estimates that take key sources of scatter in a paleomagnetic dataset into account (e.g., poor averaging of the paleosecular variation, inclination shallowing effects, field and lab measurement errors).

To this end, we compare observed paleo-declinations with the reference for the Caribbean plate, on the VGP-level instead of the overall mean direction/VGP. We show the effects of excluding outlying sites and the size of the age window on the paleo-declination estimates. With this, we ensure that we adequately average of paleosecular variation and that we reliably constrain the rotation history of the tectonic blocks relative to the reference plate. The mean paleo-declinations are then compared to a new global APWP that use an updated global database, a different statistical approach and a new flexible way of selecting the optimal time window for the reference poles (for more details, see presentation of Bram Vaes). This method increases the accuracy of the paleo-rotation estimates and allows differentiating between actual tectonic rotation and paleomagnetic uncertainties.

To test this method, the northeastern Caribbean plate appears to be an optimal region. Differential rotations were previously estimated on northern micro-blocks included in the Caribbean plate. This intraplate deformation is driven by: an Eocene global plate motion change, consequent curvature of the subducted slab and successive accretion of North American promontories (Caribean and Bahamas platform).

Our results show (1) that previous studies overestimated the paleo-rotation of the Puerto Rico-Virgin Islands block and provides new constraints on its timing, (2) that Puerto Rico, Virgin Islands and northern Lesser Antilles were rotating as a single block since (at least) Oligocene until Middle Miocene with 10 to  $20^\circ$  counter-clockwise rotation, (3) that this block did not rotate significantly since the middle Miocene and (4) that the southern limit of the northern Lesser Antilles block lies between the islands of Martinique and Antigua. These results have major implications on the past and present kinematics of the northeastern Lesser Antilles region, that host large magnitude earthquakes in the Present day and, in the past, temporary tectonically driven emerged areas that played a key role in the terrestrial fauna dispersal from South America to the Greater Antilles.

**Testing the GAD hypothesis at high-latitudes:  
A palaeomagnetic and  $^{40}\text{Ar}/^{39}\text{Ar}$  study  
of rocks from Eyjafjardardalur, northern Iceland**

A.R. Muxworthy (1), R. Supakulopas (1), M. Riishuus (2), C. Mac Niocaill (3), D. Barfod (4),  
A. Døssing (5)

- 1) Imperial College London, UK
- 2) University of Iceland, Iceland
- 3) University of Oxford, UK
- 4) University of Glasgow, UK
- 5) Technical University of Denmark, Denmark

Correspondence to: [adrian.muxworthy@imperial.ac.uk](mailto:adrian.muxworthy@imperial.ac.uk)

**Keywords:** geocentric axial dipole, palaeointensity, palaeodirection, Ar/Ar dating

The geocentric axial dipole (GAD) hypothesis states that when we average the geomagnetic field over sufficient time intervals, the time-averaged field (TAF) behaves like a dipole aligned along the Earth's spin axis. This hypothesis is central to most palaeomagnetic research, e.g., it is used to reconstruct the Earth's plates and determine their travel paths throughout the Earth's history. A 5% error in the GAD approximation would result in a 500-km plate reconstruction mismatch. However, the time interval to average the field to achieve a GAD is still debated. For example, there is evidence for the persistence of non-dipole field on time scales of  $10^5$ - $10^6$  yr, particularly at high latitudes. As most palaeomagnetic research is conducted under the GAD hypothesis, the hypothesis needs to be rigorously tested. In this study we have tested the GAD hypothesis during ca. 2.5-8 Ma using full-vector palaeomagnetic data including palaeodirection and palaeointensity from lava flows in northern Iceland. This was done in combination with  $^{40}\text{Ar}/^{39}\text{Ar}$  dating. Whilst the palaeomagnetic data has previously been presented at a conference, the  $^{40}\text{Ar}/^{39}\text{Ar}$  dates are new. With the new  $^{40}\text{Ar}/^{39}\text{Ar}$  dates we have constructed a new age model for Eyjafjardardalur and re-interpreted the palaeomagnetic data, and determine how this relates to the GAD theory at high-latitudes.

**Terranes paleoposition and chemical evolution  
of sedimentary basin materials, and the effects on measurable magnetic  
properties – the Holy Cross Mountains case**

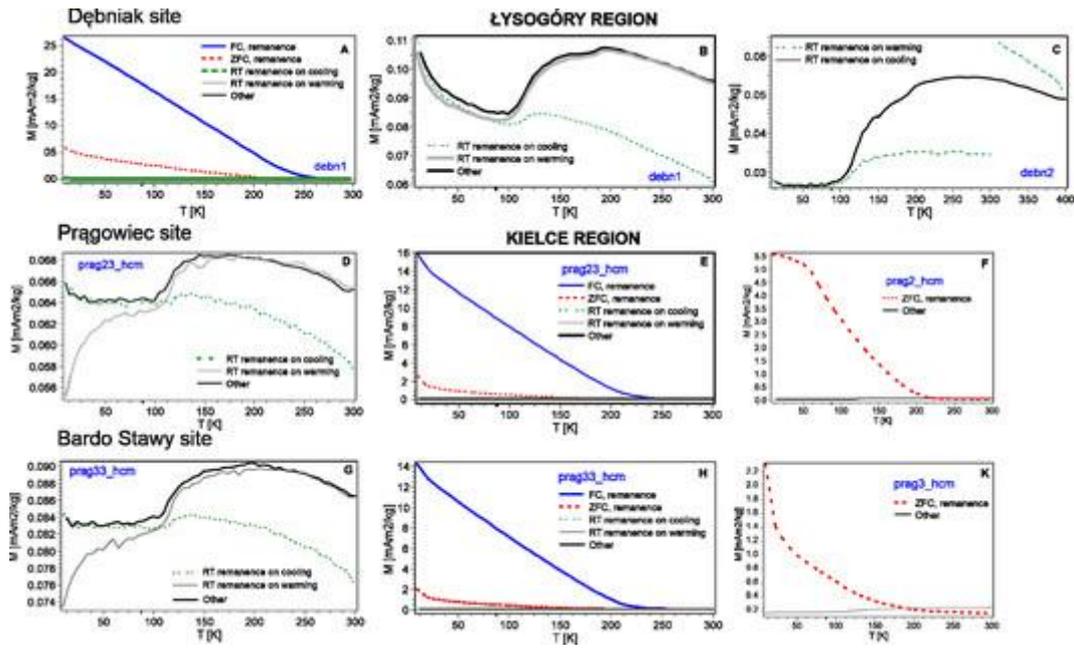
D.K. Niezabitowska, R. Szaniawski

Institute of Geophysics, Polish Academy of Sciences, Warsaw, Poland

Correspondence to: dominika.niezabitowska@gmail.com

**Keywords:** bottom water conditions, Llandovery (Silurian) mudstones, paleoenvironmental conditions, Baltica continent, paleo position

Numerous paleomagnetic and sedimentary investigations have been carried out on the Holy Cross Mountains (HCM) rocks to recognize the tectonic evolution, however, some aspects are still a matter of debate. Still under consideration is whether both southern and northern parts of the HCM (SHCM and NHCM, respectively) were separated terranes located along the Baltica margin in the early Paleozoic or they shared in common paleogeographic history before Devonian. Here, we present the results of comprehensive rock magnetic measurements applied as a tool to interpret paleoenvironmental conditions during deposition and further diagenesis. We conducted several petromagnetic measurements including low-temperature Saturated Isothermal Remanent Magnetization (SIRM), thermal demagnetization of three-component IRM, and hysteresis measurements, but also anisotropy of magnetic susceptibility (AMS) to recognize magnetic mineral composition and texture of Silurian graptolitic shales. The material was collected from three sites from the HCM from the Dębniak Beds from the NHCM and two sites from the opposite limbs of the Bardo Syncline in the SHCM. In all analyzed samples we found single domain (SD) stoichiometric magnetite of diagenetic (i.e., postdepositional) origin and goethite resulting from weathering (see Figure). In contrast to the SHCM, SD hematite and maghemite grains were observed in the Dębniak Beds (NHCM). We interpret hematite and maghemite as detrital in origin and deposited into an aerobic environment of bottom water conditions in the NHCM only. Further, the presence of more aerobic conditions solely in the NHCM implicates that during late Llandovery (Silurian) the present NHCM has had a more proximal location to the Baltica continent, in comparison to the SHCM. Our findings from rock magnetic studies support the scenario where two parts of the HCM were separated terranes during early Silurian times.



**Fig. 1:** Results of low temperature (300 – 10 K range; –263.15 to 26.85 °C) remanence measurements for selected specimens of (a, b, c) the Dębniak Beds (NHCM), (d, e, f) the Prągowiec Formation, and (g, h, k) black shales of the Zbrza Member (SHCM). Abbreviations: Zero Field Cooled (ZFC), Field Cooled (FC), Room Temperature Saturated Isothermal Remanent Magnetization (RT SIRM), the ‘Other’ curves are the results of the RT-SIRM performed while cooling in a small (+5  $\mu$ T) applied magnetic field.

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**Application of multiple rock-magnetic methods (ipAMS, opAMS, AARM)  
to examine ignimbrite petrofabrics  
of the late-Variscan Tharandt Wald Caldera (Bohemian Massif)**

I. Olšanská (1), F. Tomek (1,2), M. Chadima (3)

1) Institute of Geology and Paleontology, Faculty of Science, Charles University, Albertov 6, 128 43, Prague, Czech Republic

2) Institute of Geology, Czech Academy of Sciences, Rozvojová 269, 16500, Prague, Czech Republic

3) Agico Inc, Ječná 29a, 62100, Brno, Czech Republic

Correspondence to: olsanski@natur.cuni.cz

**Keywords:** Late-Variscan Tharandt Wald Caldera, Rock magnetism, Magnetic anisotropy, Ignimbrite

Ignimbrites are deposits of pyroclastic density currents composed of volcanic ash, pumice/fiamme, and juvenile and lithic clasts. The rock-magnetic and paleomagnetic methods are commonly used to recognize flow directions, volcanic source area(s), and emplacement processes. Here, we use the conventional in-phase AMS (ipAMS) along with out-of-phase AMS (opAMS) and the anisotropy of anhysteretic remanent magnetization (AARM) techniques to interpret the eruption dynamics of the Tharandt Wald Caldera (TWC). Magnetic mineralogy investigation includes analysis of thermomagnetic curves ( $k_m$ -T) and the frequency-dependent susceptibility ( $\chi_{FN}$ ). The bulk susceptibility ( $k_m$ ) varies from 39 to  $5750 \times 10^{-6}$ ; out of these 47 % and 52 % of specimens yielded ferromagnetic and paramagnetic values, respectively. The  $k_m$ -T curves indicate the dominant low-Ti titanomagnetite for ferromagnetic samples, while paramagnetic ones are characterized by a mixture of paramagnetic ferrosilicates with a slight contribution of fine-grained titanomagnetite, and titanohaematite. For ipAMS, the specimens predominantly indicate rather prolate-shaped AMS ellipsoids, while the degree of anisotropy is mostly clustered in a range from 0.3 % to 2.5 %. The principal susceptibility axes of individual specimens are well clustered around their mean values at most sampling sites. The ipAMS magnetic foliation is usually parallel to the mesoscopic flow foliation defined by the shape preferred orientation of flattened fiamme. The opAMS foliations are parallel to ipAMS and flow foliations at most sites. Even though  $\chi_{FN}$  is rather low its tight correlation with phase angle suggests that the opAMS signal is carried by ultra-fine, frequency-dependent, superparamagnetic magnetite grains. A comparison of the ipAMS and AARM results shows that for most of the measured sites it is possible to exclude the inverse fabrics. The preliminary interpretation of this dataset suggests that (1) the ipAMS and opAMS signals are carried by a mixture of paramagnetic to ferromagnetic phases and superparamagnetic magnetite grains, respectively. (2) Comparison of ipAMS and AARM fabrics indicate a dominance of multi-domain low-Ti titanomagnetite. (3) The overall structural record of field analysis and rock-magnetism suggests that we deal with strongly welded ignimbrites deposited from high-energetic, turbulent pyroclastic density currents within the collapsed caldera.

## Error variance analysis of different measurement schemes to improve anisotropy measurements

F.K. Ostermeier (1), S.A. Gilder (1), M.R. Wack (1), J. Jezek (2), D. Finn (3)

1) LMU Munich, Munich, Germany

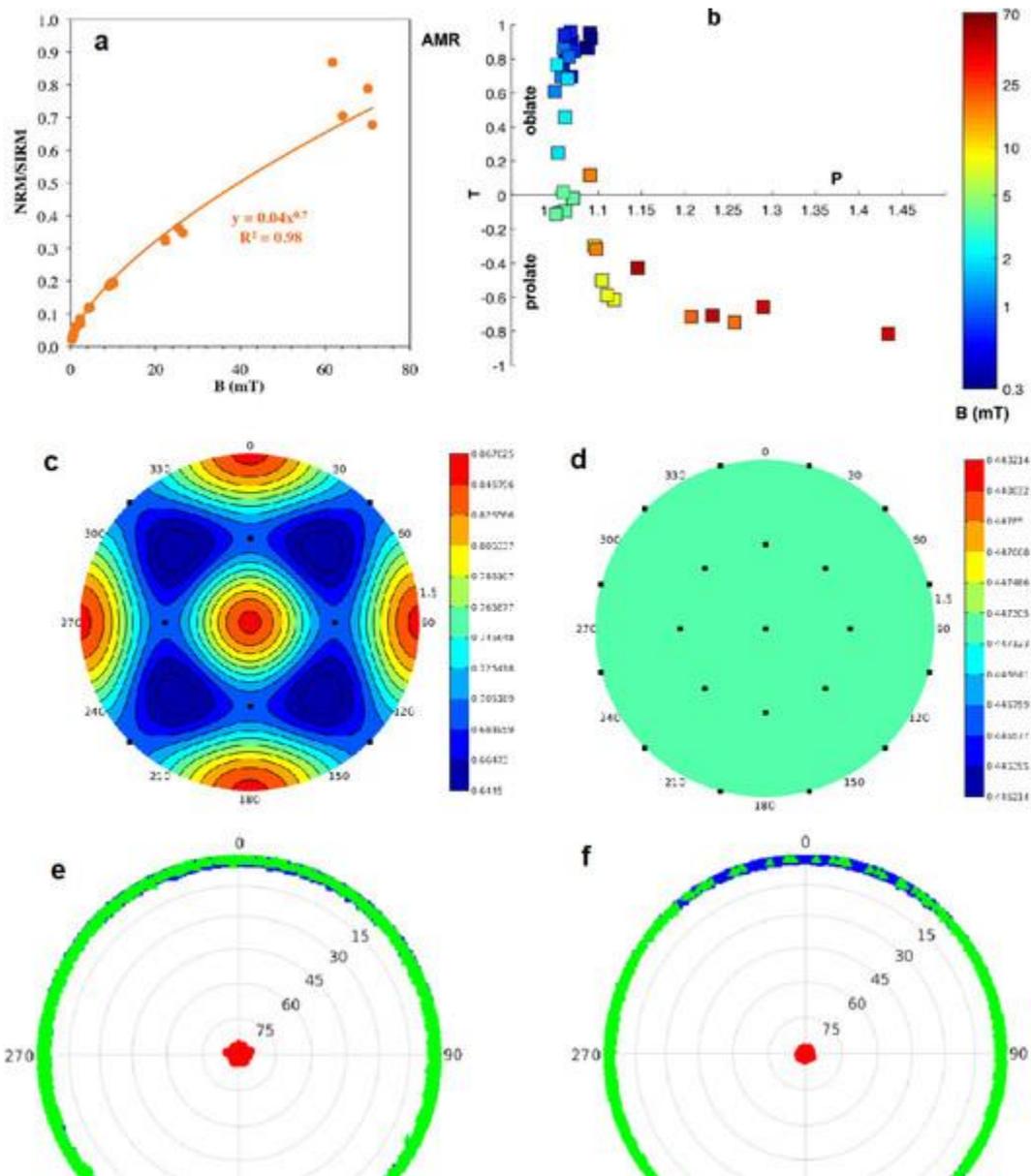
2) Charles University Prague, Prague, Czechia

3) University of California, Santa Cruz, CA, USA

Correspondence to: fostermeier@geophysik.uni-muenchen.de

**Keywords:** Error variance analysis, magnetic anisotropy, relative paleointensity, numerical simulation

Knowing how magnetic field intensity has changed over time yields critical insight into the workings of the geodynamo and the thermal state of the core-mantle boundary. Moreover, global field strength bears critically on the production of atmospheric cosmogenic radionuclides. Relative paleointensity (RPI) measurements from sediments represent the most widely used data source for long-term intensity records; however, the acquisition of natural remanent magnetization in sediments is complicated, leading to high uncertainty in single records, let alone the correlation among independent records. Our previous work showed that the anisotropy of magnetic remanence (AMR) can serve as an independent means to evaluate RPI. However, those experiments were done in field ranging from 0.3 to 70 mT, so above typical Earth-like fields of <0.1 mT (figs. a + b). Repeat redeposition experiments in Earth-like fields (0.01-0.1 mT) on 25 samples/field yields RPI values that are proportional to the field on average, however, the scatter varies by a factor of two for any given field value. Those AMR data were acquired using a 12 position (6 antiparallel pairs) measurement scheme. One possibility to explain the factor of two scatter could arise from experimental precision. To better understand this, we simulated different measurement designs. Following Hext (1963) and Owens (2000), the 12 direction design serves as a compromise between sufficient number of measurements and keeping measurement time to a minimum. From these 12 vector readings, the six independent components of the anisotropy tensor are estimated with a least squares approach. Hext (1963) also introduced the concept of a “rotatable design”, meaning the error variance of the anisotropy ellipsoid (in particular, the unique axes) does not depend on the measurement framework; thus, rotatable designs are favorable for AMR (or anisotropy of magnetic susceptibility) measurements. However, our analyses of the 12 direction design shows that it is not rotatable, with a confidence interval of the unique axes differing by up to 25% depending on the orientation (Fig. c). To reduce the error variance, we developed a new rotatable design consisting of 30 (15 antiparallel pairs) directions (Fig. d) and carried out a suite of numerical simulations. Assuming normally-distributed reading (measurement) errors, estimation of the unique axes becomes homogeneous over the unit sphere, and the deviation of the maximum principal direction from the true value can be reduced by ca. 40% compared with the 12 direction scheme (figs. e + f), albeit measurement time is more than doubled. AMR using the 30 direction design has been tested with samples redeposited in Earth-like fields ranging from 0 to 0.1 mT with the newly developed SushiBar2.0. This contribution will directly compare AMR results from the 30 and 12 direction schemes.



**Fig. 1:** a,b) relative paleointensity and Jelinek plot with depositional field, c,d) error variance of max. principal axis in 12/30 measurement directions, e,f: principal axes of the anisotropy tensor of 10000 samples, calculated with 12/30 directions

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**Towards a rock-magnetic characterization of redox change  
in anomalous environments**

D.V. Palcu (1), W. Krijgsman (1), P. Srivastava (2), M.J. Dekkers (1)

1) Paleomagnetic Laboratory Fort Hoofddijk, Utrecht University, The Netherlands

2) University of Sao Paulo, Sao Paulo, Brazil

Correspondence to: d.v.palcu@uu.nl

**Keywords:** anoxia, euxinia, mega-lake, gateways, paleoenvironmental reconstructions

Megalake Paratethys, the largest-known megalake, was a particular waterbody, larger than the Modern Mediterranean Sea that covered the inner part of Eurasia some 11-6.9 million years ago. Completely isolated from the ocean, the megalake experienced phases of extreme drought and partial desiccations alternating with humid episodes and flooding events that led to extreme chemical, physical and biotic responses in the megalake's basins.

We identify and date key partial desiccations and reflood phases of the megalake, controlled by climate to produce an age model for the lake's events. We then combine existing geochemical, paleontological, and mineralogical data, as well as new organic geochemistry data to produce a paleoenvironmental chronology of the megalake. Using a novel rock-magnetic approach we characterize changes in the composition of iron minerals preserved in the sediments. Our novel rock-magnetic results show in higher detail the paleoenvironmental fluctuations in the megalake suggesting a potential for future applications. Finally, we constrain our rock-magnetic results with paleo-redox proxies and show the potential for developing this rock-magnetic approach into a reliable palaeomagnetic redox proxy.

## Magnetic properties of deeply serpentinized peridotites from the Monte Maggiore massif, Northern Corsica

Z. Pastore (1), N.S. Church (1), M. Uehara (2), J. Gattacceca (2), A. Vitale Brovarone (3), E. Zanella (4)

1) Department of Geoscience and Petroleum, Norwegian University of Science and Technology, Trondheim, Norway

2) CEREGE/CNRS - UMR7330, Aix-en-Provence, France

3) Department of Biological, Geological, and Environmental Sciences, University of Bologna, Bologna, Italy

4) University of Turin, Turin, Italy

Correspondence to: zeudia.pastore@ntnu.no

**Keywords:** subduction zone, serpentinization, magnetic properties, magnetic anomalies

In deep settings such as subduction zones, serpentinization of ultramafic rocks can be kinetically favored by high P-T conditions and can exert a major control over the redox state of convergent margins, influencing the climate and the deep biosphere. The effects of serpentinization in these deep settings are commonly studied through petrological and geochemical analyses. Here, we investigate this process through the study of the magnetic properties of peridotites that underwent serpentinization in deep settings. Serpentinization reactions can indeed change the mineralogical assemblage and consequently alter the petrophysical properties of the protolith.

For the study we selected the Monte Maggiore (MM) massif (Figure 1). The massif is in the northern end of the Cap Corse and consists of a peridotite body of  $\sim 4 \text{ km}^2$  surrounded by eclogitized continental units. This peridotite body represents sub-continental mantle that underwent tectonic and magmatic evolution during the rifting stage of the Jurassic Ligurian Tethys oceanic basin and successive Alpine subduction to blueschist-facies conditions (40-50 km depth). The peridotite body is composed of plagioclase- and/or spinel-peridotites (including harzburgites, lherzolites and minor dunites) intruded by mafic pods and gabbroic dykes. The peridotites are variably serpentinized, and according to Debret et al. (2014) were affected by two main serpentinization episodes, one during massif oceanization and the second during subduction prograde high-pressure metamorphism.

We analyzed rock magnetic properties of samples from more than 40 sites and performed a ground magnetic survey to map changes in the petrology and to localize domains within the massif characterized by different degrees of serpentinization. Samples show wide ranges of densities (from  $2.4 \text{ g/cm}^3$  to  $3.2 \text{ g/cm}^3$ ) and magnetic properties. Rock magnetic susceptibilities range from  $1 \times 10^{-4}$  to 0.2 (SI) with an average magnetic susceptibility of  $2.7 \times 10^{-2}$  (SI) and the natural remanent magnetization (NRM) values range from less than 0.001 to 250 A/m with a median NRM of 1.43 A/m. In most rocks the ratio between the NRM and induced magnetization is above 1 and the NRM directions vary across the area, meaning that there is a strong local control of the NRM on the magnetic anomalies. The magnetic survey shows a prominent magnetic anomaly in the southern part of the massif with a mean value of approx. 2000 nT above background. We further modeled the source of this magnetic anomaly using the magnetic properties of the rocks at this location. Demagnetization of the samples using both thermal and alternating field techniques suggest multiple components of the magnetization. Preliminary data of this study confirm a complex magnetic history for the MM massif compatible with multi-stage serpentinization reactions. Further work on representative samples will allow to deepen our knowledge of these reactions.



**Fig. 1:** Monte Maggiore massif, view from the South.

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## Reconstructing the past geomagnetic field in Europe: the SCHA.DIF.4k model

F.J. Pavón-Carrasco (1), S.A. Campuzano (1), M. Rivero-Montero (2), A. Molina-Cardín (1),  
M. Gómez-Paccard (2), M.L. Osete (1)

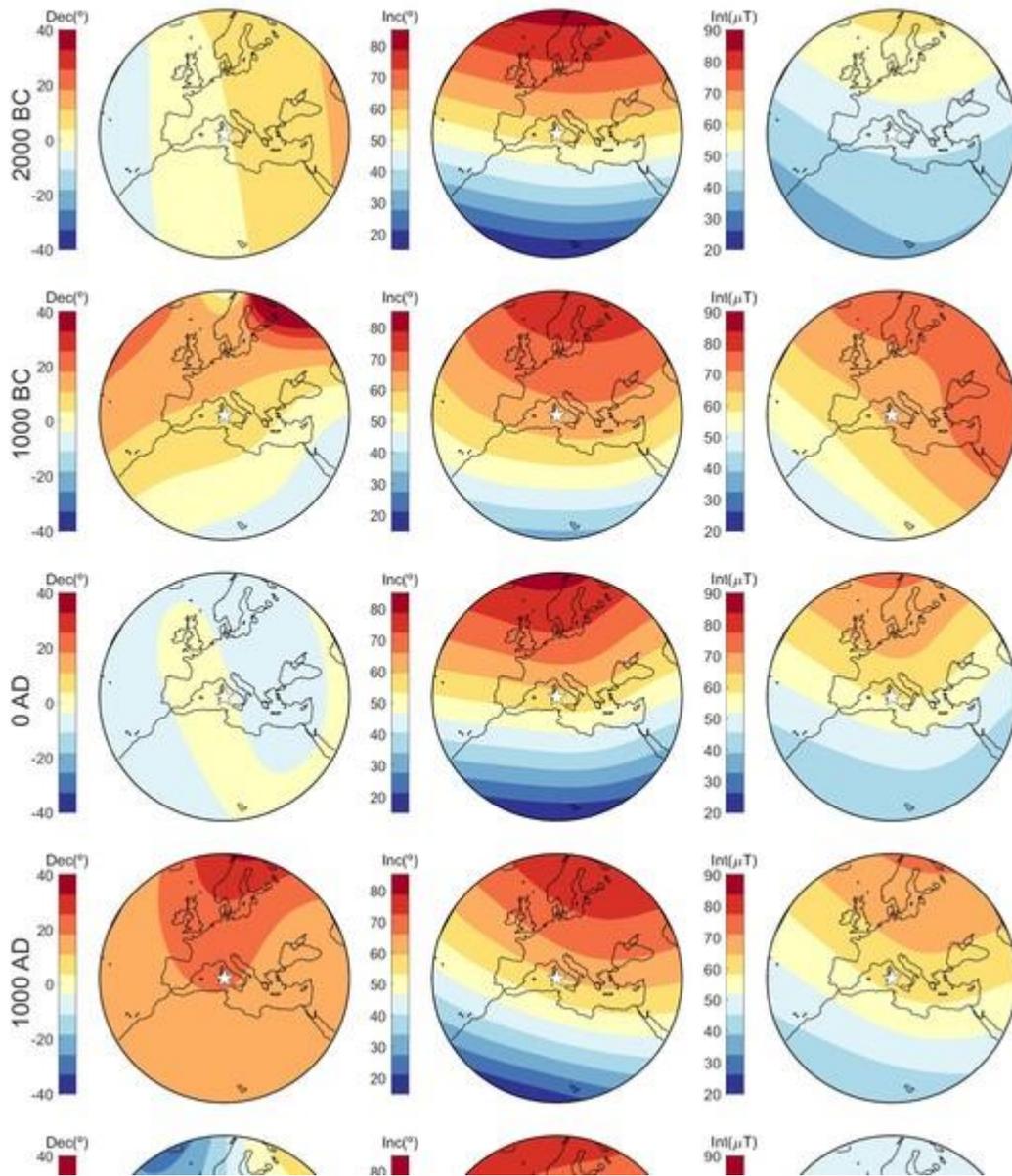
1) Complutense University of Madrid

2) Geoscience Institute CSIC-UCM

Correspondence to: fjpavon@ucm.es

**Keywords:** Archeomagnetism, Geomagnetic field model, Paleomagnetic secular variation, Dating, Europe

The number of paleomagnetic data derived from archeological materials such as baked clays and volcanic rocks coming from Europe represents a high percentage of the world dataset. Taking advantage of this high density of data, here we provide an updated regional archeomagnetic model, called SCHA.DIF.4k, for the European continent and adjacent areas covering the last four millennia. The regional paleo reconstruction involves the R-SCHA2D technique in space and cubic splines in time, applied to a selected archeomagnetic and volcanic European dataset covering the last four millennia. In addition, in order to better constrain the behavior of the archeomagnetic field during the last centuries, we include the historical data of the HISTMAG compilation. The new regional model allows us to define the paleomagnetic field over Europe (see Fig. 1) as well as to generate paleosecular variation curves for archeomagnetic dating purposes.



**Fig. 1:** Declination (left), inclination (center), and intensity (right) maps by the SCHA.DIF.4k model. Maps at 2000 BC, 1000 BC, 0 AD, 1000 AD, and 1900 AD.

## **Magnetic susceptibility of soil from Seget Gornji (South Croatia) under different heating exposure: wildfire vs. laboratory furnace**

Josip Peco (1), Hana Fajković (1), Stanislav Frančišković-Bilinski (2)

1) University of Zagreb, Faculty of Science, Department of Geology, Horvatovac 95, 10 000 Zagreb, Croatia

2) Laboratory for physical chemistry of traces (LPCT). Division for marine and environmental research, "Ruđer Bošković" Institute, POB 180, 10 002 Zagreb, Croatia

Correspondence to: josip.peco@hotmail.com

**Keywords:** wildfire, Seget Gornji, magnetic susceptibility, Fe oxides and hydroxides

Wildfires affect soil characteristics and change mineralogical composition of the soil. Fe oxides and hydroxides are prone to thermal changes during the wildfire resulting in a consequent change in magnetic susceptibility (MS) (e.g. Jordanova et al., 2019). The studied area located in the northern part of the Seget Gornji (Trogir) presents a hill slope of burned low vegetation and maquis. For this study, soil and ash samples were collected from seven different burned sites across the hill. The control soil sample was collected from unburned site about one kilometer of airline distance away western of the burned area. The wildfire occurred in the first few days of August 2021; therefore, the sampling was performed two weeks and two months after the wildfire. At the burned sites, soil samples were collected from the 0-5 cm depth in both sampling times. White and black ash samples were collected from the burned surface only in the first sampling. The sampling of the control soil was conducted at two different depths (0-5 cm and 20-30 cm) for obtaining background values and further heating laboratory experiments for data correlation. The muffle furnace was used to heat both shallow and deep control soil subsamples at 12 temperatures (25, 150, 200, 250, 300, 350, 400, 450, 550, 650, 700, and 1100°C) for two hours. The MS of the samples was determined by a small magnetic susceptibility meter SM-30. Magnetic measurements were performed three times, and the mean value was used as a final result to assure the biggest precision of the data. The overall results of mass-specific magnetic susceptibility ( $\chi$ ) are in the range of  $0.173 - 9.770 \times 10^{-3}$  International System of Units (SI). Generally, soil samples from the burned sites show  $\chi$  values from  $0.969$  to  $1.997 \times 10^{-3}$  SI units. Only for the samples from one burned site, the  $\chi$  value is almost two times higher than all the other values. Furthermore, there is no significant difference in the  $\chi$  values between the results from both sampling times. Shallow (0-5 cm) and deep (20-30 cm) heated control soil subsamples show  $\chi$  results in the range of  $0.173 - 9.770 \times 10^{-3}$  SI units. MS values for the heated control soil subsamples do not show significant variations in the range of 25 to 550°C. It is important to note that the sudden change of  $\chi$  can be seen between the 550 and 650°C where  $\chi$  value becomes almost four times higher in both shallow and deep subsamples, with the tendency to rise until 700°C. The last heating temperature of 1100°C, in turn, shows a sharp decrease of  $\chi$  value for both shallow and deep subsamples, which becomes about twelve times lower. Ash samples show  $\chi$  values from  $0.876$  to  $2.917 \times 10^{-3}$  SI units.  $\chi$  values for the white ash samples are generally higher than the ones for the black ash samples. Further research and determination of mineralogical and thermal changes of Fe oxides and hydroxides will show the main reasons for the differences in the determined  $\chi$  values for the soil and ash samples.

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## **Paleomagnetic Thellier-Coe paleointensity studies of the Glen Mountains layered complex anorthosites supporting an Ediacaran inner core nucleation**

Michael J Polashenski (1), Frank J Tetto (1), Kenneth P Kodama (1), John A Tarduno (2)

1) Lehigh University

2) University of Rochester

Correspondence to: mjp518@lehigh.edu

**Keywords:** paleomagnetic, paleointensity, Thellier-Coe, inner core nucleation, Ediacaran

Recently, we have been analyzing samples from the Cambrian Wichita igneous province in the Glen Mountains Layered Complex. We are testing the hypothesis that inner core nucleation occurred during the Ediacaran based on very low paleointensities recovered from the 565 Ma Sept-Îles Intrusives (Bono et al. 2019). The Glen Mountains anorthosites are slightly younger at about 539-530 Ma based on U-Pb ages (Hanson et al. 2013) and could record the recovery of the geomagnetic field after inner core nucleation. Over 200 anorthosite samples were drilled from 17 sites in southwestern Oklahoma in 2019 for absolute paleointensity studies. Thellier-Coe double-heating experiments based on the IZZI method with in-field set at 30  $\mu\text{T}$  were conducted to determine paleointensities of multiple samples from three sites. Parallel studies in air and nitrogen environments were run to assess possible oxidation or reduction of magnetic minerals during heating. Low-temperature demagnetization (LTD) cycling using liquid nitrogen baths was included to potentially improve results. Two of three sites yielded good results and are described further. Arai plots show linear behavior from 500° to 600°C in eight temperature steps with four successful pTRM checks for most samples based on 95% agreement. Mean paleointensities varied from 9.5 to 12.5  $\mu\text{T}$  with LTD yielding slightly higher values. The studies in air yielded better pTRM checks. LTD cycling slightly degraded the pTRM checks. Magnetite is the primary carrier of magnetization based on rapid loss of magnetization near the Curie temperature of 585°C. Samples were not significantly affected by oxidation or reduction in either air or nitrogen. Based on these pilot experiments, we will proceed with Thellier-Coe IZZI experiments in air without LTD. Results of our preliminary Thellier-Coe measurements reveal an ancient geomagnetic field intensity of about 12  $\mu\text{T}$  (around 20 percent of the present geomagnetic field intensity). This implies that the geomagnetic field may be starting to recover following inner core nucleation at 565 Ma as suggested by the extremely low paleointensities of the Sept-Îles Intrusives (about 10 percent of the present intensity). However, a more complete analysis will be reported to either confirm or revise this preliminary conclusion.

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**Magnetostratigraphy and palaeoenvironmental implications  
from the Deccan volcano-sedimentary succession,  
Dhar District, Madhya Pradesh, Central India**

S. Pratap Singh (1), M. Arif (2), A. Kumar Singh (3), S. Mishra (3), V. Vir Kapoor (3), V. Prasad (3)

1) Birbal Sahni Institute of Palaeosciences, Lucknow, India-226007

2) Department of Geology, Banaras Hindu University, Varanasi, India-221005

3) Birbal Sahni Institute of Palaeosciences, Lucknow, India-226007

Correspondence to: [chauhansp122@gmail.com](mailto:chauhansp122@gmail.com)

**Keywords:** Deccan Volcanic Province, Magnetostratigraphy, Sedimentology, Palaeoenvironment

The Deccan Volcanic Province (DVP) due to its enormous volume and overlap of lava eruption duration with that of Cretaceous-Paleogene (K-Pg) boundary has a unique place among all the Large Igneous Provinces (LIPs) of the world. The fossiliferous sedimentary sequences (Infra- and Inter-trappeans) associated with DVP offer an excellent opportunity to study the nature of biotic changes across the K-Pg boundary, including floral response to Deccan volcanism and paleogeography. Despite the continuing research from the past three decades, timing of the volcanic eruption relative to K-Pg mass extinction and terrestrial vs. marine palaeoenvironment are two critical aspects of DVP which remains problematic.

Here, we sampled three Deccan volcano-sedimentary successions in the Malwa subprovince, Dhar district, Madhya Pradesh, India. Oriented basaltic blocks and inter-trappean sediment samples were collected to ascertain the palaeomagnetic age constraints of associated lava flows and depositional environment of Inter-trappean deposits. Palaeomagnetic data revealed normal-reverse-normal magnetic polarity stratigraphy for the lava flows corresponding to C30n-C29r-C29n magnetochrons. The sedimentological analysis revealed the identification of five microfacies namely, (a) fossiliferous marly limestone; (b) silty carbonaceous mud with fossils; (c) Limy fossiliferous shale; (d) nodular calcrete layer; and (e) carbonaceous mud, suggesting deposition in a freshwater lacustrine system under hot and humid climate.

## **Magneto- and biostratigraphy of the J/K boundary at Golubac, Serbia – preliminary data correlation to magnetostratigraphy**

P. Pruner (1), D. Rabranovic (2), Š. Kdýr (1), T. Elbra (1), P. Schnabl (1), L. Kouklíková (1),  
A. Svobodová (1), D. Reháková (3), Z. Vašíček (4), P. Skupien (4)

1) Institute of Geology of the Czech Academy of Sciences, Prague, Czechia

2) Geological Survey of Serbia, Belgrade, Serbia

3) Department of Geology and Palaeontology, Comenius University in Bratislava, Bratislava, Slovakia

4) VŠB-Technical University of Ostrava, Faculty of Mining and Geology, Ostrava, Czechia

Correspondence to: pruner@gli.cas.cz

**Keywords:** Jurassic/Cretaceous boundary; magnetostratigraphy; biostratigraphy; rock magnetism

Worldwide definition of the Jurassic/Cretaceous (J/K) boundary is still not established. High resolution magnetostratigraphy is one of the three most important methods for the J/K boundary correlation and, since the magnetic field changes its polarity on the whole globe at the same time, it is considered globally the most efficient correlation tool. Magnetostratigraphy can be used as a correlation media between different kinds of biostratigraphical scales and its significance in global definition of J/K boundary is appreciated. Depending on criterion, the J/K boundary falls either in the middle of M19n2n magnetozone or at the bottom of M19n1r magnetosubzone. The new section, Golubac, is located in the National Park Djerdap in the north-eastern of Serbia, in the northernmost part of the inner Carpathian-Balkan belt, and thus the border area with the Romanian Carpathians. Due to specific and very diverse geological structure, it's a particularly interesting part of the Carpathian-Balkan areas. The Golubac 110-m-thick, section was lithologically documented and subjected to laboratory analysis by multiple methods, such as evaluating the paleomagnetic, rock magnetic, magneto- and biostratigraphic, geochemical and sedimentological data. Magnetic methods are used for compiling the magnetostratigraphy as well as understanding the carriers of remanent magnetization components used for magnetostratigraphy. Data are also used to distinguish between primary magnetite, primary or diagenetic hematite and secondary goethite (product of weathering). Geochemical, magnetostratigraphic, and paleontological data together with sedimentology will serve for paleoenvironmental interpretation of studied section and global correlations. Preliminary results indicate presence of normal and reverse polarity primary magnetization components. The declination suggests the clockwise rotation. Furthermore, part of samples shows also component with normal polarity of different declination. This component shows preserved mineralogical changes and is interpreted as remagnetized. The primary magnetization of dual polarity was compiled to magnetostratigraphy and magnetozones were correlated with the M-sequence of marine magnetic anomalies of the Global Polarity Time Scale (Ogg 2020). First data suggests magnetozones from M19N to M16R. Magnetite is the main carrier of the remanent magnetization. A short reverse polarity subzone was revealed in the normal part of magnetozone M19. According study of Calpionellids, J/K boundary occurs at the level 5, very close to the beginning of the section. However, no Tithon species were found in the specified spectrum. All the collected ammonites belong to the lower Berriasian. If we correlate these preliminary data of clockwise rotation with data from Barlya section – Bulgaria (Grabowski 2016i), we can see the same direction. Opposite rotations are published f.e. from Bosso Valley – Italy (Housa) and Velykyi Kamianets – Ukraine (Grabowski 2019).

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**Anisotropy of anhysteretic remanent magnetization  
applied to Serra do Mar dike swarm (SE Brazil):  
simplications for its emplacement and the relationship  
with Gondwana break-up**

M. Irene B. Raposo

Institute of Geosciences, São Paulo University, Brazil

Correspondence to: irene@usp.br

**Keywords:** AARM; AMS; Magnetic Fabrics; Dike Swarms; Serra do Mar Swarm

This work is the result of an intense magnetic study carried out on the mafic dikes, which out crop on the coast of the southeastern Brazil (São Paulo and Rio de Janeiro states), so called Serra do mar dike swarms. This swarm comprises at least three dike swarms that are tholeiitic, mafic alkaline (lamprophyre), and felsic alkaline (trachyte, phonolite). The dikes crosscut the Archean and Proterozoic polymetamorphic rocks of the Costeiro Complex (gneiss and migmatitic rocks), granites, alkaline stocks, and locally the layered gabbro. Their trend is predominantly N30°-60°E, which coincides with the direction of the main regional fractures and faults of the country rocks. The dip of the dikes ranges from very steep (~60°, minority) to vertical with thicknesses ranging from a few centimeters to a maximum of to 2 m for the lamprophyre and alkaline, and up to 10 m for the tholeiitic. In some areas dikes from the three swarms occur in the same place. They can show enclaves from the country rocks; one can cut off the other; they can be offset across by a younger fracture filled by another dike, occur parallel, and outcrop side by side. Magnetic fabrics were determined using anisotropy of low-field magnetic susceptibility (AMS) and anisotropy of anhysteretic remanent magnetization (AARM). Rock-magnetism measurements reveal that magnetite grains in the range of 2-5  $\mu\text{m}$  are the magnetic mineral, which is responsible for magnetic susceptibility, but not for AMS, as shown by AARM for most dikes. The main AMS fabric for the dikes is due to magmatic flow, in which the analysis of the  $K_{\text{max}}$  inclination shows that the dikes were fed by horizontal to vertical flow. For most dikes, AMS and AARM fabrics are not coaxial. The AARM lineation (AARM $_{\text{max}}$ ) is N30-60W oriented, which is approximately perpendicular to the AMS lineation ( $K_{\text{max}}$ ). The AARM $_{\text{max}}$  is similar to the direction of fault systems found in the offshore Santos and Campos basins. The comparison of the AMS and AARM fabrics suggests that the dikes (lamprophyre and tholeiitic) were emplaced in three tectonic events in the initial stages of the Gondwana break-up. There is no difference between AARM $_{\text{max}}$  and  $K_{\text{max}}$  for the alkaline dikes, suggesting that they were emplaced in the last stages of the Atlantic Ocean opening.

**Spikes in the geomagnetic field:  
A case study of the Levantine Iron Age anomaly**

Pablo Rivera (1), F. Javier Pavón-Carrasco (2), María Luisa Osete (3)

1) Dpto. Física de la Tierra y Astrofísica, Universidad Complutense de Madrid (UCM), Avd. Complutense s/n, 28040, Madrid, España

2) Instituto de Geociencias IGEO (UCM-CSIC), Calle Severo Ochoa 7, Edificio Entrepabellones 7 y 8, 28040, Madrid, España

3) Dpto. Física de la Tierra y Astrofísica, Universidad Complutense de Madrid (UCM), Avd. Complutense s/n, 28040, Madrid, España

Correspondence to: pablorig@uclm.es

**Keywords:** Archeomagnetism, Levantine Iron Age Anomaly, Geomagnetic spike, Spherical Harmonic Modelling

The Levantine Iron Age Anomaly (LIAA) corresponds to a short-decadal geomagnetic intensity variation in the Levantine region defined by Shaar *et al.* (2016, 2017). The LIAA is characterized by a high intensity maximum (about 190 ZAm<sup>2</sup> in terms of the virtual dipole moment) that is related to a large geomagnetic positive anomaly (the so-called spike) at the Earth's surface. The occurrence in both space and time of the LIAA has been constrained by archeomagnetic data coming from Eastern Europe and Western Asia between 1050 BC and 700 BC.

Davies and Constable (2017) indicated that the LIAA spike is characterized by small spatial wavelengths and thus it is due to the contribution of high spherical harmonic degrees. Here, we revisit this work by using the most recent archeomagnetic dataset covering the spatial and temporal period of the LIAA. To reconstruct the spike event, we develop a spherical harmonic global model as a perturbation of the Gauss coefficients from a previous paleomagnetic global model that did not use the LIAA data record. Our results indicate that the LIAA event could be characterized by larger spatial wavelengths and thus it is defined by lower harmonic degrees than expected by the previous work.

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**Unveiling the influence of lithological heterogeneities  
on the magnetic fabric record of faulting processes:  
Insights into para- and ferromagnetic fabrics  
in megathrust shear zones**

C. Robustelli Test (1,2), A.R. Biedermann (3), E. Zanella (4), A. Festa (1)

1) Dipartimento di Scienze della Terra, Università degli Studi di Torino, Torino, Italy

2) CIMaN-ALP, Centro Interuniversitario di Magnetismo Naturale - Alpine Laboratory of Paleomagnetism, Peveragno, Italy

3) University of Bern, Institute of Geological Sciences, Bern, Switzerland

4) CNR-IGG – Consiglio Nazionale delle Ricerche, Istituto di Geoscienze e Georisorse, Torino, Italy

Correspondence to: [claudio.robustellitest@edu.unito.it](mailto:claudio.robustellitest@edu.unito.it)

**Keywords:** Magnetic fabric, Anisotropy of magnetic remanence, High-field torque magnetometry, Megathrust shear zones, Lithological heterogeneities

In active convergent margins, shallow intraplate shear zones and megathrusts display a continuous spectrum of slip behaviours, ranging from great thrust earthquakes (GEQs) to stable sliding (i.e., aseismic creep). Among other factors, lithological heterogeneities are documented to influence the frictional properties, resulting in variations of slip behaviour. Magnetic fabric analysis has proven to be a reliable petrofabric tool for examining variations in the stress regime, providing insight into physical and chemical processes associated with faulting. Since each mineral may respond differently to the same deformation mechanisms, separating the preferred orientation of iron oxides and paramagnetic minerals may help to discern multiple deformation events. We investigate the relationships between magnetic and mesoscale structural fabric of three exhumed analogues of megathrust faults, located in the Northern Apennines (Italy). Here, carbonate and clay-rich sediments have undergone multiple deformations and the meso-structural fabric reveals different response to deformation. Our results show changes in the magnetic fabric shape and orientation, in close relation to the structural position (i.e., distance from the fault plane) and the pervasivity of tectonic features. In the proximity of the shear zone, the magnetic fabric is oblate with magnetic lineation sub-parallel to the shear direction, suggesting that shear localization is recorded along the main faults. Away from the thrusts, we observed a gradual decrease in oblateness, and magnetic fabrics reflecting previous tectonic events or less intense deformation, with minor to no evidence of shearing. Moreover, we isolated the orientation of different remanence-bearing grain subpopulations performing four separate anisotropy of magnetic remanence experiments. Additionally, the paramagnetic and ferromagnetic fabric was derived by high-field torque magnetometry. Depending on the lithology, we observed different sensitivity of ferro- and para-magnetic grains to the deformation. In clay-rich sediments the ferromagnetic fabrics reveal axis orientations independent from those of the paramagnetic matrix, which indicate the record of different deformation stages. Instead, carbonate-rich rocks show a slight variation in para- and ferromagnetic fabrics axis orientation, suggesting similar registration of the strain by different subpopulation of grains. Our findings show the potential of ferro- and paramagnetic fabric separation to constrain the role of lithological variation in the registration of faulting processes. We recommend sampling at increasing distance to favour the discrimination between localized and distributed deformation as well as integration with petrology and geochemistry to strengthen the links between lithology and strain recording.

## Over two centuries of magnetic declination recorded in historical documents in Mexico

Alejandro Rodriguez-Trejo, Harald Böhnelt, Hector Ibarra-Ortega

Centro de Geociencias – Universidad Nacional Autónoma de México, Campus Juriquilla, Mexico

Correspondence to: alexrt@geociencias.unam.mx

**Keywords:** paleomagnetism Mexico magnetic-declination historical-documents maps, Mexico

Knowledge of the existence of the earth's magnetic field (EMF) is related to ancient cultures. Over the IV century in China, a simple compass was used for orientation with a magnetite artifact pointing constantly to the south. Even, there is a hypothesis that propose that the Olmec civilization in ancient Mexico, over 2000 BCE, had knowledge of the presence of the (EMF), according to different artifacts found on the region, however this has not been proven. With the existence of the compass as an instrument for orientation, the navigation and exploration were increased around the world. With this expansion, the use of the compass was implemented on the developing of several maps, designed either for navigation, building or delimitation of territory. That implementation, leave a historical heritage of documents that recorded directly and indirectly the magnetic declination over the centuries. The use of historical records to describe the secular behavior of the EMF were described from different authors. Such as Jackson et al (2000), that used direct historical observations over the last 4 centuries around the world. Yilmaz et al (2010) recover declination data by georeferencing an relocating historical maps with the magnetic north drawn on it, and then comparing the declination with different PDSV models. In this work, we present a secular variation model for declination of the earth's magnetic field over the last 2 centuries, recorded on historical documents from different sources such as: maps, geomagnetic observatories, navigation charts paleomagnetic and archaeomagnetic data. The collection of the data is from about 600 maps available from Mexico and surrounding areas, and historical data available from the Magnetic Observatory of Teoloyucan (UNAM-Mexico). Recovering declination from four different sources: Recorded directly from the map, measuring the angle drawn, georeferencing an relocating, and historical data from direct observations. The data collected used to develop a high-resolution regional model for declination for the last two centuries. With this kind of model, several documents that include a magnetic record with a lack of an accurate date, could be dated.

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## Introducing the Latin American paleomagnetic and archaeomagnetic online database (LAPOD)

Alejandro Rodriguez-Trejo, Harald Böhnel, Hector Ibarra-Ortega

Centro de Geociencias – Universidad Nacional Autónoma de México, Campus Juriquilla, Mexico

Correspondence to: alexrt@geociencias.unam.mx

**Keywords:** paleomagnetism, database, Latin-America, Mexico, paleointensity

The earth's magnetic field (EMF) is constantly changing in time and space. And it's continuously recorded by different processes in several materials, such as volcanic rocks and archaeological materials. Thus, paleomagnetist around the world are looking for new data recorded at those materials for a better understanding of the secular behavior of the EMF at different time scales. Over the last decades, several models of the EMF at different time scales were developed (e.g., McElhinny and McFadden, 1997; Johnson et al, 2008; Cromwell et al, 2018; Doubrovine et al, 2019). Models were developed by using large volumes of data reported from all the world. A large amount of paleomagnetic data from Mexico were used on the models available until today. It's reasonable, in central Mexico is located a very active volcanic area, the Trans Mexican Volcanic Belt (TMBV), with a very active volcanism during the last 5 Ma. And at the north and central Mexico exist a semicontinuous volcanic record with intense activity during the last 25 Ma. Even during the last 3 ka, intense volcanic activity had been recorded in Mexico and Central America. Furthermore, a continuous occupation of ancient civilizations in all Mexico and Mesoamerica were documented for the last 5 ka. With all those intense volcanic and human activity, several paleomagnetic data was reported on the literature. Therefore, becomes necessary gather all the data available from Mexico and Central America on a unique database. We present the Latin American Paleomagnetic Online Database (LAPOD), that gather up to 2,000 paleomagnetic data such as: declination, inclination, paleointensity, VGP's, and statistical and scatter parameters ( $k$  and  $\alpha_{95}$ ). The associated location is included, either the basic geological data and author's information. Data were validated on location and the age reported were updated on many cases to a recent reference. Database is fully functional, predictive and easy to use, with up to 20 different filters included to refine a specific query and for an optimal filtering of the data. With a friendly graphical interface, is simple to select the data for a query and selection of a specific row to be displayed. Simple plots of different parameters for visual correlations, location georeferencing of the sites are also available. The data could be downloaded on different formats for further processing. The MPOD is constantly updated and refreshed with the most recent data published for Mexico and surrounding areas. The LAPOD is now available online on the next link: <https://paleomagnetismo.com/pmagdb/database-query/>.

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## **Magnetic properties as indicators of toxic elements pollution in surface sediments of the Vlasina River (Serbia) and Kupa River (Croatia)**

Sanja Sakan (1), Stanislav Frančišković-Bilinski (2), Dragana Đorđević (1), Aleksandar Popović (3), Aleksandra Mihajlidi-Zelić (1), Sandra Škrivanj (4), Halka Bilinski (2)

1) Centre of Excellence in Environmental Chemistry and Engineering – ICTM, University of Belgrade, Njegoševa 12, Belgrade 11158, Serbia

2) Ruđer Bošković Institute, Division for marine and environmental research, Zagreb, Croatia

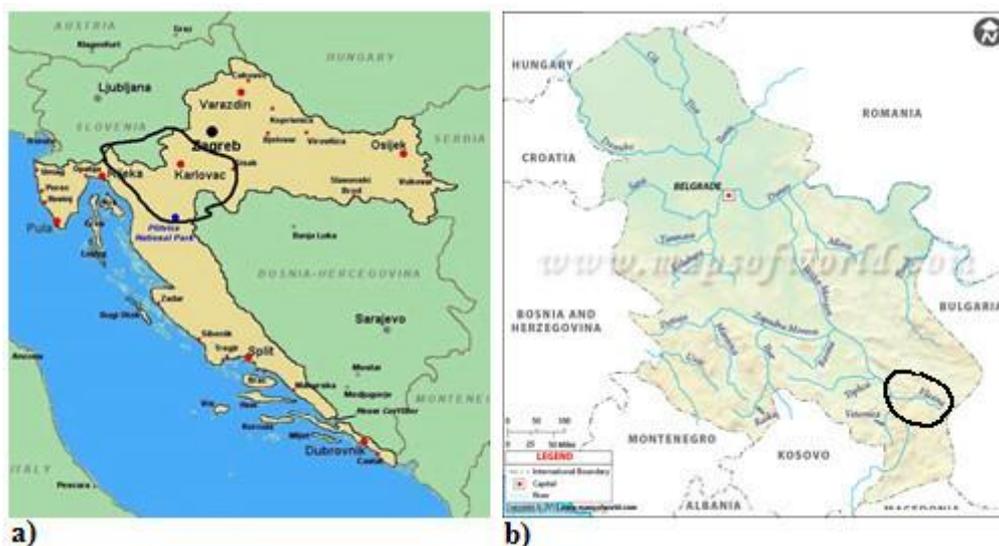
3) Faculty of Chemistry, University of Belgrade, Studentski trg 12-16, Belgrade 11000, Serbia

4) Faculty of Chemistry, University of Belgrade, Studentski trg 12-16, Belgrade 11000, Serbia

Correspondence to: ssakan@chem.bg.ac.rs

**Keywords:** magnetic susceptibility; toxic elements; statistical methods; Vlasina River; Kupa River

The relationships between magnetic susceptibility (MS) and elemental variations have been the focus of considerable study in the fields of environmental assessment. The aim of this study was to apply a rapid and inexpensive, low-field magnetic susceptibility method to stream sediments from Vlasina (Serbia) and Kupa (Croatia) river basins, and discuss the relationships between MS and content of 26 studied elements using statistical approaches. In this research, magnetic susceptibility was measured using SM30, a small magnetic susceptibility meter with a very high sensitivity of  $1 \times 10^{-7}$  SI units. Inductively Coupled Plasma Optical Emission Spectroscopy was used to determine the concentration of the studied elements, after sequential extraction procedure (Sakan et al., 2016). Total concentrations of each element were determined as the sum of concentrations determined in each fraction. The Kupa River basin, occupies the west-central part of Croatia and is shared by two neighboring countries (Slovenia, Bosnia and Herzegovina). The Kupa itself is a tributary to the Sava River and meets the latter at Sisak after traversing a distance of 294 km. The river basin is one of the most significant water resources in Croatia (Frančišković-Bilinski et al., 2012). Vlasina River Basin covers an area of 1,061.72 km<sup>2</sup> and covers the south eastern part of Serbia. The total length of Vlasina River is 65.9 km. The largest part of the geological base of the Vlasina River Basin belongs to the Serbo-Macedonian mass, formed in the Palaeozoic (Carbon-Perm) (Durlević et al., 2019). Correlation analysis was performed to reveal statistical correlations between MS and 26 elements analyzed by ICP-OES in Kupa sediment samples. Ten of them showed negative correlation (As, B, Ba, Fe, K, Li, Mg, Na, P, S), while other elements showed positive. Chromium showed excellent correlation with MS (0.91) and is element with the highest correlation to MS, what could indicate its anthropogenic origin. Element with strongest correlation to MS after Cr is vanadium (0.62), followed by Mn (0.52), Al (0.52) and Cd (0.50). All other elements have rather weak correlation with MS, among which highest are those of Sr (0.45), Zn (0.35), Be (0.28), Co (0.27), Pb (0.27) and Ti (0.26). Measured MS values in Vlasina samples are mostly very low, with several locations where values are a bit higher; they range from  $0.02 \times 10^{-3}$  to  $1.113 \times 10^{-3}$  SI units. The strongest correlation was observed with Mo (0.43), then with Ag (0.29). Correlations > 0.10 are determined between MS and following elements: Zn (0.17); Cu (0.12); Pb (0.17); Ba (0.13); Mn (0.10); Ti (0.20); V (0.21); In (0.16); Sn (0.16); Tm (0.10); Lu (0.12); Hg (0.16); Bi (0.13); Th (0.15) and U (0.24). Correlation analysis between MS and measured chemical elements has shown that strong correlations do not exist. From that it could be concluded that in Vlasina samples there is no significant anthropogenic influence.



**Fig. 1:** Position of a) Kupa River drainage basin in Croatia, and b) Vlasina River drainage basin in Serbia.

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## A pseudo-Thellier relative paleointensity record in a stalagmite from the Soprador do Carvalho cave (central Portugal)

Elisa M. Sánchez-Moreno (1), Eric Font (2,3), F. Javier Pavón-Carrasco (4,5), Luca A. Dimuccio (6),  
Lúcio Cunha (6)

- 1) Departamento de Física, EPS Campus Rio Vena, Universidad de Burgos, Spain
- 2) Instituto Dom Luís, Faculdade de Ciências, Universidade de Lisboa, Portugal
- 3) Departamento de Ciências da Terra, Faculdade de Ciências e Tecnologia, Universidade de Coimbra, Portugal
- 4) Universidad Complutense de Madrid, Spain
- 5) Instituto de Geociencias, CSIC-UCM, Madrid, Spain
- 6) University of Coimbra, Centre of Studies in Geography and Spatial Planning (CEGOT), Department of Geography and Tourism, Coimbra, Portugal

Correspondence to: emsanchez@ubu.es

**Keywords:** speleothems, relative paleointensity, pseudo-Thellier, Holocene, Portugal

The natural remanent magnetization (NRM) in speleothems is generally detrital in origin and carried mainly by magnetite transported by drip water from the sedimentary cover and soils capping the caves into karst systems. Magnetic minerals are aligned with the magnetic field when they are blocked in the calcite layers after precipitation. The speleothem may thus provide high-resolution and relatively continuous record of the ancient magnetic field without being affected by effects such as bioturbation or compaction. Although speleothems are considered good recorders of the Earth's magnetic field direction, little is known about their capability to record relative paleointensities (RPI) (e.g., Ponte et al., 2018). Here, we report an analysis of the RPI obtained with the pseudo-Thellier method in 45 samples of a stalagmite from the Soprador do Carvalho cave (central Portugal). This stalagmite was dated between ~ 5760 BCE and 1920 CE based on U-Th and <sup>14</sup>C dating (Sanchez-Moreno et al., under review). To verify that magnetic mineralogical changes do not affect the relative paleointensities, we compared the pseudo-Thellier data with the NRM normalization by anhysteretic remanent magnetization (ARM) and isothermal remanent magnetization field at saturation (SIRM). Results are comparable independently of the used method, indicating that changes in the proportion of magnetic minerals do not affect the RPI results. The reliability of relative paleointensity data is usually checked by normalizing RPI by absolute paleointensity, which should provide nearly constant ratios. However, in our case, RPI normalized by absolute paleointensity taken from the SHADIF.14K model (Pavón-Carrasco et al., 2014) provides non-constant ratios and shows a decreasing trend along the stalagmite stratigraphy, suggesting that age calibration is discrepant or that the relative paleointensity data are questionable. More investigations are needed to unravel this discrepancy.

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**Preliminary paleomagnetic results from the Fucino lacustrine basin (Italy):  
Implications for the tectonic evolution of the Central Apennines**

S. Satolli (1), P. Macrì (2), F. Florindo (2), P. Boncio (1), G.P. Cavinato (3), P. Galli (4), B. Giaccio (5),  
F. Iezzi (6), I. Mazzini (5), P. Messina (5), L. Monaco (3), A. Notaro (1), A. Testa (1)

1) Dipartimento di Ingegneria e Geologia, Università degli Studi "G. d'Annunzio" di Chieti-Pescara, via dei Vestini 31, 66100 Chieti, Italy

2) National Institute of Geophysics and Volcanology, Via di Vigna Murata 605, I-00143 Roma, Italy

3) Dipartimento di Scienze della Terra, Università di Roma, Rome, Italy

4) Dipartimento di protezione Civile, Rome, Italy

5) Consiglio Nazionale delle Ricerche, CNR-IGAG, Roma, Italy

6) Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università degli Studi di Napoli, I-80126 Napoli, Italy

Correspondence to: sara.satolli@unich.it

**Keywords:** Magnetostratigraphy, Anisotropy of magnetic susceptibility, Brunhes–Matuyama

Paleomagnetic, tephrostratigraphic, paleontological and structural investigations are being performed on a ca. 270-m deep hole drilled with rotary core system in the Fucino lacustrine succession in order to constrain its tectonic evolution.

The Fucino Basin is an intramontane half-graben located in the Central Apennines (Italy) characterized by active crustal seismicity, as recorded by the 1915 Avezzano earthquake with Magnitude (Ms) 7.0, that caused around 30.000 fatalities. The Fucino lake was completely drained at the end of 19th century and is filled by Pliocene-Holocene lacustrine and alluvial deposits, unconformably overlying Meso-Cenozoic carbonate sequences and Neogene terrigenous sequences, also exposed in the surrounding mountains (Cavinato et al., 2002).

After the Neogene Apennine orogenesis, this area was affected in the Upper Pliocene and Quaternary time by extensional tectonics, both with NW–SE and WSW–ENE-trending normal and normal-oblique faults, that played an important role on the sedimentary and tectonic evolution of the Basin.

The core was drilled in September/October 2019 and sampled for paleomagnetism at 1m spacing; after preliminary analyses, further high-resolution sampling was addressed to intervals documenting magnetic polarity inversions. Samples were processed at the Istituto Nazionale di Geofisica e Vulcanologia, Rome. After measuring the anisotropy of magnetic susceptibility with an AGICO KLY-5, the samples were stepwise demagnetized by alternating field (AF), and in a few cases by thermal treatment, and measured using a narrow-access pass through 2-G-Enterprises cryogenic magnetometer housed in a magnetically shielded room.

Two components of magnetization have been isolated with the AF treatment: i) a low-coercivity component usually isolated in the 0-10 mT interval that always shows normal polarity and is likely due to a drilling overprint or a viscous remagnetization episode occurred soon after the drilling; ii) characteristic remanent magnetization directions: for most analyzed samples tend toward the origin of the vector component diagrams and both normal and reversed polarities were isolated.

The palaeomagnetic data indicate the Brunhes/Matuyama boundary at ca. 40 m depth, in good agreement with the preliminary results from tephrostratigraphy, and allowed to constrain the

sedimentation rate and the correlation with the nearby Sulmona lacustrine sediments (Giaccio et al., 2013; Sagnotti et al., 2016).

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## Assessment of different components of cosmogenic beryllium records

Tatiana Savranskaia (1), Monika Korte (1), Sanja Panovska (1), Ramon Egli (2)

1) GeoForschungsZentrum (GFZ) Potsdam, Telegrafenberg, 14473 Potsdam, Germany

2) Central Institute for Meteorology and Geodynamics (ZAMG), 1190, Vienna, Austria

Correspondence to: tatiana.savranskaia@gfz-potsdam.de

**Keywords:** cosmogenic isotopes, beryllium,  $^{10}\text{Be}$ , geomagnetic field, environment

Records of paleomagnetic field intensity variations are of paramount importance for understanding the evolution and driving mechanisms sustaining the geodynamo. One of the few means of obtaining continuous reconstructions of this evolution relies on sedimentary sequences that provide relative paleointensity (RPI) and/or changes in production rate of cosmogenic isotope Be-10 (expressed in terms of Be-10/Be-9). Be-10 production depends on variations of the incoming flux of primary galactic cosmic rays, which are modulated by the geomagnetic field strength and by the solar activity. Decreases of dipole strength, and thus, lower cutoff rigidities, lead to enhanced cosmic ray collisions, increasing the cosmogenic Be-10 production rate. Although beryllium records primarily reflect the evolution of geomagnetic field, additional variations are introduced by complex transfer processes related to  $^{10}\text{Be}$  removal from the atmosphere, deposition into the ocean through wet and dry precipitation, and finally scavenging by particles suspended in the water column. First indications of environmental influences come from comparison of globally distributed high-resolution marine sedimentary Be-10 records over the Matuyama-Brunhes (MB) magnetic field reversal. Discrepancies between Be-10 records of the MB reversal can be explained by a site-dependent linear relationship between the global Be-10 production rate and sedimentary Be-10 signal (Savranskaia et al., 2021). These differences were further investigated through principal component analysis (PCA) of globally distributed Be-10 records of seven geomagnetic excursions that occurred over the last 300 ka. While the first PCA component clearly reflects geomagnetic dipole changes, it seems that the second component is time-invariant and site-dependent, pointing to different constant beryllium inputs at each location, which are unrelated to geomagnetic field variations. We investigate whether sedimentary Be-10 signals reflect the mean isotopic composition of water masses flowing at each site, which might be expressed through the second principal component of the beryllium records.

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## The re-established Rock and Palaeomagnetic Laboratory at the University of Cologne

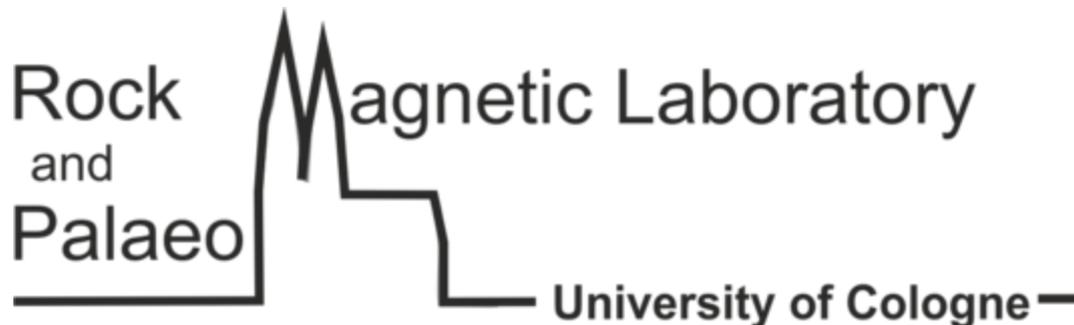
Stephanie Scheidt, Martin Melles

Institute of Geology and Mineralogy, University of Cologne, Cologne, Germany

Correspondence to: [stephanie.scheidt@uni-koeln.de](mailto:stephanie.scheidt@uni-koeln.de)

**Keywords:** Magnetic Laboratory, Cryogenic Magnetometer, Vibration Sample Magnetometer, MFK2 Kappabridge

In 2005 the cryogenic magnetometer of the University of Cologne's was taken out of service, because no skilled operator remained at the University. The centrepiece of the palaeomagnetic lab was disassembled and stored, just as the remaining equipment of the palaeomagnetic laboratory. Since 2013 the working group of Quaternary Geology of the University of Cologne aims at recommissioning of the lab. The work was considerably delayed by the decision to install the lab in a new building, which was finished as late as 2017. Now, the 2G cryogenic magnetometer model 755 has returned to an operational mode. New devices were purchased to update and complete the equipment of the lab. In this presentation we inform about the technical opportunities provided by the Rock and Palaeomagnetic Laboratory of the University of Cologne. In times, when more and more facilities are shut down or remain unguided after retirement of the head of the labs, the re-establishment of the lab is an important contribution for the rock and palaeomagnetic community in Europe.



**Fig. 1:** Logo of the Rock and Palaeomagnetic Laboratory of the University of Cologne

## The high-resolution relative palaeointensity record from Lake Levinson-Lessing, northern Central Siberia

Stephanie Scheidt (1), Ramon Egli (2), Matthias Lenz (3), Marlene M. Lenz (1), Martin Klug (4),  
Grigoriy Fedorov (5), Martin Melles (1)

1) Institute of Geology and Mineralogy, University of Cologne, Cologne, Germany

2) Central Institute for Meteorology and Geo-dynamics (ZAMG), Vienna, Austria

3) Research Center Jülich, Jülich, Germany

4) Geological Survey of Norway (NGU), Trondheim, Norway

5) Faculty of Geography and Geoecology, St. Petersburg State University, Russia / Arctic and Antarctic Research Institute, St. Petersburg, Russia

Correspondence to: stephanie.scheidt@uni-koeln.de

**Keywords:** Relative palaeointensity, magnetic mineralogy, lake sediment core, Taymyr Peninsula, Arctic

Lake Levinson-Lessing is with ~120 m the deepest lake of the northern Taymyr Peninsula (Central Siberia). The lake basin is 15 km long, 1 to 2 km wide, and covers an area of approximately 25 km<sup>2</sup>. Since the mid-1990s, the well stratified sediment infill of the lake basin has been a target for palaeoenvironmental and palaeoclimatic studies. However, the first palaeomagnetic investigations have only recently been accomplished using the 46-metre-long core Co1401, which was recovered from the central part of the lake in 2017. Although the lowermost 8 m were shown to be disturbed (Scheidt et al. 2021, Lenz et al. 2022), the upper 38 m of core Co1401 provide an unusually uniform mineral-magnetic composition with homogenous magnetic properties. Only in the uppermost 6.7 m initial greigite formation changes the magnetic mineralogy slightly (Scheidt et al., 2021). Based on these results, 730 discrete samples from the upper 38 m were used to study the relative palaeointensity (RPI) of the sedimentary succession. The record includes the geomagnetic excursions Laschamps and Mono Lake, and resolves sufficient geomagnetic features to establish a chronology that continuously covers the last ~62 ka (Scheidt et al. 2022). To date, this dataset is the first palaeomagnetic record in a radius of more than 1500 km that documents the behaviour of the Earth's magnetic field of this time range in high resolution. However, due to the initial greigite formation the RPI record <10 ka was classified as preliminary until further samples are analysed. To verify the existing data set, another 100 discrete samples are currently being processed. In addition, further mineral magnetic analyses are scheduled. We show and discuss first results of this supplementary study and its implications to the records of RPI and palaeosecular variations of Levinson-Lessing Lake.

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## Palaeomagnetic dating of the 'Deckenschotter' in northern Switzerland and southern Germany

Stephanie Scheidt (1), Andrea R. Biedermann (2), Gaudenz Deplazes (3)

1) Institute for Geology and Mineralogy, University of Cologne, Germany

2) Institute of Geological Sciences, University of Bern, Switzerland

3) Nagra, Wettingen, Switzerland

Correspondence to: stephanie.scheidt@uni-koeln.de

**Keywords:** Deckenschotter, Magnetostratigraphy, Sediment, Germany, Switzerland

The 'Deckenschotter' (literally cover gravel) is a glaciofluvial sedimentary sequence in the northern Alpine Foreland. The morphostratigraphic unit is divided in an upper part (Höhere Deckenschotter) and a lower part (Tiefere Deckenschotter), which both consist of mainly thick gravel layers. Although the age of the Deckenschotter has been investigated using biostratigraphy (Bollinger et al. 1996) magnetic polarity stratigraphy (Graf, 1993) and cosmogenic isochron burial dating (e.g., Claude et al. 2019), it is still controversially discussed, and subject of several dating projects. In this study palaeomagnetic analyses of samples from fine clastic interlayers within the Deckenschotter are analysed. So far, 182 samples from 16 outcrops in northern Switzerland and southern Germany were subjected to thermal or alternating field demagnetisation. Further mineral magnetic analyses were conducted on selected samples. The palaeomagnetic work was challenging in all parts of the study. We discuss the difficulties arising during sampling, preparation, and measurements of the brittle and rather weakly magnetic sediments with low signal-to-noise ratios and strongly anisotropic behaviour. We detected normal and reverse directions of the Earth magnetic field. However, the occurrence of secondary overprints cannot be ruled out. For clarification, further mineral magnetic analyses are on their way. Overall, the preliminary results of the study already provide constraints on the time of deposition. The palaeomagnetic evidence in combination with the outcome from other dating techniques will presumably shed light on the complex depositional history of the region.

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## New archaeomagnetic directional data from the Czech Republic

P. Schnabl (1), H. Grison (2), E. Aidona (3), Š. Kdýr (1), L. Kubišová (4)

- 1) Institute of Geology of the Czech Academy of Sciences, Prague, Czechia
- 2) Institute of Geophysics of the Czech Academy of Sciences, Prague, Czechia
- 3) Geophysical Department, School of Geology, Aristotle University of Thessaloniki, Thessaloniki, Greece
- 4) Vodohospodárska Výstavba š.p., Bratislava, Slovakia

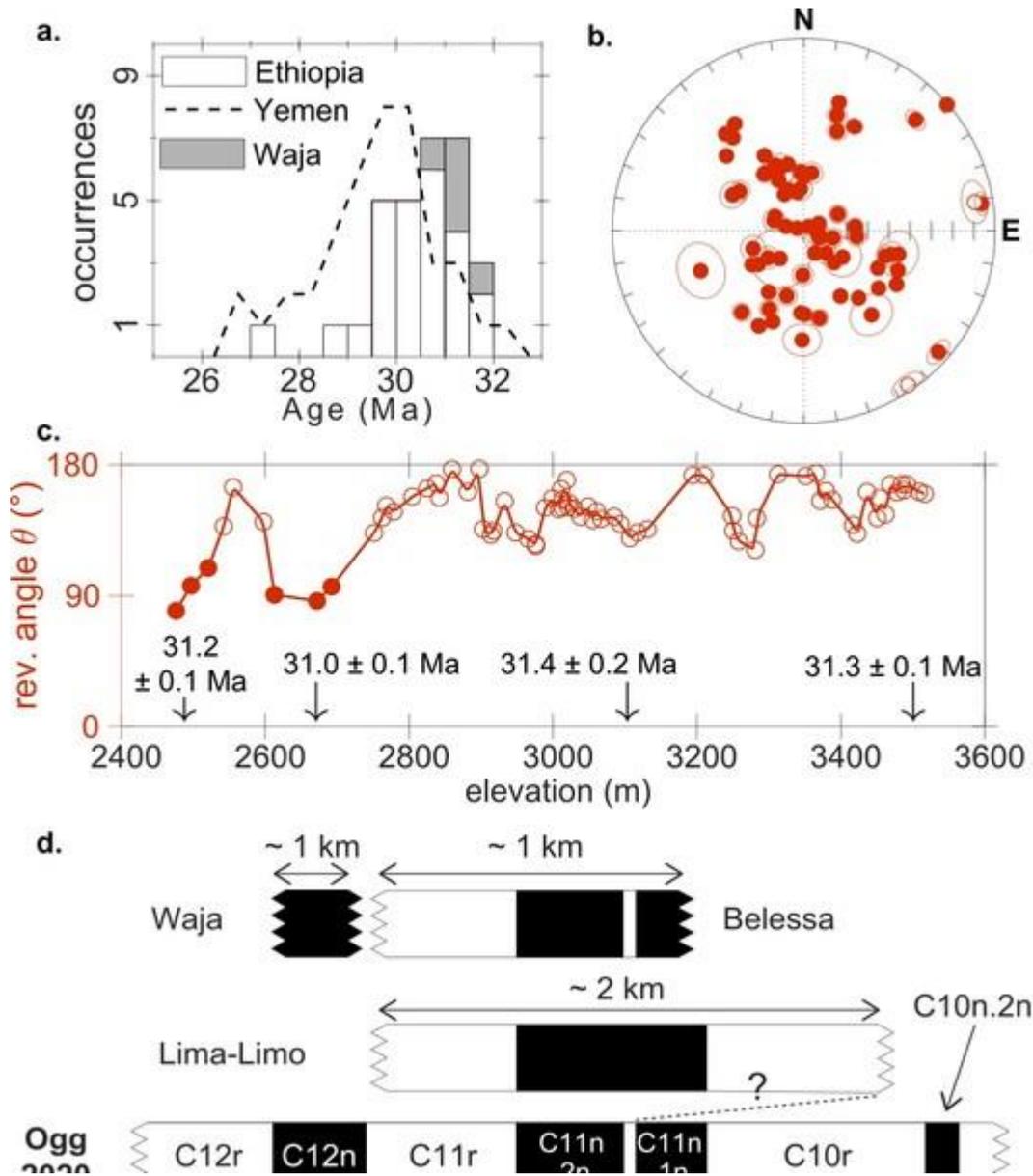
Correspondence to: [schnabl@gli.cas.cz](mailto:schnabl@gli.cas.cz)

Archaeomagnetism is flourishing over the last four decades in many countries worldwide. Especially in Europe, dozens of studies have been performed in order to identify the variation of the elements of the geomagnetic field over the last 8 millennia. An overview has been recently published by Brown et al., (2021). However, in the Czech Republic only limited data were published almost 30 years ago, and no real development of the archaeomagnetic method has taken place since then. Therefore, we attempt to fill this gap and we present new archaeomagnetic directional data from 10 burnt archaeological structures located at 7 different sites. Most of the sampling sites came to light during the construction of the new highways in Hradec Králové and South Moravia regions, while the rest revealed due to the reconstruction of houses throughout the Czech Republic. In all cases the sampling was performed in cooperation with the Czech Rescue Archaeology. The new data cover the period from 6000 BC to 1700 AD based on archaeological evidence. In total 260 oriented samples have been collected. The results of the natural remanent magnetization indicate that the majority of the samples were burnt in situ, providing thus a reliable direction of the ancient field. The magnetic cleaning by alternate field disclosed the presence of one stable component of magnetization. Additionally, rock magnetic experiments (isothermal remanent magnetization acquisition curve) have been performed in pilot samples suggesting the dominance of low coercivity magnetic minerals such as magnetite. The new directional results are compared with the available data from neighboring countries as well as recent compilations and global models. Our results provide an important basis for the creation of the Czech archaeomagnetic dating curve.

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**Fig. 1:** a) Ar-Ar ages of Ethiopia-Yemen Traps, b) Waja section's recentered directions c) reversal angle W.R.T. elevation with Ar-Ar ages, d) tentative match of Waja, Belessa (Lhuillier & Gilder, 2019) & Lima-Limo (Rochette et al., 1998) sections with the GPTS.

## Magnetostratigraphy and biostratigraphy of the Berrias section

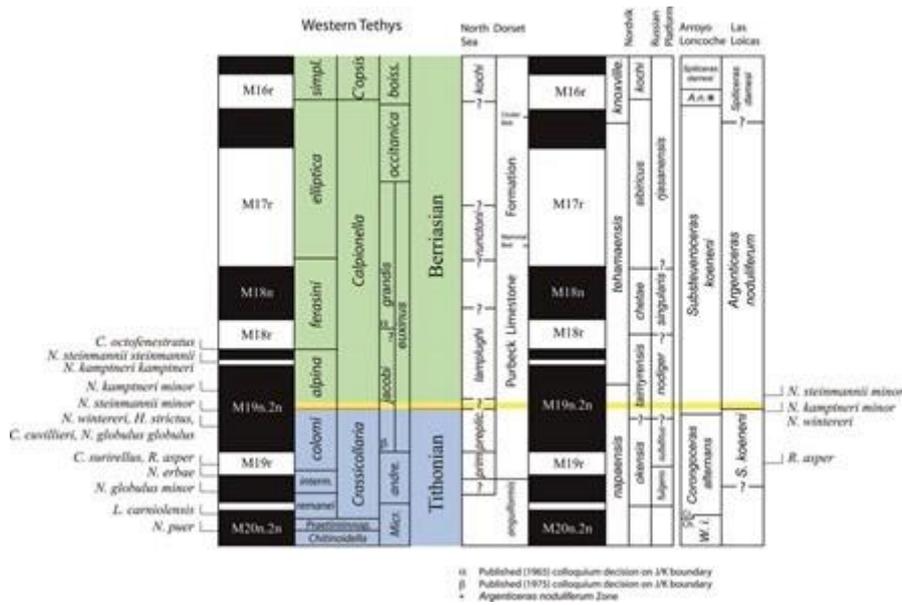
P. Schnabl (1), Š. Kdýr (1), T. Elbra (1), C. Frau (2), L. Bulloot (3), D. Reháková (4), A. Svobodová (1),  
R. Mikuláš (1), L. Kouklíková (1), W.A.P Wimbledon (5), P. Pruner (1)

- 1) Institute of Geology of the Czech Academy of Sciences, Rozvojová 269, Prague, Czech Republic
- 2) Groupement d'Intérêt Paléontologique, Science et Exposition, 60 bd Georges Richard, Toulon, France
- 3) Laboratoire Geosciences Ocean, Université de Bretagne Occidentale, Brest, France
- 4) Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University, Ilkovičova 6, Bratislava, Slovakia
- 5) School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol, United Kingdom

Correspondence to: schnabl@gli.cas.cz

**Keywords:** Jurassic/Cretaceous boundary, Berrias, magnetostratigraphy

Detailed magnetostratigraphic and micropaleontological investigation on the Jurassic/Cretaceous (J/K) boundary is being carried out to precisely determine the boundaries of magnetozones and narrow reverse subzones, and to find global correlation across the J/K boundary as well as define the GSSP – Global Stratotype Section and Point. The main goal of current study on the Berrias section in Ardèche, France, is a revision of anomalous magnetozones M16n1r, which was interpreted by Galbrun & Rasplus (1984) and Galbrun (1985). The main lithology of the Berrias locality is well-bedded blue-gray pelagic limestone. Regarding the ichnological intensity of sediment mixing by the organism activities, the most common grade of bioturbation is BI = 1, showing that 1% to 4% of the matter is transferred to current position by bioturbation. This value corresponds to 65% of samples in this study. Approximately 30% of the samples do not show any bioturbation structure (BI = 0); the remaining 5% are samples with a bioturbated mass greater than 4% and less than 30% (BI = 2). Due to magnetic field polarity changes occurring simultaneously around the entire globe, the high resolution magnetostratigraphy is one of the most efficient tools for J/K boundary correlation. However, the interpreted polarity zones have to be in concordance with macrofauna and microfauna. Ammonite stratigraphy in Berrias is based on seven subzones from Jacobi to Callisto. Calpionellid zonations contain five zones that are spreading between Alpina and Oblonga zones. The lower part of the Berrias section is also well defined by nannoplankton stratigraphy and spans a stratigraphic range from the nannoplankton Zone NC0 to the Zone NC1, documenting the Early Berriasian age. The upper part was not studied for nannoplankton yet. The detailed magnetostratigraphy shows seven normally and seven reversely polarized magnetozones, interpreted to span from M19n to M14r. The rare subzone M16n1r was proved on one of the three parallel sections. Main paleomagnetic directions are  $D=10^\circ$ ,  $I=44^\circ$  for the normal polarity and  $D=161^\circ$ ,  $I=-43^\circ$  for the reversed polarity.



**Fig. 1:** Stratigraphic chart for J-K boundary interval prepared by Berriasian Working Group, published by Wimbledon (2017).

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**Anisotropy of magnetic susceptibility (AMS) analysis  
of Mount Calanna dykes swarm of Mount Etna, Italy:  
Implication of its emplacement mechanism**

R. Shajahan (1), Dr Elena Zanella (1), Dr Sara Mana (2), Dr Andrew Harris (3), Dr Benjamin van Wyk de Vries (3)

1) University of Turin, Italy

2) Salem State University, Massachusetts

3) Clermont Auvergne University, France

Correspondence to: [rasia.shajahan@unito.it](mailto:rasia.shajahan@unito.it)

The study of volcanic systems is never complete without examining its plumbing system and the associated magma-filled conduits such as dykes or sills. Indication of magma flow direction in these magma-filled vertical or sub-vertical volcanic bodies can give information about the complex subvolcanic structure and the associated magma migration in the upper crust. The dyke geometry along with its fabrics reveal insights into the location and orientation of the magma chamber which allows the reconstruction of flow dynamics during emplacement.

We present a detailed account of the magnetic aspects of Mount Calanna (MC) dyke swarms of Mount Etna to understand the lava flow direction and dyke-emplacement mechanisms. MC is an isolated hill, which is covered by the lava flow of the Valle del Bove phase, extending over an area of 0.7km<sup>2</sup>. The basaltic dykes of the quaternary age intruded into this highly fractured and hydrothermally weathered unit. We performed systematic anisotropy of magnetic susceptibility (AMS) analysis on 45 oriented hand samples from 11 dykes where at least two samples were collected from both dyke boundary and core.

Based on the mode of eruption on the surface and structural data, Mount Calanna dykes can be divided into two main classes, one in which the dyke emplaced by summit eruption and the other where the dyke emplaced by the flank eruption. The dikes intruded directly from the central conduit have inclined to sub horizontal magnetic foliation plane, while those emplaced by the flank eruption have a sub-horizontal foliation plane. It is inferred that the magnetic foliation plane of most of the samples is parallel to either sub-horizontal or sub-vertical joints. Nevertheless, the variation in the shape parameter from core to boundary shows the effect of shear, magma viscosity, and the host rock strength on magma emplacement. Rock- and paleo-magnetic techniques enable us to unravel the relative timing of the injection of the dykes and the possible tectonic control on their emplacement.

## Paleomagnetism of Late Quaternary Pico de Orizaba volcano, Mexico

Katrin Sieron (1), Evelin Martínez-Izaguirre (2), Harald Böhnel (3), Erick Juarez (3)

1) Universidad Veracruzana, Mexico

2) UMDI UNAM, Mexico

3) Centro de Geociencias – Universidad Nacional Autónoma de México, Campus Juriquilla, Mexico

Correspondence to: erickja@geociencias.unam.mx

**Keywords:** paleomagnetism, paleomagnetic dating, Holocene volcanism, Pico de Orizaba, Mexico

Pico de Orizaba is the highest volcano of Mexico, with important activity during the Holocene. This activity has been defined in time mainly by a few pyroclastic flows which were far reaching and where C-14 data could be obtained. Many of the young lava flow emplacements have not been dated so far. In this work we present paleomagnetic data from 39 sites of such lava flows, focused to determine if their record is distinguishable and thus is suitable for paleomagnetic dating, using the program *archaeo\_dating* (Pavón-Carrasco et al., 2011) and geomagnetic field model for the Holocene (Pavón-Carrasco et al., 2014). During extensive field work, such flows were sampled in multiple sites which were previously selected by satellite images and a map made by Carrasco-Núñez 2000, but often had to be changed on the run. Field work was challenging, as hiking had to start early in the morning at about 3400 masl, carrying all equipment for the rest of the day, and sometimes finishing above 4800 masl; all this under extreme weather conditions including snow and gravel. The preselection of potential sites and the refinement during the field work resulted in a highly successful sampling: 30 sites provided mean directions with  $\alpha_{95} < 5^\circ$ , important in the context of paleomagnetic dating. Paleomagnetic results show that many lava flows have similar paleomagnetic directions, possibly indicating that there may have been short periods of increased effusive activity, similar to monogenetic volcanoes, separated by periods of inactivity. Which would mean that volcanic activity of Pico de Orizaba varied between periods of calm and sudden and extensive effusive activity.

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**Magnetobiochronology of the Nardués-Andurra section  
(Jaca-Pamplona basin, Central Pyrenees);  
initial results from a prospective Bartonian GSSP**

P. Sierra-Campos (1), P. Calvín (1), G. Bernaola (2), J.C. Larrasoaña (3), A. Payros (4), E.L. Pueyo (1),  
M. Montes (5), A. Luzón (6), J.I. Pérez-Landazabal (7), M.P. Mata (5), E. Bellido (5)

- 1) CN IGME, CSIC, 50006 Zaragoza, Spain
- 2) Escuela de Ingeniería, Universidad del País Vasco, 48013 Bilbao, Spain
- 3) Departamento de Ciencias, UPNA, 31006 Pamplona, Spain
- 4) Facultad de Ciencias, Universidad del País Vasco, 48080 Bilbao, Spain
- 5) CN IGME, CSIC, 28760 Tres Cantos, Spain
- 6) Departamento de Ciencias de la Tierra, Universidad de Zaragoza, 50009 Zaragoza, Spain
- 7) INAMAT2, UPNA, 31006 Pamplona, Spain

Correspondence to: p.sierra@igme.es

**Keywords:** Lutetian/Bartonian boundary, Chron C19n, Jaca-Pamplona basin, GSSP

The Bartonian is the only Paleogene GSSP that is still pending definition due to the lack of suitable sections. Here we present initial magnetobiostratigraphic results for the Nardués-Andurra section (Jaca-Pamplona basin), where a Lutetian/Bartonian succession cropping out extensively and with minimal tectonic disturbances is located. This section is made up by marls and distal turbidites that constitute the uppermost 1000 m of the Hecho Group and by 200 m of prodeltaic marls that constitute the overlying Urroz-Sabiñánigo and the lowermost part of the Pamplona-Arguis formations. More than 170 magnetostratigraphic sites were evenly sampled throughout the succession with a mean resolution of 7 m. Thermal demagnetization results enable identification of a low temperature component (<200-250°C) that corresponds to a present-day field overprint. Above this temperature, a Characteristic Remanent Magnetization (ChRM) is identified despite of neof ormation of magnetic phases upon heating, which prevents further delineation of the ChRM at temperatures above 375-400°C. Nevertheless, a large percentage of samples show stable ChRM directions that either display linear trends directed towards the origin of the demagnetization plots or less linear paths that can be anchored to their origin. A weak to moderate decrease in intensity often observed below 350°C points to the contribution of magnetic iron sulphides, in addition to magnetite, to the ChRM. When the components attributed to both minerals can be reliably calculated, they usually show the same polarity. This suggests that magnetite represents a primary magnetization and that magnetic iron sulphides of authigenic origin carry a magnetization acquired shortly after deposition without significant time delays. The sequence of VGP latitudes enables delineation of a short reverse interval (R1) followed by a thin normal magnetozone (N1) in the lowermost part of the succession. A long reverse interval (R2) changes into normal polarity interval (N2) in the uppermost 300 m of the section. Calcareous nannofossil preliminary results locate the last occurrence (LO) of *Sphenolithus furcatolithoides* B at the middle part of R2 indicating that N2 and R2 correlate with C18n.2n and C18r, respectively. This is consistent with the correlation of the succession with the neighbouring sections of Gállego-Aragón (Oms et al., 2003) and Yebra de Basa (Vinyoles et al., 2021). This correlation implies that R1 and N1 correspond with the uppermost part of C19r and C19n, respectively. Since chron C19n is the main marker of the Lutetian/Bartonian boundary, we tentatively propose the Nardués-Andurra section as a suitable candidate to host the Bartonian GSSP. Further paleomagnetic, rock magnetic, geochemical and biostratigraphic analyses will be conducted to

validate this interpretation and to investigate the possible role of authigenic magnetic iron sulphide formation on the paleomagnetic recording fidelity of the studied succession.

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**Contributions of AMS and paleomagnetism  
to the study of volcanoclastic systems:  
example of the Late-Carboniferous-Permian Cadí basin (Central Pyrenees)**

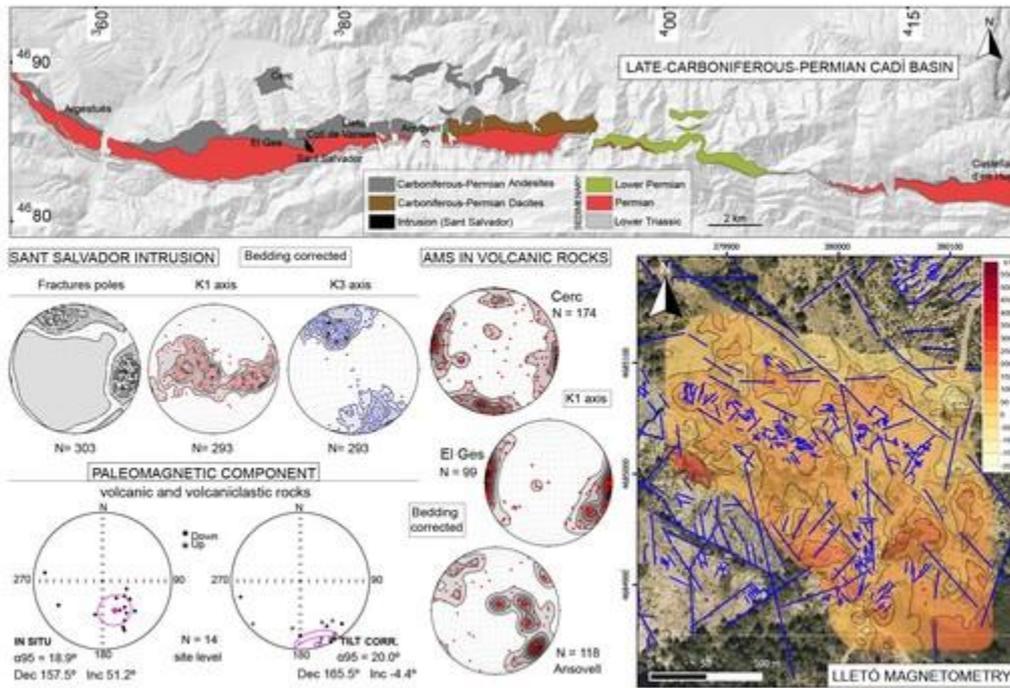
A. Simón-Muzás (1), A. M. Casas-Sainz (1), R. Soto (2), J. Gisbert (1), T. Román-Berdiel (1),  
B. Oliva-Urcia (3), E. Pueyo (2), E. Beamud (4), P. Calvín (2), J.J. Villalaín (5)

- 1) Departamento de Ciencias de la Tierra, Geotransfer-IUCA, Universidad de Zaragoza, 50009 Zaragoza, Spain
- 2) IGME, Instituto Geológico y Minero de España, Unidad de Zaragoza, 50006 Zaragoza, Spain
- 3) Departamento de Geología y Geoquímica, Universidad Autónoma de Madrid, 28049 Madrid, Spain
- 4) Paleomagnetic Laboratory CCI TUB - Geosciences Barcelona (Geo3Bcn), CSIC, 08028 Barcelona, Spain
- 5) Departamento de Física, Universidad de Burgos, Burgos, Spain

Correspondence to: [anasimon@unizar.es](mailto:anasimon@unizar.es)

**Keywords:** Magnetic fabrics, paleomagnetism, Late Carboniferous-Permian, Pyrenees

This study has been carried out in the Cadí basin, which is an example of an intramountainous basin located in the central-eastern part of the Southern Pyrenees (Spain), south of the Axial Zone. The basin is involved in the hanging wall of a significant basement thrust sheet, transported southwards during the Eocene-Oligocene Pyrenean orogeny. It presents a great variability of Late Carboniferous-Permian volcanic and sedimentary deposits, distributed along E-W outcrops. Magnetic techniques applied to the study of volcanoclastic rocks and lava flows include RT-AMS and LT-AMS analysis with a cooling measurement routine in liquid nitrogen (~77 K) performed in the Univ. of Zaragoza using a KLY-3S (AGICO Inc). Paleomagnetic analysis focused only on stepwise thermal demagnetization from room temperature to 670°C through a TD48-DC thermal demagnetizer (16 stages) at the CCI TUB-GEO3BCN and Univ. of Burgos. Magnetic mineralogy was determined from temperature-dependent susceptibility curves between 40–700 °C measured in the CS-3 furnace coupled to the the KLY-3S and hysteresis loops obtained in the variable-field translation balance (MMVFTB) at the Univ. of Burgos. The AMS results, along the studied N-S and NE-SW transects, show that magnetic fabrics were acquired during the emplacement of the volcanic and volcanoclastic rocks and are related to flow. Microstructural study and field observations show mineral alignments consistent with the magnetic fabrics. Even though the Cadí basin has undergone compressional deformation stages, the contribution of Cenozoic deformation to the original magnetic fabric is negligible apart from a regional southwards tilting. The magnetic lineation presents a general trend parallel to the basin axis in a main WNW-ESE-trending and in a N-S secondary direction. Nevertheless, paleoflow sense indicators and source areas cannot be defined at this stage. In addition, two detailed studies are being carried out in two specific areas of the basin of particular interest: 1) the Sant Salvador intrusive body that can be interpreted as a feeding pipe where the magnetic foliation (carried by ferromagnetic minerals) is subparallel to the foliation plane defined by the preferred arrangement of the plagioclases and both foliation and lineation are subvertical in the bedding-restored position. Magnetic fabrics also show a close relationship with thermal jointing. 2) The Lletó zone, that is a large area with lava flows and volcanic breccias with a strong magnetic signature in magnetic surveys. Strong variations in susceptibility values are observed at the centimeter and meter scales and it may be due to enrichments in ferromagnetic minerals in the rocks during mineral alteration. Paleomagnetic results in volcanic and volcanoclastic rocks show a very well defined primary or early diagenetic Permian direction (equatorial reverse polarity).



**Fig. 1:** Situation of the studied sites in the geological map; Fracture poles; AMS and paleomagnetic component stereoplots and Magnetometry in Lletó area.

## **Remanent magnetization in Bunte Breccia from the Ries impact structure, Germany**

I.V. Sleptsova, S.A. Gilder, F. Dellefant, C.A. Trepmann, J. Pohl

Department of Earth and Environmental Sciences, Ludwig-Maximilians-University

Correspondence to: [sleptsova@geophysik.uni-muenchen.de](mailto:sleptsova@geophysik.uni-muenchen.de)

The 15 Ma, 26 km-diameter Ries (Germany) impact structure contains well-preserved ejecta deposits consisting of polymict breccia (Bunte Breccia) overlain by suevite of variable thickness. Suevite typically contains crystalline basement rock fragments in all stages of shock metamorphism including melt fragments. The suevite carries a thermal remanent magnetization with reverse polarity acquired during the impact event that produces negative magnetic anomalies in today's normal polarity field. In contrast, the Bunte Breccia has been previously reported to contain dominantly sedimentary target rock clasts exhibiting low shock stages with no evidence for melting. It is commonly believed that the Bunte Breccia was deposited relatively cold. To test shock and temperature conditions of the Bunte Breccia during deposition, we investigated the magnetic properties and microfabrics of 16 polymict clasts and a stratigraphic profile from the clasts into the suevite at the Aumühle quarry where a sharp contact between the breccia and suevite is clearly visible. The clasts sampled in the Bunte Breccia at the contact to the suevite include amphibolites, gneisses, limestones, and sandstones, as investigated by optical and electron microscopy as well as Raman spectroscopy. In the sedimentary components no shock effects are apparent. The shock effects in the basement clasts include planar deformation features (PDFs) in quartz, maskelynite, and twinned amphiboles. The remanent magnetizations in the Bunte Breccia can be divided into 3 groups: (1) those with directions close to the characteristic remanent magnetization (ChRM) direction typical of Ries suevite, (2) those with directions antipodal to the suevite direction, and (3) those with randomly distributed directions as confirmed by a positive conglomerate test. Thermoremanent (in-field) and stepwise demagnetization curves show significant deflections at  $\sim 580^{\circ}\text{C}$  in the suevites, suggestive of magnetite, whereas the underlying polymict breccia exhibits systematically higher deflections around  $640\text{-}680^{\circ}\text{C}$ , suggestive of Ti-free to Ti-poor titanohematite. The microscopically observed Fe-oxide phases in the samples are consistent with the magnetic results showing  $>10\ \mu\text{m}$  magnetite and hematite grains as well as sub- $\mu\text{m}$  hematite. Titanohematite is known to exhibit self-reversal behavior, which we think is responsible for the case (2) directions. We tentatively prefer a model that the Bunte Breccia was partly chemically altered and remagnetized by impact-related hydrothermal activity that converted existing Fe-bearing phases into titanohematite in most of the sedimentary clasts. The interpretation is less clear for the basement clasts, where the random conglomerate test implies the magnetizations were locked-in prior to deposition. In the suevite, the hematite content decreases going upward from the contact as suggested by lowering coercivity spectra (higher coercivity toward the base). Magnetite unblocking temperatures are dominant 10 cm above the contact. Hence, the overlying suevite acted as a semi-permeable barrier that confined hot fluids to the breccia zone, yet the suevite was altered by the underlying fluids near the contact.

**Magnetotactic bacteria as a proxy of paleoproductivity  
at the Eocene- Oligocene transition:  
Paleoenvironmental evidences from ODP Site 709C, Leg 115**

A.P. de M de Souza (1), F. Florindo (2), P. Srivastava (1), L. Jovane (1)

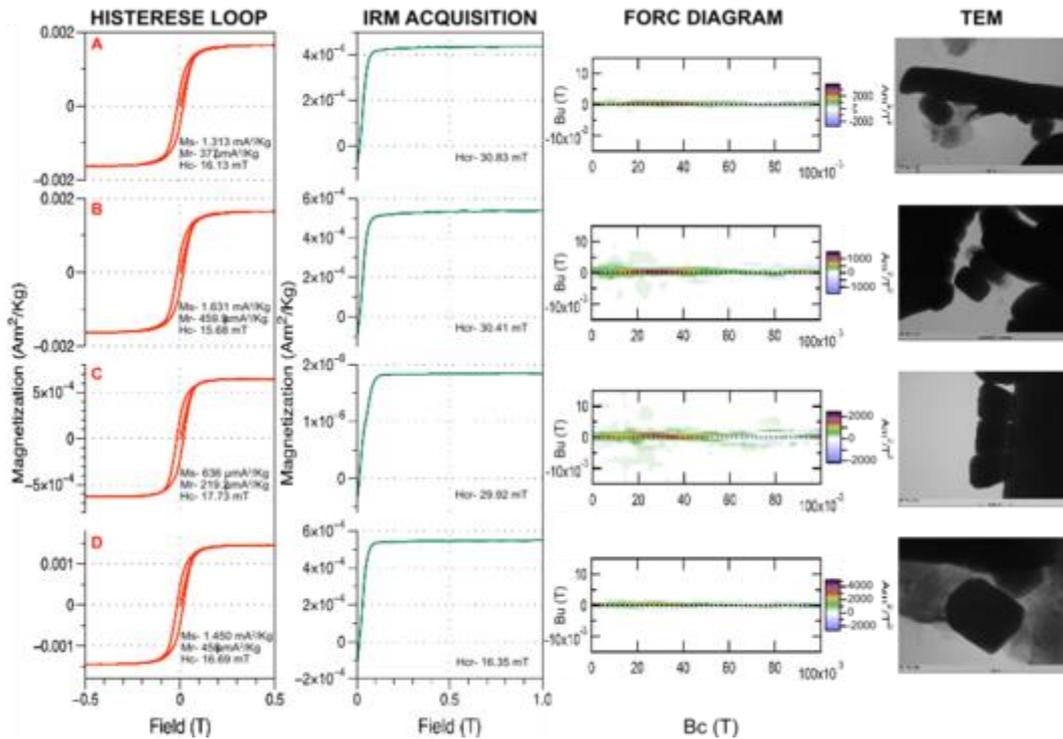
1) University of São Paulo, Instituto Oceanográfico, University of São Paulo, Brazil

2) National Institute of Geophysics and Volcanology, Via di Vigna Murata 605, I-00143 Roma, Italy

Correspondence to: anamartini@usp.br

**Keywords:** Eocene Oligocene Transition, Magnetotactic Bacteria, Paleoproductivity, Rock Magnetism, Indian Ocean

Magnetotactic bacteria (MTB) are prokaryotes that mineralize magnetic crystals (single domain size-SD) in structures called magnetosomes, which permit them to orient themselves and migrate along magnetic fields. The magnetosomes can be preserved in marine sediments as magnetofossils. Previous studies suggest that the morphology of magnetofossils provides an archive of redox conditions which are related with paleoenvironmental information and sensitive to climate change. In this context, the Cenozoic global climate evolution represents a period of drastic climate transitions, shifting from an intersection of greenhouse effect during the Eocene to conditions of cooling until the climax of glaciation at the Eocene-Oligocene Transition (EOT). The EOT lasted for about 500 kyr and marks a major step towards the development of the modern glaciated climate. During this transition period, a phase of oceanic reorganization, temperature decrease (5 - 6 °C), biotic turnovers, sea level change (-55 m), positive isotopic excursions of oxygen, the growth of the first semi-permanent ice-sheets on Antarctica, the deepening of the global Carbonate Compensation Depth (CCD) and a decrease in atmospheric  $p\text{CO}_2$  have been detected. In order to characterize the paleoenvironmental conditions around the EOT, marine sediments from the western equatorial Indian Ocean (site 709C, expedition Leg115) were provided by the Ocean Drilling Program (ODP) spanning from the Middle Eocene to the onset of the Oligocene. A total of 235 samples were demagnetized using step-wise alternating field demagnetization method for reconstruction of magnetic polarity change. This data was combined with previous biostratigraphic analyzes in order to construct an age model. The sediment samples were also analyzed for environmental magnetism, rock magnetism, X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF). The high resolution magnetostratigraphy of studied sediments revealed age range from Mid Eocene Climatic Optimum (MECO) to EOT. Environmental magnetism properties indicate decreasing magnetic grain size from MECO to EOT suggesting a change in sediment source. The Rock magnetism data indicates biogenic magnetite as the main magnetic contribution in the sediments (Fig. 1). From FORC analysis three different signals of biogenic magnetite were identified, further analysis is required to confirm the MTB presence in these depths and their morphology related with redox conditions. The higher input of Fe, Al, K, Mg and Mn coincides with the peak in biogenic magnetite production; rock magnetic data combined with XRF results indicates bimodal shifts in high productivity during EOT. These shifts in paleoproductivity are probably enhanced by the flux of nutrients from increased eolian iron fertilization, which may have increased ocean surface productivity, thus intensifying the delivery of iron and nutrients to the seafloor, heighten magnetotactic bacterial populations.



**Fig. 1:** Rock magnetism for samples from 709C indicating contribution of ferromagnetic components, such as biogenic magnetite, which is confirmed by the TEM analysis. A) 268.38 mbsf at C12r, B) 278.44 m at C13n, C) 321.28 m at C18r and D) 334.12 m at C20n.

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## Yet another approach for establishing palaeosecular variation reference curves for archaeomagnetic dating

S. Spassov (1), E. Aidona (2)

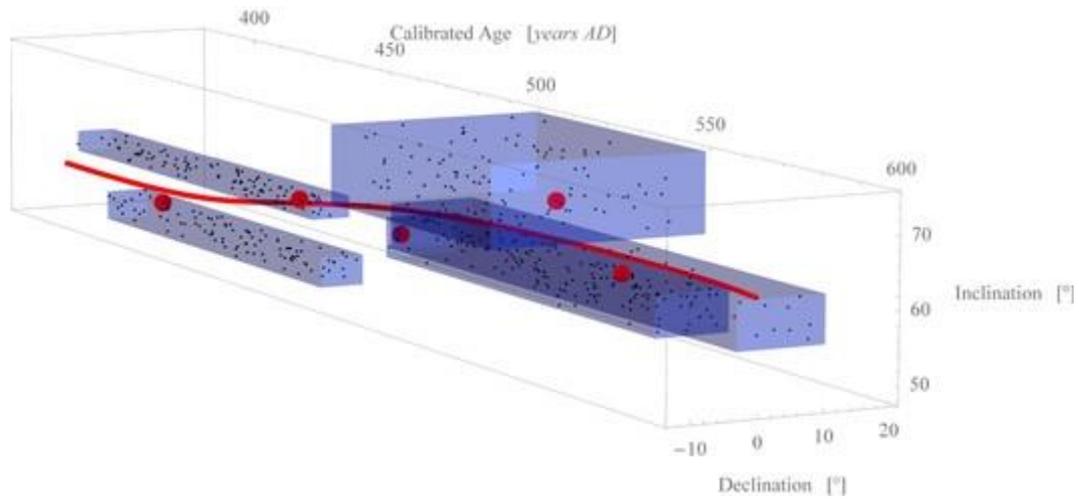
1) Geophysical Centre of the Royal Meteorological Institute of Belgium.

2) Department of Geophysics, School of Geology, Aristotle University of Thessaloniki, Greece.

Correspondence to: simo@meteo.be

**Keywords:** Archaeomagnetic dating, Palaeosecular variation reference curve, Simple random sampling, Principle of insufficient reason, Bag plot

The difficulty in establishing palaeosecular variation (PSV) reference curves draws back to rather large uncertainties of individual database points, their uneven distribution over time / geographic space and unknown or often not verified distributions of experimental errors. The majority of PSV calculation methods assumes or simulates particular marginal probability density functions for age and direction and intensity and thus incorporates informative priors that are difficult to estimate correctly. The methodology here proposed follows therefore an inverse logic, *i.e.* neglecting inconsistent knowledge of informative priors in archaeomagnetic databases and using uninformative priors instead. A concept à *l'ars conjectandi* is applied, relying on the principle of insufficient reason; *i.e.* an epistemological principle tracing back to Jakob I Bernoulli (1713). According to this principle, a discrete uniform distribution is assumed for the probability of occurrence of distinguishable and mutually exclusive events, when no further information is available. Concretely, individual age, remanence and intensity determinations of a given archaeological structure, thus at sample level, are assumed to be uniformly distributed within their confidence limits. The intentional choice of this uninformative prior results from the argumentation above, *i.e.* the inconsistent knowledge of marginal age, direction and intensity probabilities in archaeomagnetic databases. To this end, a stochastic approach is being proposed, based on a bundle of weighted non-uniform rational B-spline (NURBS) curves that are determined through sets of spline control point sequences. The three-dimensional (3D) control points (age, declination, inclination) are drawn for each spline by simple random sampling with replacement from the 3D uncertainty region (UR) of each datum (Fig. 1). The URs are taken as uniform, *i.e.* as uninformative prior. Weighting accounts for the extent of the 3D uncertainty region, Euclidean distances between uncertainty regions and between control points and eventually for geographical distances with respect to the relocation centre. The PSV uncertainty envelope is then determined from the convex hull of the spline bundle and integrated into an archaeomagnetic dating routine based on computational geometry. Dating examples from Bulgaria and France reveal a precision common to that of usual PSV dating methods. The asset of the proposed method is that it relies exclusively on uncertainty ranges without making assumptions about the marginal probability distributions (*cf.* principle of insufficient reason).



**Fig. 1:** A set of random points (black dots) is generated in each UR (blue), but without underlying distribution. One of these dots is chosen at random to be the spline control point of the UR (red points). Eventually, a NURB curve (red line) is determined.

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## Paleoclimatic changes during the late Maastrichtian and early Danian in South Atlantic

Priyeshu Srivastava (1,2), Dan V. Palcu (1,3), Luigi Jovane (1), Jiubin Chen (4), Fabio Florindo (2), Alcides N. Sial (5), Jahnvi Puneekar (6), Suman Rawat (7), Manoel Damaceno (1), Gabriel Tagliaro (1)

- 1) Instituto Oceanográfico, Universidade de São Paulo, Brazil
- 2) Istituto Nazionale di Geofisica e Vulcanologia, Roma, Italy
- 3) Department of Earth Sciences, Utrecht University, The Netherlands
- 4) Institute of Surface-Earth System Science, Tianjin University, China
- 5) NEG-LABISE, Federal University of Pernambuco, Brazil
- 6) Department of Earth Sciences, Indian Institute of Technology Bombay, India
- 7) Wadia Institute of Himalayan Geology, Dehradun, India

Correspondence to: priyeshusrivastava@gmail.com

**Keywords:** Cretaceous-Paleogene extinction; Dan-C2; Deccan flood volcanism; Environmental magnetism; South Atlantic

The temporal link between large igneous provinces (LIPs) magmatism and global environmental changes, including mass extinctions, have led to extensive studies on cause-and-effects relationship between them. The volatiles released from LIPs magmatism (e.g., SO<sub>2</sub>, CO<sub>2</sub>, HCl) have been hypothesized to have both short term effects (e.g., cooling associated with sulphate aerosols, acid rain, ozone depletion) on a decadal time scale to long term environmental changes on a millennial time scale. The Deccan flood volcanism (DFV) is one such well-studied LIP which erupted between ~66.3 and 65.4 Ma and is temporally linked with the Cretaceous-Paleogene (K/Pg) boundary mass extinctions at ~66 Ma. The K/Pg boundary mass extinction has also been linked to the Chicxulub asteroid impact, which is often argued as the primary driver of the mass extinction. The latest Maastrichtian warming event (LMWE), and Dan-C2 hyperthermal event in the early Danian fall within the timeline of the DFV and are generally linked with the early (/main) and the late phase of Deccan eruptions. However, these hyperthermal events are also debated to be mere regional expressions rather than global events. To better understand such climatic changes in the South Atlantic, we conducted multi-proxy studies on the DSDP site 356 core that spans these events. The chronology of the core was improved using high resolution magnetostratigraphic analyses (~240 samples were demagnetized using alternating-field and thermal demagnetization analyses). For the paleoclimate reconstruction, environmental magnetic, geochemical, and C, O (bulk carbonate) and Hg isotopic analyses were performed. The low magnetic susceptibility (MS) zone, ~50 to 60 ka before the K/Pg boundary, often reported from western Tethys records (e.g., Gubbio Italy, Bidart France and Zumaia Spain), was also found in the DSDP site 356 core with almost complete loss of detrital magnetic signal. This low MS zone was characterized by low Fe intensity and high Ca/Ti. The  $\delta^{18}\text{O}$  results showed significantly decreased values (warming) in the early Danian coinciding with eruptions of the DFV, accompanied by the Hg and Pb anomalies (markers for volcanism). The new multi-proxy results from the late Maastrichtian and early Danian of the South Atlantic significantly improves our understanding of the volcanism induced changes in the global climate.

## Vector unmixing of multicomponent palaeomagnetic data

Justin A.D. Tonti-Filippini, Stuart A. Gilder

LMU München, Germany

Correspondence to: justin.tonti@gmail.com

**Keywords:** Magnetic properties, Palaeomagnetism, Remagnetisation, Statistical methods, Numerical approximations and analysis

A common issue encountered during palaeomagnetic investigations is that of remagnetisation, where secondary processes have obscured, overprinted, or completely replaced the primary magnetisation. The identification and separation of primary and secondary magnetisations is generally carried out by principal component analysis of stepwise demagnetisation data, but this method can only unravel magnetic components with discrete unblocking spectra. Rocks and sediments often contain multiple generations of magnetic minerals with similar properties and coincident unblocking ranges. In these cases, researchers must rely on other rock magnetic, geochemical, and petrographic observations to resolve individual component contributions. A method of differentiating and quantifying contributions from overlapping magnetic components using directional data is therefore highly desirable. In this paper, we present a method of unmixing stepwise demagnetisation data using an inverse modelling approach. We show that the method is capable of accurately resolving two or three magnetisations with overlapping or indiscrete unblocking spectra as well as quantifying absolute and relative component contributions. However, the method depends on accurate identification of end-member components prior to analysis and an assumption that there are no magnetic interactions between components. The efficacy of the method is demonstrated with thermal demagnetisation data obtained from hematite-bearing sandstones. We expect this method could be broadly applied to multicomponent magnetisation problems in palaeomagnetism.

This research was supported by the German Research Foundation (DFG project GI712-18/1).

## The greigite proxy: constraining formation mechanisms using thermodynamic modelling

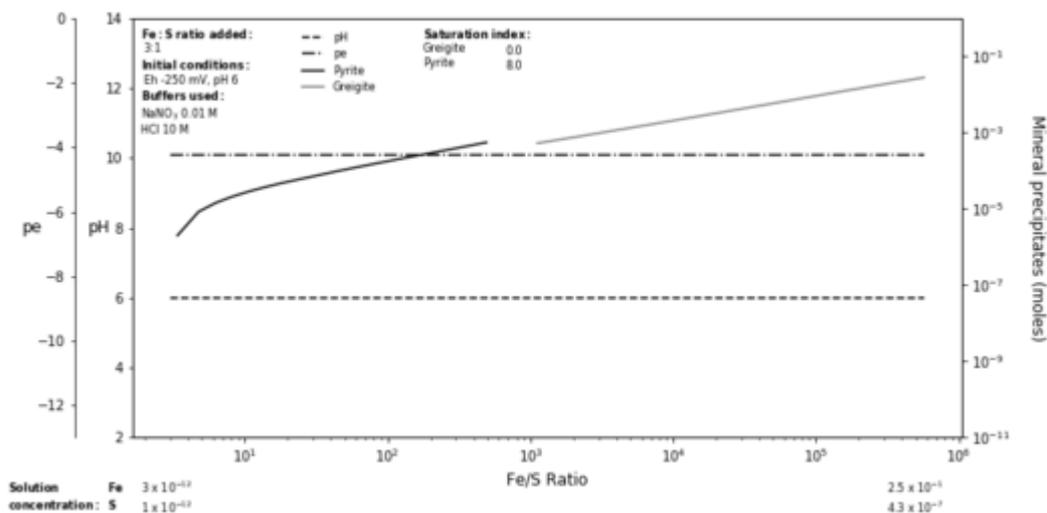
J. Turney, D. Weiss, A. Muxworthy, Al Fraser

Imperial College London

Correspondence to: jt2020@ic.ac.uk

**Keywords:** greigite, thermodynamics, modelling, proxy

Ferrimagnetic greigite forms as an intermediate phase along the pyrite reaction pathway, via sulphur addition, however, it is observed in numerous natural systems making it a unique proxy for diagenetic and environmental conditions, i.e., pH and redox state (pe). Authigenic greigite can also obscure detrital magnetic readings which has important implications for the palaeomagnetic record. Despite its significance, how greigite is identified, and the conditions at which it forms, are poorly constrained. Thermodynamic modelling is used to predict mineral formation under specific conditions, however, more stable endmembers are typically predicted as opposed to intermediate phases. The aim of this study is to develop a geochemical model that identifies the boundary conditions and possible mechanisms for greigite formation. The objectives are 1) to conduct a series of computational experiments, including incrementally adding ratios of iron and sulphur, and fixing and unfixing pH and pe, and 2) combine model results with natural sediments to determine how useful greigite is as an environmental proxy. The models show greigite formation is promoted by iron-dominant, neutral to alkali solutions in anoxic conditions. By increasing the saturation index at which pyrite precipitates, at the highest iron-sulphur ratios greigite is thermodynamically preferred (Fig. 1). Bulk-water geochemistry of greigite-hosted sediments also show iron-rich, sulphur-poor solutions, however, the concentrations seen in the models are far higher which may be representative of microenvironments with locally steep concentration gradients, such as in pore spaces and around bacteria. Comparisons with natural sediments suggest greigite may be a useful proxy for high-iron, low-sulphur environments at thermodynamic equilibrium, however, further modelling is required, such as incorporating kinetics, to help understand formation mechanisms.



**Fig. 1:** Geochemical model of pyrite and greigite precipitation in an iron-dominant solution. To promote greigite formation, pyrite is set to a high saturation index.

## Preliminary paleomagnetic results from the Most Basin, Czech Republic

Hakan Ucar (1), Gunther Kletetschka (1,2), Petr Schnabl (2), Karel Mach (3)

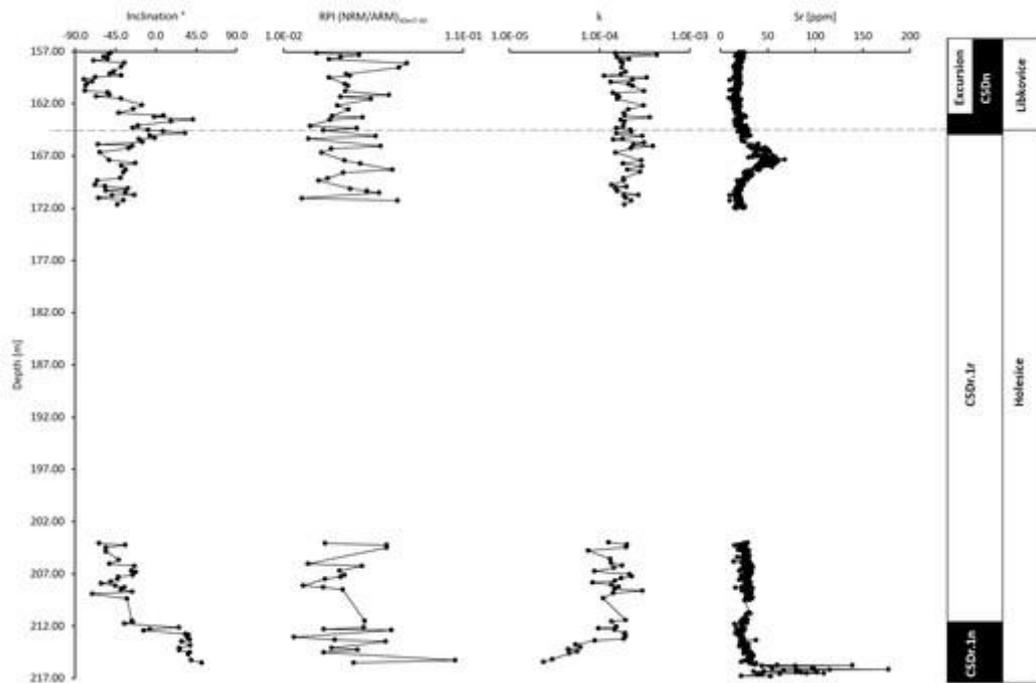
1) Faculty of Science, Charles University, Prague, Czech Republic

2) Institute of Geology, The Czech Academy of Sciences, Prague, Czech Republic

3) North Bohemian Mines, j.s.c., Bilina, Czech Republic

Correspondence to: ucarh@natur.cuni.cz

Here we present the preliminary paleomagnetic results from Miocene lacustrine sediments in the Most Basin, Czech Republic. Characteristic remanent magnetization (ChRM) directions of discrete samples from 28 m sediment cores showed two magnetic reversals that corresponds to polarity chrons C5Dr.1n/C5Dr.1r/C5Dn and an excursion during C5Dn chron. Relative paleointensity (RPI) data indicated fluctuations before the transitions, and the Earth's field increased after the transitions. Isothermal remanent magnetization (IRM) and S-ratio measurements showed low-coercivity minerals in the samples. Anisotropy of magnetic susceptibility (AMS) data showed horizontal bedding, and deformation on some sediment cores due to drilling. Susceptibility (k) values range between  $2.5 \times 10^{-5}$  and  $4.5 \times 10^{-4}$  [SI]. X-ray fluorescence (XRF) analyses supported the stratigraphical correlation of the sediment with the prior works with sediment from nearby locations. Further investigation will focus on magnetic transition zones and detailed rock magnetism measurements.



**Fig. 1:** Paleomagnetic data from the sediment cores with magnetic polarity diagram and the lithological members of the Most Basin. Dashed lines show the boundary between Libkovice and Holesice members. RPI: Relative paleointensity, k: volume susceptibility.

We thank the Pruhonice Paleomagnetism Laboratory and its members Simon Kdyr, Lada Kouklikova, and Katerina Bachova for allowing and helping us to measure the paleomagnetic samples. North Bohemian Mines, j.s.c. is thanked for providing the sediment cores. Radana Kavkova is thanked for helping with the transportation of the sediment cores. The research was supported by the Grant Agency of Charles University (project no. 265321).

## Iron oxide transformations in Technosols developed from thermal power station ash

Ł. Uzarowicz (1), B. Górka-Kostrubiec (2), K. Dudzisz (2)

1) Warsaw University of Life Sciences - SGGW, Institute of Agriculture, Department of Soil Science, Nowoursynowska St. 159, PL02-776 Warsaw, Poland

2) Institute of Geophysics, Polish Academy of Sciences, Księcia Janusza 64, PL01-452 Warsaw, Poland

Correspondence to: katarzyna.dudzisz@gmail.com

**Keywords:** Technosols, fly and bottom ash, Magnetite, Hematite, Soil-forming processes

Fly and bottom ash originating from coal combustion in thermal power stations (TPSs) are types of industrial waste exhibiting magnetic properties and containing primarily Fe-bearing phases. This material, after deposition on disposal sites, becomes the parent material for technogenic soils (Technosols), in which the transformations of Fe-bearing magnetic minerals accompany the soil-forming processes. The studied samples were (1) fresh (unweathered) fly and bottom ash resulting from bituminous coal and lignite combustion and (2) soil samples from Technosols developed on ash disposal sites. The study aimed to determine the magnetic properties and mineral composition of fresh ash and soils. The results of our study show that the magnetic properties of Technosols developed from thermal power station ash are significantly affected by the heterogeneity of the parent material and mainly depend on the type of fuel (bituminous coal vs lignite), type of ash (fly vs bottom ash) and the mode of ash deposition on the land surface (dry landfills vs settling ponds). The magnetic enhancement is a typical feature of the studied Technosols due to the contribution of a strongly ferrimagnetic component from the parent material. It is reflected in high values of magnetic susceptibility which ranges from 771 to  $2538 \times 10^{-8} \text{ m}^3/\text{kg}$  in soil profile developed from bituminous coal ash and from 622 to  $7657 \times 10^{-8} \text{ m}^3/\text{kg}$  for Technosol originated from lignite ash. Magnetite with a mean coercivity  $< 50 \text{ mT}$  and hematite ( $< 1000 \text{ mT}$ ) were found to be the major magnetic minerals of fresh fly and bottom ash. Hematite contribution did not exceed 15% in the samples, however, in Technosols also maghemite was detected, most likely originating from the surface oxidation of fine magnetite grains inherited from the parent material. Magnetite in fresh ash is in the range of grain size typical of the PSD state (1–20  $\mu\text{m}$ ). Regardless of the type of combusted fuel (bituminous coal or lignite), magnetite in bottom ash displays finer grain size than in fly ash whereas magnetite in Technosols is in the range size of 20–200  $\mu\text{m}$  which may indicate some pedogenic processes of aggregation of magnetic particles in soils. Magnetic methods were found to be a valuable research technique in the case of TPS ash-derived Technosols, for the identification of Fe-bearing magnetic minerals that are hardly recognizable by mineralogical methods, and for tracking the transformations of magnetic minerals resulting from soil-forming processes.

## Calculating global apparent polar wander since 320 Ma from site-level paleomagnetic data

B. Vaes (1), L.C. Gallo (2), D.J. Van Hinsbergen (1)

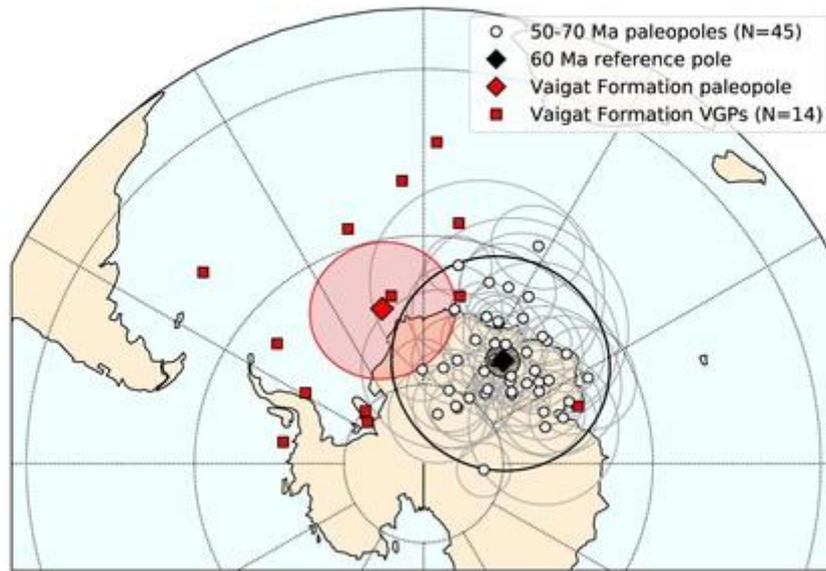
1) Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

2) Centre for Earth Evolution and Dynamics, University of Oslo, Oslo, Norway

Correspondence to: b.vaes@uu.nl

**Keywords:** apparent polar wander path, paleomagnetic pole, paleosecular variation

Paleomagnetic poles used to compute apparent polar wander paths (APWPs) are strongly dispersed, which was recently shown to cause a large fraction (>50%) of these poles to be statistically distinct from the APWP to which they contributed, suggesting that current statistical approaches overestimate paleomagnetic resolution. In this study, we first analyze why coeval paleopoles are so dispersed, using the paleopoles behind the most recent global APWP and a compilation of paleomagnetic data obtained from <10 Ma volcanic rocks (PSV10). We find that paleopoles derived from sedimentary rocks, or from data sets underrepresenting paleosecular variation (PSV), are more dispersed and more frequently displaced. We show that paleopoles based on a smaller number of paleomagnetic sites are more dispersed than poles based on larger data sets, revealing that the degree to which PSV is averaged is an important contributor to the pole dispersion. We identify as a fundamental problem, however, that the number of sites used to calculate a paleopole, and thus the dispersion of coeval paleopoles, is essentially arbitrary. We therefore explore a different approach in which reference poles of APWPs are calculated from site-level data instead of paleopoles, thereby assigning larger weight to larger data sets. Using this approach, we present a new high-resolution global apparent polar wander path for the last 320 Ma based on an updated global paleomagnetic database. In addition, we introduce a bootstrap-based method for comparing a paleomagnetic data set with a reference APWP on the same hierarchical level, such that geologically meaningful differences may be determined. Finally, our study highlights that demonstrating smaller tectonic displacements requires larger paleomagnetic data sets, and that such data sets can strongly improve future APWPs.



**Fig. 1:** 50-70 Ma paleopoles (circles, plotted with A95) used to compute the 60 Ma reference pole (black diamond) of the global APWP of Torsvik et al. (2012). Vaigat Formation paleopole shown as an example of a statistically distinct pole. Figure from Vaes et al. (2022).

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**Archeomagnetic results from burnt sediments  
in a medieval archeological site  
(Caleruega, Burgos, North-Central Spain)**

E. Vernet (1), Á. Carrancho (1), M. Calvo-Rathert (1), M. Crespo (2), S. Jorge (1), M. F. Bógalo (1)

1) Universidad de Burgos, Departamento de Física, Escuela Politécnica Superior, E-09006 Burgos, Spain

2) Patrimonio Inteligente S.L., 30004 Murcia, Spain

Correspondence to: evernet@ubu.es

**Keywords:** Archeomagnetism, Archeointensity, Medieval church,

We present an archeomagnetic study carried out in a medieval hearth from an archeological site, named *Cañada Real* and located in Caleruega (Burgos, North Spain). The main goal of the study is to determine the age of the last fire event occurred in the site. The studied materials included 12 hand samples, 9 of them oriented, collected from a hearth preserved on the floor of a medieval church. The archeomagnetic study has been carried out using both thermal and AF demagnetizations. Archeomagnetic analysis reveals the following mean direction: declination,  $D = 17.2^\circ$ , inclination,  $I = 53.8^\circ$ ,  $k = 270$  and  $\alpha_{95} = 1.4^\circ$ . Using the regional model SHA.DIF.4k of Pavón-Carrasco *et al.* (2021) and the updated Iberian paleosecular variation curve of Molina-Cardín *et al.* (2018), points towards a preliminary dating between 1014 - 1113 AD using the former model and 934 - 1028 AD with the Iberian one. These results agree with the archeological context. To assess the suitability of the studied samples for paleointensity determinations a mineralogical characterization of the samples, including high-temperature susceptibility curves, RAMAN spectroscopy and other rock magnetic studies with the Variable Field Translation Balance were performed. The results suggest a magnetic mineralogy composed of magnetite but in some cases, also other components with lower Curie temperatures are observed. Archeointensity experiments with the Thellier-Coe method on 12 specimens are still in progress. Archeointensity analysis includes pTRM-checks and anisotropy corrections. These determinations will allow a full-vector archeomagnetic dating, better constraining the obtained ages.

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## A new attempt to define the chronology of Iberian rotation during the Cretaceous

J.J. Villalaín (1), L. Yenes (1), P. Calvín (2), M. Marcén (3), A.M. Casas (3), V.C. Ruiz (4), T. Román-Verdiel (3), M.F. Bógalo (1), S. Torres-López (1)

1) Universidad de Burgos, Departamento de Física, Escuela Politécnica Superior, 09006 Burgos, Spain

2) Instituto Geológico y Minero de España, Oficina de Zaragoza, 50006 Zaragoza, Spain

3) Departamento de Ciencias de la Tierra, Geotransfer-IUCA, Universidad de Zaragoza, 50009 Zaragoza, Spain

4) Departamento de Física de la Tierra y Astrofísica, Universidad Complutense de Madrid, 28040 Madrid, Spain

Correspondence to: villa@ubu.es

**Keywords:** Paleomagnetism, Iberian plate, Cretaceous, APWP, Rotation

The Mesozoic, and particularly the Cretaceous, evolution of the Iberian microplate is a recurring topic in Earth Sciences and regional tectonics, still open to controversy. Its interest lies in its location between the two major tectonic plates, their interaction and significance in relation to the evolution of the western Tethys domain. Geodynamic models of Mesozoic Iberian evolution are based upon the knowledge of the kinematics of the microplate obtained from the ocean floor magnetic anomalies and particularly its apparent polar wander path (APWP) defined by existing paleomagnetic data. In this sense, the most important feature is the anticlockwise 30°-40° rotation that Iberia underwent during the Cretaceous, linked to the opening of the Bay of Biscay (Van der Voo, 1969; Gong et al., 2008). Nevertheless, there are still uncertainties about the chronology of this movement due to the poor definition of oceanic magnetic anomalies and the scarcity of high-quality paleomagnetic data in the microplate. Some works demonstrate that existing paleomagnetic poles are contradictory and inconsistent with the global apparent wander path (GAPWP) and ocean floor anomalies (Neres et al., 2013). This is due to the widespread presence of remagnetizations in the Mesozoic basins within Iberia. To address this question, we are starting to develop a new project that aims to obtain new paleomagnetic data from unexplored geological units meeting the necessary condition to obtain new Cretaceous paleomagnetic poles representative of the Iberian plate, namely rocks carrying primary natural remanent magnetization not erased by the so common overprints in the Iberian basins and not detached from the Paleozoic basement. We are investigating alternative cretaceous lithologies located outside of the great Iberian basins, such as the Utrillas formation consisting of sands or scarcely cemented sandstones of Albian age, widely extended along the Iberian plate or the Areniscas de Salamanca Formation, detritic deposits with siliceous cement located at the Duero basin (North Iberian Meseta) ascribed to the upper Cretaceous-Paleocene. In this talk we show new paleomagnetic results in these units and discuss the primary character of magnetizations as well as the implications on the kinematic evolution of the Iberian plate.

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## **An integrated, RPI-based magnetostratigraphy of five abyssal Plio-Pleistocene sediment cores from the Central North Pacific**

Wanzhang Wang (1), Tilo von Dobeneck (1), Thomas Frederichs (1), Yang Zhang (1), Lester Lembke-Jene (2), Ralf Tiedemann (2), Michael Winklhofer (3), Dirk Nürnberg (4)

1) MARUM – Center for Marine Environmental Sciences and Faculty of Geosciences, University of Bremen, Leobener Straße, D-28359 Bremen, Germany

2) AWI — Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, D-27570 Bremerhaven, Germany

3) Institute for Biology and Environmental Sciences IBU, and Research Center for Neurosensory Sciences, Carl von Ossietzky University Oldenburg, 26111 Oldenburg, Germany

4) GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstrasse 1-3, 24148 Kiel, Germany

Correspondence to: [wwang@uni-bremen.de](mailto:wwang@uni-bremen.de)

**Keywords:** North Pacific, abyssal sediment, relative paleointensity, age model, biogenic magnetite

Paleoceanographic proxy research always depends on the accuracy of sediment age-depth relationships. For large non-fossiliferous sediments below the carbonate compensation depth (CCD), where traditional dating methods are hardly available, relative paleointensity (RPI) provides a continuous geomagnetic field record of high temporal resolution and excellent chronostratigraphic suitability. RPI estimation is based on a series of assumptions, where a key assumption is that all magnetic carriers acquire magnetization identically. In sediments with changing biogenic and detrital magnetic mineral content, a bias on the RPI record must be considered. Here we report on an integrated high-resolution abyssal North Pacific RPI record spanning over ~3.3 Ma, based on five sediment cores from the Emperor Seamount Chain region in Northwest Pacific. Among these, two cores were collected during the SO202 expedition in 2009 at water depths of 5581m and 6159m, and three cores during the SO264 expedition in 2018 at water depths of 5311m, 5704m and 3973m. By analyzing natural remanent magnetization (NRM) under AF-demagnetization, we could document all known polarity reversals in these cores as basic age control. NRM is mainly carried by two magnetic components, a biogenic and a detrital magnetite component. We recognized two types of biogenic magnetofossils by transmission electron microscopy tests on selected samples and applied FORC tests that showed a strong contribution of single domain particles, ideal RPI carriers. The magnetic properties showed little variation in concentration and grain size and no indication for diagenetic overprint, suggesting that these RPI records are trustworthy. To choose RPI normalizer, we decided to use a pseudo-Thellier slope method and analyzed coercivity windows proposed by Chen et al. (2017). We defined volcanoclastic layers in each core, which may origin from concurrent eruptions and gravitational sediment redeposition and diagenesis layers from one of studied core and analyzed the impact of biogenic, diagenesis and volcanoclastic components on the RPI signal. We found long term NRM loss and RPI amplitude decreasing in our long cores which related to changing of magnetic grain size that older sections of the RPI record with their finer (biogenic) magnetic particle sizes have consistently lower values. We consider this effect as the consequence of differences of the detrital magnetic carriers in studied cores or unstable magnetic behavior of highly oxidized or clustered fine-grained magnetite. Using this age model, we compared our RPI-enhanced magnetostratigraphy with other existing RPI stack and tested cyclostratigraphic alternatives paleoclimate proxy records (Ba/Ti, S-ratio) of our cores, these comparisons imply our RPI method might be the best available dating method for abyssal North Pacific sediments.

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**Beyond PM10 concentration levels: A (bio)magnetic monitoring approach for assessing and mitigating the impact of vehicular emissions in urban and cultural heritage sites. (invited talk)**

A. Winkler (1), A. Amoroso (2), T. Contardo (3), V. Lapenta (4), S. Loppi (3), G. Marchegiani (2),  
A. Sgamellotti (4)

1) Istituto Nazionale di Geofisica e Vulcanologia

2) ARPA Lazio

3) University of Siena, Department of Life Sciences

4) Accademia Nazionale dei Lincei

Correspondence to: aldo.winkler@ingv.it

**Keywords:** Airborne particulate matter, magnetic (bio)monitoring, cultural heritage, covid-19 lockdown

Humans and urban environments can be adversely threatened by exposure to air pollutants, including particulate matter (PM). Extensive bodies of legislation regulate the health-based standards and objectives that rely on PM concentration levels. Nevertheless, the interpretation of PM concentration data can be controversial, as it was evident in Rome during the Covid-19 lockdown, when the abrupt decrease of vehicular traffic – up to -78% - was followed by a minor only decrease of PM concentration, with respect to the previous months.

In this talk, the magnetic properties of PM<sub>10</sub> filters, lichens and leaves, collected during and after the lockdown, were inferred from magnetic susceptibility values, hysteresis loops and first order reversal curves.

In the first study, it was carried out a detailed comparison of the magnetic properties of PM<sub>10</sub> filters from automated stations for air quality monitoring, to assess the impact of the COVID-19 containment measures on the traffic-related fraction of PM.

In traffic urban sites, PM<sub>10</sub> concentration, on average, did not significantly change after the lockdown, when traffic promptly returned to its usual levels. Conversely, the average magnetic susceptibility of PM<sub>10</sub> filters more than doubled, with significant changes in the correlations between PM<sub>10</sub> concentration, mass and volume susceptibilities. The magnetic mineralogy of PM<sub>10</sub> filters was dominated by magnetite-like minerals arising from brakes emissions; natural magnetic sources emerged in rural contexts and during exogenous dusts atmospheric events.

In the second study, magnetic biomonitoring methodologies were applied at Villa Farnesina, Rome, a masterpiece of the Italian Renaissance, with loggias frescoed by renowned artists such as Raffaello Sanzio. Plant leaves and lichen transplants were respectively sampled and exposed at increasing distances from the main trafficked road, introducing an outdoor vs. indoor mixed sampling design for outlining the impact of vehicular particulate matter on the Villa Loggias. This work was carried out under partial Covid19 restrictions, with museums closed to visitors and negligible sources of indoor PM.

The magnetic properties of leaves and lichens showed that the bioaccumulation of magnetite-like particles, mainly linked to vehicle brake emissions, decreased exponentially with the distance from the road. The frescoed halls were preserved from important inputs of metallic PM, due to the

combined effect of the distance from the road and the ecosystem preventive services provided by tree and shrub leaves along the road and inside the Villa's Gardens, intercepting vehicular PM.

(Bio)magnetic monitoring provided unique proxies of the traffic related vehicular emission, diagnostic of important variations in traffic conditions that are not evident from PM<sub>10</sub> concentration data alone, and demonstrating that a proper reduction of brake wear, as the main source of airborne pollutants, is demanded.

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## **Paleomagnetic, structural and magnetic fabric study of the Anemzi syncline (Central High Atlas): Towards a 3D palinspastic reconstruction**

L. Yenes (1), P. Calvín (2), J.J. Villalaín (1), A.M. Casas-Sáinz (3), Á. Jiménez-Sanz (1)

1) University of Burgos

2) IGME

3) University of Zaragoza

Correspondence to: lyenes@ubu.es

**Keywords:** Atlas, Remagnetization, Small Circle, Paleomagnetism, AMS

The Atlas is the largest intraplate mountain range in North Africa, being the High Atlas the Moroccan part of the Atlas System. Its evolution during the Mesozoic is defined by an important extensional tectonics, magmatic activity and deformation associated with salt tectonics. It mainly consists of a series of basins developed during the Triassic and the Jurassic that were inverted during the Cenozoic. The area is characterized by dominant NE-SW and ENE-WSW trending folds, which interfere with smaller-scale oblique or perpendicular folds.

Previous studies have shown that the natural remanent magnetization (NRM) of the Central High Atlas Jurassic limestones is dominated by a Cretaceous regional remagnetization. This overprint is interfolding since it is separating different tectonic events: it happened after the syn-sedimentary tectonic during the extensional stage but before the Cenozoic inversion of the basins linked to the convergence between Africa and European plates. The fact that it is an interfolding remagnetization permits to restore the structures of the area and filter the Cenozoic deformation to better understand all the structural evolution of the area. The remagnetization direction has been calculated using the Small Circle Intersection (SCI) technique and was dated at ca. 100 Ma. It has been concluded that it is a synchronous phenomenon for the entire High Atlas.

In this work, a high-resolution paleomagnetic study in the Anemzi syncline area is presented. Ninety-one paleomagnetic sites of Jurassic limestones have been sampled over an area of 35 km<sup>2</sup> that includes paradigmatic structures of the Central High Atlas. The Anemzi syncline has a southern limb which limits with a vertical set of Jurassic intrusive bodies and Triassic shales and basalts, whereas in the northern limb Lower Jurassic carbonates are outcropping and overthrust Middle Jurassic rocks.

Subsequently, a detailed study of paleomagnetism and anisotropy of the magnetic susceptibility (AMS) has been carried out at the 91 sites (~ 800 samples), as well as a tectonic analysis of the entire area, including 170 sites with structural data. The paleomagnetic study revealed that the Cretaceous remagnetization is observed systematically in all stations as a paleomagnetic component with maximum unblocking temperature between 425 °C and 500 °C carried by magnetite.

Using Small Circles analysis 91 paleobeddings from the corresponding sites have been determined at the age of remagnetization (i.e., 100 Ma). These paleobeddings have been used to make several high-resolution geological cross-sections that represent the geometry of the structure 100 Ma ago to be compared with their present-day geometry allowing to determine the evolution of characteristic structures of the High Atlas. The ultimate objective will be to build two 3D palinspastic models showing the present-day and the restored structure at 100 Ma by using these paleomagnetic results, AMS analysis and structural data.

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**The Proterozoic supercontinent Rodinia at 925 Ma:  
paleomagnetic constraints from North China and Brazil**

Xixi Zhao

Southern University of Science and Technology, China

Correspondence to: xzhao@tongji.edu.cn

**Keywords:** Rodinia, Mafic dykes, Paleomagnetism, North China Craton, São Francisco Craton

Rodinia is a relatively young supercontinent in Neoproterozoic, unified by various Precambrian continental cratons during the time period of 1300 - 900 Ma. Several recent papers favor the hypothesis that North China Craton (NCC) of China and São Francisco Craton (SFC) of Brazil may have been connected at 925 Ma and are parts of building cratons for supercontinent Rodinia. However, this view is currently still debated. Coeval Neoproterozoic mafic dykes with well-dated isotopic age of 925 Ma are distributed in both NCC and SFC. Here, we present new and published data of these dykes from both cratons. Detailed thermal and alternating-field demagnetization results revealed that stable components of magnetization with unblocking temperatures below the Curie temperature of magnetite have been recorded in the studied dykes of NCC and SFC. Results from thermomagnetic experiments, hysteresis loop and scanning electron microscope further confirm that the major magnetic minerals in dyke samples are titanomagnetites with pseudo-single-domain grains. The mean directions of the characteristic remanent magnetization (ChRM) of the dykes from both cratons yield positive baked contact tests and are completely different from those of both older and younger strata in the sampling localities, indicating primary remanence. The ChRM from the SFC dykes is also of dual polarity. Our results imply that the NCC and SFC were in the moderate to high paleolatitudes of the southern hemisphere at about 925 Ma, suggesting a paleogeographic connection between the two cratons. A new paleogeographic reconstruction of Rodinia at 925 Ma is proposed, which is supported by other geologic and rock magnetic evidence and facilitates a more contingently paleo-relationship in the subsequent assembly of supercontinent Gondwana.

**Comparing magnetic pore fabrics, X-ray tomography-derived pore fabrics and permeability anisotropy tensors in homogeneous uniaxially symmetric synthetic samples and heterogeneous sedimentary rocks**

Yi Zhou (1), Anneleen Foubert (2), Pierre Lanari (1), Andrea R. Biedermann (1)

1) Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012 Bern, Switzerland

2) Department of Geosciences, University of Fribourg, Chemin du Musée 6, CH-1700 Fribourg, Switzerland

Correspondence to: yi.zhou@geo.unibe.ch

Preferred fluid flow directions are controlled by pore fabrics, i.e., pore shape, alignment and distribution, and their reliable characterization is crucial for hydrocarbon and geothermal energy exploitation. Permeability anisotropy can be measured directly, but most studies calculate the ratio of horizontal and vertical permeabilities, which probably underestimates the anisotropy. Heterogeneity can further affect the permeability anisotropy determination, possibly leading to over- or under-estimation of the anisotropy degree. Magnetic pore fabric (MPF) is an alternative way of estimating permeability anisotropy and preferred flow directions, with the major advantage that the full tensor is obtained from a single core. Empirical studies show correlations between MPF orientation and principal permeability directions, and between MPF and permeability anisotropy degrees. The latter vary largely between studies, highlighting the need for better constraints. Alternatively, X-ray computed tomography (XRCT) allows the non-destructive determination of three-dimensional pore fabrics, but image analyses is time-consuming and the voxel resolution depends on density and sample size. Here, XRCT-derived pore fabrics, MPFs and permeability anisotropy tensors were compared using homogeneous uniaxially symmetric synthetic samples, and heterogeneous sandstone and limestone. Synthetic samples were hot isostatically pressed (HIP) at 160 MPa pressure and 670 °C temperature, mixing multiple ratios and grain sizes of calcite and muscovite powders. The uniaxial sample symmetry is reflected in the physical properties, so that two independent measurements are sufficient to determine the second-order permeability tensor. To evaluate confidence limits for the tensor, four cores were drilled in three perpendicular directions. For sandstone and limestone, no symmetry constraints apply, and six independent measurements are needed to define the permeability tensor. To assess data quality and variability on the dm-scale, 14 cores were drilled along six directions from a single block. Four permeability tensors were calculated from different combinations of directional cores, to assess the influence of heterogeneity. An additional core of each sample was scanned by XRCT (5.5  $\mu\text{m}$  voxel size) to analyze pore fabrics and to simulate permeability anisotropy. Subsequently, the core was impregnated with ferrofluid for MPF measurements. The maximum principal directions of permeability anisotropy, XRCT-derived pore fabrics and MPFs are coaxial or sub-parallel. Anisotropy degree and shape vary. Simulated and laboratory-measured permeability anisotropy differ, likely due to undetected micropores. Heterogeneity leads to permeability tensors that depend on the cores included. Therefore, we suggest MPFs as an efficient way to evaluate between-sample heterogeneity, and to determine the principal pore fabric directions, along which permeability can then be measured for cross-calibration.