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Inside...

Towards a holistic understanding of complex magnetic fabrics

Andrea R. Biedermann
Institute for Rock Magnetism
biede029@umn.edu

Magnetic fabrics have initially been attributed to rock texture by Graham (1954) and Balsley and Buddington (1960), who found that the maximum susceptibility was parallel to the lineation and the minimum susceptibility normal to the foliation in a series of granitic rocks. Anisotropy of magnetic susceptibility (AMS) or remanence (e.g. anhysteretic, AARM, isothermal, AIRM, or thermal, ATRM) have since been used to infer lava flow directions and emplacement models in igneous rocks, deformation and tectonic transport directions in metamorphic rocks, and water-current or wind directions in sediments (cf. Borradaile and Henry, 1997; Borradaile and Jackson 2010; Hrouda 1982; Martín-Hernández et al., 2004; Owens and Bamford, 1976; Tarling and Hrouda, 1993), and the degree of anisotropy has been linked to the strength of deformation (Cogné and Perroud, 1988; Kligfield et al., 1977, 1981; Kneen, 1976; Parés and van der Pluijm, 2004; Weil and Yonkee, 2009). More recent studies have shown that anisotropy-deformation relationships need to be established for every specific rock type, taking into account the mineralogy and the relative proportions of ferromagnetic minerals with respect to the paramagnetic and diamagnetic constituents of the rocks, for example (Borradaile and Henry, 1997; Housen and van der Pluijm, 1990; Housen et al., 1993). Furthermore, grain-size can influence magnetic anisotropy; for example single-domain (SD) magnetite carries “inverse AMS fabrics”, with minimum susceptibility parallel to the flow direction or lineation, opposite to the common interpretation (e.g. Gialanella et al., 1994; Rochette et al., 1999; Hrouda and Jezek, 2017). Still, magnetic fabrics are a powerful indicator of a rock’s texture, particularly the preferred alignment of grains, which is modified during geodynamic processes by grain re-alignment, grain-deformation, or recrystallization.

Rock texture is a complex property, involving the different mineral constituents and their crystallographic preferred orientation (CPO), shape preferred orientation (SPO), and spatial distribution in the rock. Whereas textures can be described directly using a variety of techniques like electron backscatter diffraction (EBSD; Prior et al., 1999), or image analysis (Heilbronner and Barrett, 2014), it is often easier, and more representative for heterogeneous materials, to assess preferred mineral orientation by measuring the anisotropy of physical properties, like seismic or magnetic anisotropy (Engler and Randle, 2009; Ullemeyer et al., 2000). Magnetic fabrics are described by a magnitude ellipsoid whose properties

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Beautiful folding in Oppdal, Norway. Photo: A. R. Biedermann

Important Notice!

It is with a heavy heart that we announce that the current issue of the IRM Quarterly will be the last to be mailed in printed form.

Regretfully, budget cuts have forced us to this decision. The IRM Quarterly will be mailed in digital form to the email addressess that we have on record, but please do not hesitate to send your updated email contact by following the link posted on our website:

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Visiting Fellow Report

A behavioral archeomagnetic investigation of burnt rock middens in central Texas.

Brendan Nash
Gault School of Archaeological Research
bn1058@txstate.edu

I visited the IRM to conduct a magnetic study of hot rock cooking technology on the Edwards plateau, which initiated around 8,000 BP. Use of hot rock cooking technology is extremely visible in the study area, often producing very large (>50m in diameter) mounds or 'middens' of used burnt rock. Goal of the project was to provide quantitative observations to identify specific behaviors associated with the formation and use of these structures.

The first scientific investigations of burnt rock middens in central Texas were conducted by J.E. Pearce from 1903 to 1938, who concluded that middens were comprised of cooking debris from hearth structures. In 1942 Kelly and Campbell instead suggested that middens are made up of remnants of stone-lined basins that were used for cooking. In 1969 Sorrow proposed the interpretation that middens were dump areas where broken hearth stones were discarded, but it was not until 1974 that Prewitt (n.d) argued for middens representing the remains of covered stone-lined earth ovens. The data I gathered at the Institute for Rock Magnetism (IRM) at the University of Minnesota will be used to further test these hypotheses at the Gault site.

During my time at the IRM I carried out thermal demagnetization of oriented cores collected from middens of the Gault site to investigate whether any post-heating movement of the individual limestone blocks had occurred (Fig. 1). I also carried out low temperature remanence measurements (Fig. 2), magnetic hysteresis (Fig. 3) and magnetic susceptibility as a function of temperature to characterize the mineralogies responsible for the magnetic remanence.

The information collected will be used to reconstruct the original morphology of a stone heating structure from the scattered debris that make up middens (i.e. simple hearths, stone-lined basins, or covered earth ovens), which directly addresses the aforementioned hypothesis.

One significant example about the formation of burnt rock middens comes from the Wilson Leonard site in Central Texas. Archaeologists were able to use archaeomagnetic data from culturally heated limestone rocks to determine that middens at the Wilson Leonard site are likely aggrading living surfaces rather than large discard piles. Another significant discovery was that many of the stone-lined middens which were assumed to be open roasting or grilling pits, were actually earth ovens that were closed with a stone lid, as asserted by Prewitt. This was determined by examining rocks directly adjacent to stone-lined pits. At many sites the majority of these rocks were moved away from the pit at a common low temperature, and are interpreted to be the lid of the ovens.

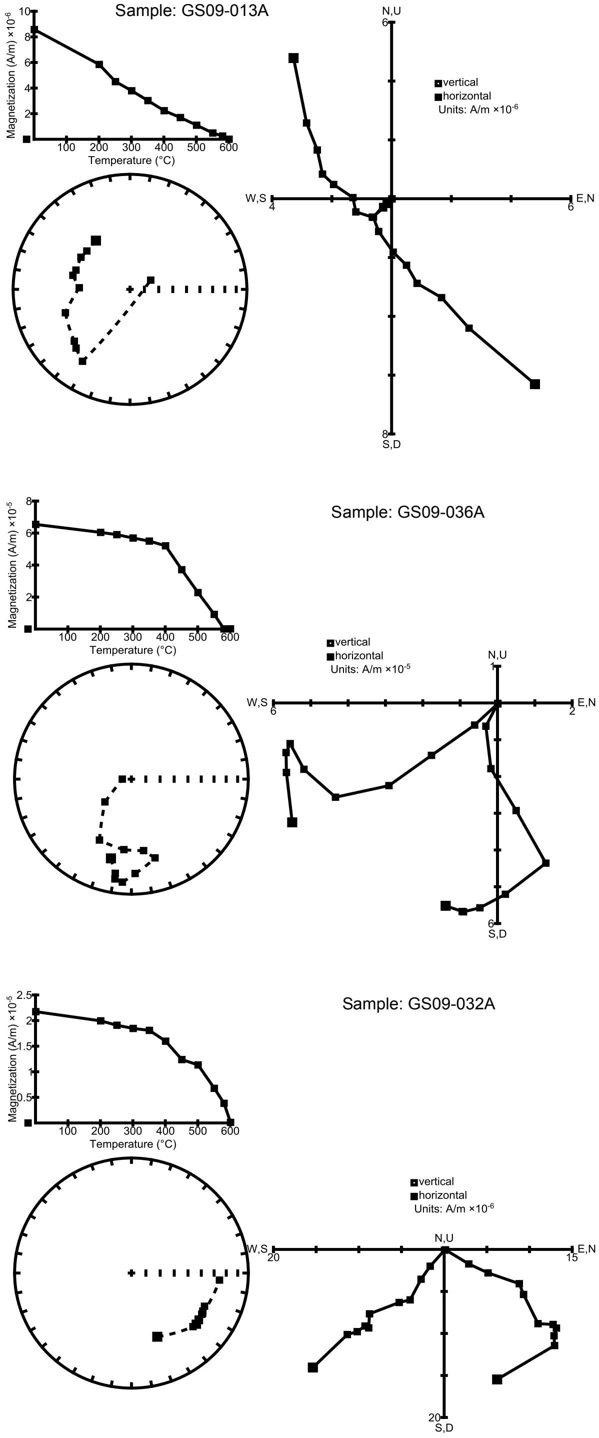
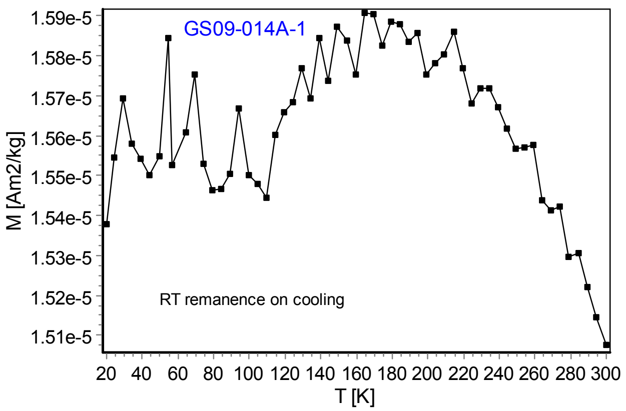


Figure 1. Thermal demagnetization of the NRM indicating three different demagnetization behaviors: a quasi constant decay of remanence between room and 600°C indicating a range of magnetite grain-sizes as dominant magnetic carrier, and two distinct magnetization components; a "narrower" range of magnetite unblocking temperatures between 400° and 580°C, and multiple superimposed magnetization components; and two dominant unblocking temperatures ~400° and 600°C, and at least two associated components of magnetization.



2. Low-temperature demagnetization of a 300K saturation isothermal remanent magnetization, showing a distinct magnetite Verwey transition over an overall weak magnetization. Goethite is also apparent from measurements of other specimens, not shown.

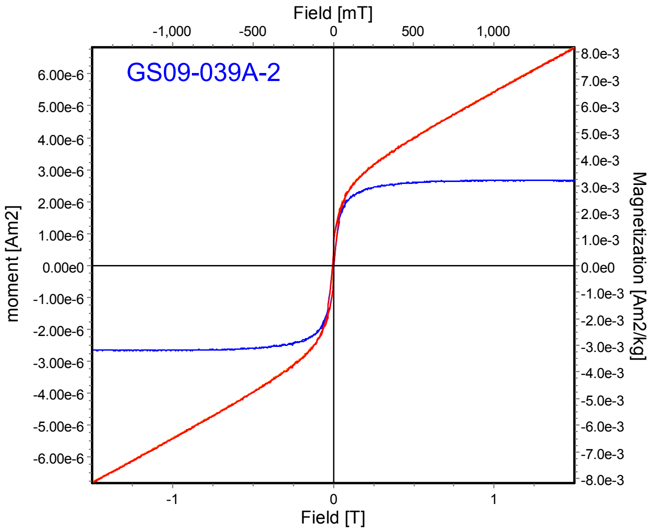


Fig. 3. Hysteresis loop indicating multi-domain magnetite dominant signal, and little wasp-wastedness indicating a mixture of coercivities present.

My magnetic findings from the Gault site will complement the observations of the Wilson Leonard site, further proving this new understanding of behaviors associated with the use of stone cooking structures, and the formation of burnt rock middens. Furthermore the identification of specific actions taken by individuals at a particular moments in time, will strengthen the case for behavioral archeology and place the role of the individual in the broader pictures painted by archeologists.

Behavioral archeomagnetism in central Texas offers the rare chance to identify specific behaviors taken by individuals at a specific moment in time. Like preserved human footprints, the thermal history of a culturally heated rock is a trace fossil of human behavior.

References cited

Kelley, J. C., & Campbell, T. N., 1942. What Are the Burnt Rock Mounds of Texas?. American Antiquity, 7(3), 319-322.1969 .

Prewitt, E. R., (n.d) The Rodger Spring site: 1974 Investigations. Manuscript on File, Texas Archaeological Laboratory, The University of Texas at Austin.

Sorrow, W. M., .1969. Archaeological Investigation of the John Ischy Site: A Burnrt Rock Midden in Williamson County Texas. Papers of the Texas Archaeological Salvage Project 18. The University of Texas at Austin.

Current Articles

A list of current research articles dealing with various topics in the physics and chemistry of magnetism is a regular feature of the IRM Quarterly. Articles published in familiar geology and geophysics journals are included; special emphasis is given to current articles from physics, chemistry, and materials-science journals. Most are taken from ISI Web of Knowledge, after which they are subjected to Procrustean culling for this newsletter. An extensive reference list of articles (primarily about rock magnetism, the physics and chemistry of magnetism, and some paleomagnetism) is continually updated at the IRM. This list, with more than 10,000 references, is available free of charge. Your contributions both to the list and to the Current Articles section of the IRM Quarterly are always welcome.

Aeromagnetism, Magnetic Anomalies, and Surveying

Anudu, G. K., R. A. Stephenson, D. I. M. Macdonald, and G. N. Oakey (2016), Geological features of the northeastern Canadian Arctic margin revealed from analysis of potential field data, Tectonophysics, 691, 48-64.

Espindola, J. M., H. Lopez-Loera, M. Mena, and A. Zamora-Camacho (2016), Internal architecture of the Tuxtla volcanic field, Veracruz, Mexico, inferred from gravity and magnetic data, Journal of Volcanology and Geothermal Research, 324, 15-27.

Farhi, W., A. Boudella, H. Saibi, and M. O. A. Bounif (2016), Integration of magnetic, gravity, and well data in imaging subsurface geology in the Ksar Hirane region (Laghouat, Algeria), Journal of African Earth Sciences, 124, 63-74.

Fnais, M., E. Ibrahim, E. Abd El-Motaal, K. Abdelrahman, A. Al-Heniedi, and K. Al-Kahtany (2016), Structural development of northwest Saudi Arabia using aeromagnetic and seismological data, Journal of Earth Science, 27(6), 998-1007.

Hendrickson, M. D. (2016), Structural analysis of aeromagnetic data from the Rainy River Block, Wabigoon subprovince, Minnesota, USA and Ontario, Canada: Strain partitioning along a Neoarchean terrane boundary and implications for mineral exploration, Precambrian Research, 286, 20-34.

Longo, L. M., R. De Ritis, G. Ventura, and M. Chiappini (2016), Analysis of the Aeromagnetic Anomalies of the Auca Mahuida Volcano, Patagonia, Argentina, Pure and Applied Geophysics, 173(10-11), 3273-3290.

Obiora, D. N., M. N. Ossai, F. N. Okeke, and A. I. Oha (2016), Interpretation of Airborne Geophysical Data of Nsukka Area, Southeastern Nigeria, Journal of the Geological Society of India, 88(5), 654-667.

Ogden, T. E., M. A. McLean, T. J. Rawling, and R. A. Cayley (2016), Redefined crustal structure of the Buchan Rift, northeast Victoria: evidence from potential field modelling of newly acquired land-based gravity data, Australian Journal of Earth Sciences, 63(5), 551-570.

Oskooi, B., H. Henkel, L. B. Pedersen, A. Backstrom, and M. Abedi (2016), Magnetotelluric investigation on Bjorko impact structure, west of Stockholm, Sweden, Arabian Journal of Geosciences, 9(13).

Ramotoroko, C. D., R. T. Ranganai, and P. Nyabeze (2016), Extension of the Archaean Madibe-Kraaipan granite-greenstone terrane in southeast Botswana: Constraints from gravity and magnetic data, Journal of African Earth Sciences, 123, 39-56.

Saada, S. A., and A. Abdelhay (2016), Structural setup of Ras Banas area, Red Sea, Egypt, as inferred from aeromagnetic data, Arabian Journal of Geosciences, 9(15).

Skiba, P., G. Gabriel, C. M. Krawczyk, M. Konig, C. Bucker, and C. Rolf (2016), On the use of small amplitude magnetic anomalies for the improvement of geological models: case studies from Northern Germany, Zeitschrift Der Deutschen Gesellschaft Fur Geowissenschaften, 167(2-3), 131-148.

Xiao, F., and Z. H. Wang (2017), Geological interpretation of Bouguer gravity and aeromagnetic data from the Gobi-desert covered area, Eastern Tianshan, China: Implications for porphyry Cu-Mo polymetallic deposits exploration, Ore Geology Reviews, 80, 1042-1055.

Xiong, S. Q., H. Yang, Y. Y. Ding, Z. K. Li, and W. Li (2016), Distribution of igneous rocks in China revealed by aeromagnetic data, Journal of Asian Earth Sciences, 129, 231-242.

Xu, Y., T. Y. Hao, H. Zeyen, and F. Z. Nan (2017), Curie Point Depths in North China Craton Based on Spectral Analysis of Magnetic Anomalies, Pure and Applied Geophysics, 174(1), 339-347.

Yang, B., A. Q. Zhang, S. Zhang, Y. Liu, S. Y. Zhang, Y. T. Li, Y. X. Xu, and Q. Y. Wang (2016), Three-dimensional audio-frequency magnetotelluric imaging of Akebasitao granitic intrusions in Western Junggar, NW China, Journal of Applied Geophysics, 135, 288-296.

Archeomagnteism

Cai, S. H., L. Tauxe, C. L. Deng, H. F. Qin, Y. X. Pan, G. Y. Jin, X. X. Chen, W. Chen, F. Xie, and R. X. Zhu (2016), New archaeomagnetic direction results from China and their constraints on palaeosecular variation of the geomagnetic field in Eastern Asia, Geophysical Journal International, 207(2), 1332-1342.

Carrancho, A., J. J. Villalain, J. Vallverdu, and E. Carbonell (2016), Is it possible to identify temporal differences among combustion features in Middle Palaeolithic palimpsests? The archaeomagnetic evidence: A case study from level O at the Abric Romani rock-shelter (Capellades, Spain), Quaternary International, 417, 39-50.

Frahm, E., J. M. Feinberg, G. E. Monnier, G. B. Tostevin, B. Gasparyan, and D. S. Adler (2016), Lithic raw material units based on magnetic properties: A blind test with Armenian obsidian and application to the Middle Palaeolithic site of Lusakert Cave 1, Journal of Archaeological Science, 74, 102-123.

Matasova, G. G., A. Y. Kazansky, and O. A. Pozdnyakova (2016), The Experience of Using the Rock Magnetic Methods for Assessing the Prospects of Magnetic Exploration in the Territory of Archaeological Monuments of the Barabinsk Forest Steppe, Izvestiya-Physics of the Solid Earth, 52(6), 869-883.

Osete, M. L., A. Chauvin, G. Catanzariti, A. Jimeno, S. A. Campuzano, J. P. Benito-Batanero, C. Tabernero-Galan, and P. Roperch (2016), New archaeomagnetic data recovered from the study of celtiberic remains from central Spain (Numantia and Ciaduena, 3rd-1st centuries BC). Implications on the fidelity of the Iberian paleointensity database, Physics of the Earth and Planetary Interiors, 260, 74-86.

Environmental magnetism and Climate

Aidona, E., H. Grison, E. Petrovsky, N. Kazakis, L. Papadopoulou, and K. Voudouris (2016), Magnetic characteristics and trace elements concentration in soils from Anthemountas River basin (North Greece): discrimination of different sources of magnetic enhancement, Environmental Earth Sciences, 75(20).

Badesab, F., Dewangan, P., Usapkar, A., Kocherla, M., Peketi, A., Mohite, K., Sangode, S.J. and Deenadayalan, K. (2016), Controls on evolution of gas-hydrate system in the Krishna-Godavari Basin, offshore India. Geochem. Geophys. Geosyst.. Accepted Author Manuscript. doi:10.1002/2016GC006606

Beaudoin, A., R. Pienitz, P. Francus, C. Zdanowicz, and G. St-Onge (2016), Palaeoenvironmental history of the last six centuries in the Nettilling Lake area (Baffin Island, Canada): A multi-proxy analysis, Holocene, 26(11), 1835-1846.

Dergacheva, M., O. Nekrasova, A. Uchaev, and N. Bazhina (2016), Sarykul paleosol in Southern Urals sediments (Russia), Quaternary International, 420, 90-100.

Gwizdala, M., M. Jelenska, and L. Leczynski (2016), Magnetometry as a Tool to Estimate the Pollution of Marine Environment Around Small Shipwrecks (Gulf of Gdansk) - Preliminary Results, Acta Geophysica, 64(5), 1691-1702.

Jaqueto, P., R. I. F. Trindade, G. A. Hartmann, V. F. Novello, F. W. Cruz, I. Karmann, B. E. Strauss, and J. M. Feinberg (2016), Linking speleothem and soil magnetism in the Pau d'Alho cave (central South America), Journal of Geophysical Research-Solid Earth, 121(10), 7024-7039.

Johnson, A., and H. Daigle (2016), Nuclear magnetic resonance secular relaxation measurements as a method of extracting internal magnetic field gradients and pore sizes, Interpretation-a Journal of Subsurface Characterization, 4(4), T557-T565.

Liu, C. S., Z. K. Zhu, F. B. Li, T. X. Liu, C. Z. Liao, J. J. Lee, K. M. Shih, L. Tao, and Y. D. Wu (2016), Fe(II)-induced phase transformation of ferrihydrite: The inhibition effects and stabilization of divalent metal cations, Chemical Geology, 444, 110-119.

Mabuza, B. B., and C. W. van Huyssteen (2016), Effect of synthetic amorphous and crystalline iron oxides on redox potential and exchangeable cations in wetland soils of Maputaland Kwazulu-Natal, South Africa, South African Journal of Geology, 119(1), 15-24.

Macphail, M., L. K. Fifield, B. Pillans, and G. Hope (2016), Lake George revisited: new evidence for the origin and evolution of a large closed lake, Southern Tablelands, NSW, Australia. 2: earliest Pleistocene (Gelasian) environments, Australian Journal of Earth Sciences, 63(4), 453-468.

Maher, B. A. (2016), Palaeoclimatic records of the loess/palaeosol sequences of the Chinese Loess Plateau, Quaternary Science Reviews, 154, 23-84.

Nizou, J., F. Demory, and C. Dubrulle-Brunaud (2016), Monitoring of dredged-dumped sediment dispersal off the Bay of the Seine (northern France) using environmental magnetism, Comptes Rendus Geoscience, 348(6), 451-461.

Ocampo-Rios, B. G., P. D. Roy, M. C. Macias, M. P. Jonathan, and R. Lozano-Santacruz (2017), Tsunami deposits of September 21st 1985 in Barra de Potosi: comparison with other studies and evaluation of some geological proxies for southwestern Mexico, Geofisica Internacional, 56(1), 57-69.

Oda, H., Y. Yamamoto, X. X. Zhao, S. Bijaksana, and Q. S. Liu (2016), Special issue on "Recent advances in environmental magnetism and paleomagnetism", Earth Planets and Space, 68.

Owens, P. N., W. H. Blake, L. Gaspar, D. Gateuille, A. J. Koiter, D. A. Lobb, E. L. Petticrew, D. G. Reiffarth, H. G. Smith, and J. C. Woodward (2016), Fingerprinting and tracing the sources of soils and sediments: Earth and ocean science, geoarchaeological, forensic, and human health applications, Earth-Science Reviews, 162, 1-23.

Riffel, S. B., P. M. Vasconcelos, I. O. Carmo, and K. A. Farley (2016), Goethite (U-Th)/He geochronology and precipitation mechanisms during weathering of basalts, Chemical Geology, 446, 18-32.

Sager, W. W., T. Sano, and J. Geldmacher (2016), Formation and evolution of Shatsky Rise oceanic plateau: Insights from IODP Expedition 324 and recent geophysical cruises, Earth-Science Reviews, 159, 306-336.

Seslija, M., A. Rosic, N. Radovic, M. Vasic, M. Dogo, and M. Jotic (2016), Properties of fly ash and slag from the power plants, Geologia Croatica, 69(3), 317-324.

Venuti, A., L. Alfonsi, and A. Cavallo (2016), Anthropogenic pollutants on top soils along a section of the Salaria state road, central Italy, Annals of Geophysics, 59(5).

Wang, X. Y., H. Y. Lu, W. G. Zhang, P. X. Hu, H. Y. Zhang, Z. Y. Han, S. J. Wang, and B. G. Li (2016), Rock magnetic investigation of loess deposits in the Eastern Qingling Mountains (central China) and its implications for the environment of early humans, Geophysical Journal International, 207(2), 889-900.

Zeeden, C., H. Kels, U. Hambach, P. Schulte, J. Protze, E. Eckmeier, S. B. Markovic, N. Klasen, and F. Lehmkuhl (2016), Three climatic cycles recorded in a loess-palaeosol sequence at Semlac (Romania) - Implications for dust accumulation in south-eastern Europe, Quaternary Science Reviews, 154, 130-142.

Zhu, C. X., H. Daigle, and S. L. Bryant (2016), Paramagnetic nanoparticles as nuclear magnetic resonance contrast agents in sandstone: Importance of nanofluid-rock interactions, Interpretation-a Journal of Subsurface Characterization, 4(2), SF55-SF65.

Extraterrestrial Magnetism

Arvidson, R. E. (2016), Aqueous history of Mars as inferred from landed mission measurements of rocks, soils, and water ice, Journal of Geophysical Research-Planets, 121(9), 1602-1626.

Bezaeva, N. S., N. L. Swanson-Hysell, S. M. Tikoo, M. Kars, and R. Egli (2016), On discrimination of thermal versus mechanical effects of shock on rock magnetic properties of spherically shocked up to similar to 10-140 GPa basalt and diabase, Meteoritics & Planetary Science, 51, A166-A166.

Chan, Q. H. S., M. E. Zolensky, J. E. Martinez, A. Tsuchiyama, and A. Miyake (2016), Magnetite plaquettes are naturally asymmetric materials in meteorites, American Mineralogist, 101(9-10), 2041-2050.

Chareev, D. A., N. S. Bezaeva, P. Rochette, M. Kars, J. Gattacceca, and J. M. Feinberg (2016), Magnetic characterization of non-ideal single-domain monoclinic pyrrhotite and its demagnetization under hydrostatic pressure up to 2 GPa with implications for impact demagnetization, Meteoritics & Planetary Science, 51, A201-A201.

Cournede, C., I. Garrick-Bethell, R. S. Coe, M. Le Goff, and Y. Gallet (2016), Mineralogical changes upon heating in the Millbillillie meteorite: Implications for paleointensity determination in Apollo samples, Comptes Rendus Geoscience, 348(8), 551-560.

Donohue, P. H., G. R. Huss, K. Nagashima, and M. Telus (2016), The search for fe-60 in secondary magnetite and fayalite, Meteoritics & Planetary Science, 51, A232-A232.

Dunn, T. L., J. Gross, M. A. Ivanova, S. E. Runyon, and A. M. Bruck (2016), Magnetite in the unequilibrated CK chondrites: Implications for metamorphism and new insights into the relationship between the CV and CK chondrites, Meteoritics & Planetary Science, 51(9), 1701-1720.

Einsle, J. F., R. J. Harrison, T. Kasama, P. O. Conbhui, K. Fabian, W. Williams, L. Woodland, R. R. Fu, B. P. Weiss, and P. A. Midgley (2016), Multi-scale three-dimensional characterization of iron particles in dusty olivine: Implications for paleomagnetism of chondritic meteorites, American Mineralogist, 101(9-10), 2070-2084.

Gattacceca, J., B. P. Weiss, and M. Gounelle (2016), New constraints on the magnetic history of the CV parent body and the solar nebula from the Kaba meteorite, Earth and Planetary Science Letters, 455, 166-175.

Harries, D. (2016), Experimental magnetite formation under protosolar conditions, Meteoritics & Planetary Science, 51, A314-A314.

Jambon, A., V. Sautter, J. A. Barrat, J. Gattacceca, P. Rochette, O. Boudouma, D. Badia, and B. Devouard (2016), Northwest Africa 5790: Revisiting nakhlite petrogenesis, Geochimica Et Cosmochimica Acta, 190, 191-212.

Kontny, A., and Grothaus, L. (2017), Effects of shock pressure and temperature on titanomagnetite from ICDP cores and target rocks of the El'gygytgyn impact structure, Russia, Studia Geophysica Et Geodaetica, 61, 1, 162-183.

MacArthur, J. L., J. C. Bridges, L. J. Hicks, G. M. Hansford, and L. Paget (2016), Goethite in northwest Africa 8114, Meteoritics & Planetary Science, 51, A437-A437.

Orgeira, M. J., et al. (2017), Extraterrestrial microspherules from Bajada del Diablo, Chubut, Argentina, Geoscience Frontiers, 8(1), 137-149.

Singh, M., J. Singhal, K. A. Prasad, V. J. Rajesh, D. Ray, and P. Sahoo (2016), Spectral characteristics of banded iron formations in Singhbhum craton, eastern India: Implications for hematite deposits on Mars, Geoscience Frontiers, 7(6), 927-936.

Volk, M. W. R., and S. A. Gilder (2016), Effect of static pressure on absolute paleointensity recording with implications for meteorites, Journal of Geophysical Research-Solid Earth, 121(8), 5596-5610.

Fundamental Rock and Mineral Magnetism

Almeida, T. P., A. R. Muxworthy, A. Kovacs, W. Williams, L. Nagy, P. O. Conbhui, C. Frandsen, R. Supakulopas, and R. E. Dunin-Borkowski (2016), Direct observation of the thermal demagnetization of magnetic vortex structures in nonideal magnetite recorders, Geophysical Research Letters, 43(16), 8426-8434.

Lima, E. A., and B. P. Weiss (2016), Ultra-high sensitivity moment magnetometry of geological samples using magnetic microscopy, Geochemistry Geophysics Geosystems, 17(9), 3754-3774.

Oda, H., et al. (2016), Scanning SQUID microscope system for geological samples: system integration and initial evaluation, Earth Planets and Space, 68.

Robinson, P., McEnroe, S.A., Miyajima, N., Fabian, K., and N. Church, 2016. Remanent magnetization, magnetic coupling, and interface ionic configurations of intergrown rhombohedral and cubic Fe-Ti oxides: A short survey, American Mineralogist, 101, 518-530.

Srivastava, P., S. J. Sangode, N. Parmar, D. C. Meshram, P. Jadhav, and A. K. Singhvi (2016), Mineral magnetic characteristics of the late Quaternary coastal red sands of Bheemuni, East Coast (India), Journal of Applied Geophysics, 134, 77-88.

Volk, M. W. R., S. A. Gilder, and J. M. Feinberg (2016), Low-temperature magnetic properties of monoclinic pyrrhotite with particular relevance to the Besnus transition, Geophysical Journal International, 207(3), 1783-1795.

Geodynamo

Bouligand, C., N. Gillet, D. Jault, N. Schaeffer, A. Fournier, and J. Aubert (2016), Frequency spectrum of the geomagnetic field harmonic coefficients from dynamo simulations, Geophysical Journal International, 207(2), 1142-1157.

Choblet, G., H. Amit, and L. Husson (2016), Constraining mantle convection models with palaeomagnetic reversals record and numerical dynamos, Geophysical Journal International, 207(2), 1165-1184.

Magnetic Fabrics and Anisotropy

Biedermann, A. R., F. Heidelbach, M. Jackson, D. Bilardello, and S. A. McEnroe (2016), Magnetic fabrics in the Bjerkreim Sokndal Layered Intrusion, Rogaland, southern Norway: Mineral sources and geological significance, Tectonophysics, 688, 101-118.

Dudzisz, K., R. Szaniawski, K. Michalski, and G. Manby (2016), Applying the anisotropy of magnetic susceptibility technique to the study of the tectonic evolution of the West Spitsbergen Fold-and-Thrust Belt, Polar Research, 35.

Hrouda, F., and Jezek, J., (2017), Role of single-domain magnetic particles in creation of inverse magnetic fabrics in volcanic rocks: A mathematical model study, Studia Geophysica Et Geodaetica, 61, 1, 145-161.

Vikas, C., V. Prasannakumar, and P. Pratheesh (2016), Role of microfabrics and magnetic fabrics in the tectonic evolution of the Achankovil shear-zone, South India, Journal of Asian Earth Sciences, 131, 95-108.

Mineralogy, Petrology, Mineral Physics and Chemistry

Cooperdock, E. H. G., and D. F. Stockli (2016), Unraveling alteration histories in serpentinites and associated ultramafic rocks with magnetite (U-Th)/He geochronology, Geology, 44(11), 967-970.

Merkulova, M., M. Munoz, O. Vidal, and F. Brunet (2016), Role of iron content on serpentinite dehydration depth in subduction zones: Experiments and thermodynamic modeling, Lithos, 264, 441-452.

Peterson, K. M., P. J. Heaney, and J. E. Post (2016), A kinetic analysis of the transformation from akaganeite to hematite: An in situ time-resolved X-ray diffraction study, Chemical Geology, 444, 27-36.

Rasmussen, B., J. R. Muhling, A. Suvorova, and B. Krapez (2016), Dust to dust: Evidence for the formation of "primary" hematite dust in banded iron formations via oxidation of iron silicate nanoparticles, Precambrian Research, 284, 49-63.

Zhou, Z. J., H. S. Tang, Y. J. Chen, and Z. L. Chen (2017), Trace elements of magnetite and iron isotopes of the Zankan iron deposit, westernmost Kunlun, China: A case study of seafloor hydrothermal iron deposits, Ore Geology Reviews, 80, 1191-1205.

Paleointensity and records of the geomagnetic field

Anwar, T., L. Hawkins, V. A. Kravchinsky, A. J. Biggin, and V. E. Pavlov (2016), Microwave paleointensities indicate a low paleomagnetic dipole moment at the Permo-Triassic boundary, Physics of the Earth and Planetary Interiors, 260, 62-73.

Calvo-Rathert, M., J. Morales-Contreras, A. Carrancho, and A. Goguitchaichvili (2016), A comparison of Thellier-type and multispecimen paleointensity determinations on Pleistocene and historical lava flows from Lanzarote (Canary Islands, Spain), Geochemistry Geophysics Geosystems, 17(9), 3638-3654.

Chen, J. S., X. M. Liu, V. A. Kravchinsky, B. Lu, and Q. Chen (2016), Post-depositional forcing of magnetic susceptibility variations at Kurtak section, Siberia, Quaternary International, 418, 2-9.

Doumbia, V., K. Boka, N. Kouassi, O. D. F. Grodji, C. Amory-Mazaudier, and M. Menvielle (2017), Induction effects of geomagnetic disturbances in the geo-electric field variations at low latitudes, Annales Geophysicae, 35(1), 39-51.

Onovughe, E. (2016), Can the comprehensive model phase 4 (CM4) predict the geomagnetic diurnal field for days away from quiet time?, Annales Geophysicae, 34(10), 887-900.

Paterson, G. A., D. Heslop, and Y. X. Pan (2016), The pseudo-Thellier palaeointensity method: new calibration and uncertainty estimates, Geophysical Journal International, 207(3), 1596-1608.

Simon, Q., N. Thouveny, D. L. Bourles, J. P. Valet, F. Bassinot, L. Menabreaz, V. Guillou, S. Choy, and L. Beaufort (2016), Authigenic Be-10/Be-9 ratio signatures of the cosmogenic nuclide production linked to geomagnetic dipole moment variation since the Brunhes/Matuyama boundary, Journal of Geophysical Research-Solid Earth, 121(11), 7716-7741.

Valet, J. P., and A. Fournier (2016), Deciphering records of geomagnetic reversals, Reviews of Geophysics, 54(2), 410-446.

Wicht, J., and D. G. Meduri (2016), A gaussian model for simulated geomagnetic field reversals, Physics of the Earth and Planetary Interiors, 259, 45-60.

Yamazaki, T., T. Shimono, and S. Inoue (2016), Paleomagnetic inclination variations during the last 200 kyr in the Okhotsk Sea and their relation to persistent non-axial-dipole field, Earth Planets and Space, 68.

Paleomagnetism

Anastasio, D., J. M. Pares, K. P. Kodama, J. Troy, and E. L. Pueyo (2016), Anisotropy of magnetic susceptibility (AMS) records synsedimentary deformation kinematics at Pico del Aguila anticline, Pyrenees, Spain, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 129-144.

Bazhenov, M. L., N. M. Levashova, and J. G. Meert (2016), How well do Precambrian paleomagnetic data agree with the Phanerozoic apparent polar wander path? A Baltica case study, Precambrian Research, 285, 80-90.

Bohnel, H., F. J. Pavon-Carrasco, K. Sieron, and A. N. Mahgoub (2016), Palaeomagnetic dating of two recent lava flows from Ceboruco volcano, western Mexico, Geophysical Journal International, 207(2), 1203-1215.

Bradak-Hayashi, B., T. Biro, E. Horvath, T. Vegh, and G. Csillag (2016), New aspects of the interpretation of the loess magnetic fabric, Cerna Valley succession, Hungary, Quaternary Research, 86(3), 348-358.

Cardello, G. L., B. S. G. Almqvist, A. M. Hirt, and N. S. Mancktelow (2016), Determining the timing of formation of the Rawil Depression in the Helvetic Alps by palaeomagnetic and structural methods, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 145-168.

Carrigan, J. H., D. J. Anastasio, K. P. Kodama, and J. M. Pares (2016), Fault-related fold kinematics recorded by terrestrial growth strata, Sant Llorenc de Morunys, Pyrenees Mountains, NE Spain, Journal of Structural Geology, 91, 161-176.

Cifelli, F., C. Caricchi, and M. Mattei (2016), Formation of arc-shaped orogenic belts in the Western and Central Mediterranean: a palaeomagnetic review, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 37-63.

Cinku, M. C., M. Hisarli, A. M. Hirt, F. Heller, T. Ustaomer, N. Kaya, E. Oksum, and N. Orbay (2016), Evidence of Late Cretaceous oroclinal bending in north-central Anatolia: palaeomagnetic results from Mesozoic and Cenozoic rocks along the I. zmir-Ankara-Erzincan Suture Zone, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 189-212.

D'Agrella-Filho, M. S., F. Bispo-Santos, R. I. F. Trindade, and P. Y. J. Antonio (2016), Paleomagnetism of the Amazonian Craton and its role in paleocontinents, Brazilian Journal of Geology, 46(2), 275-299.

Didenko, A. N., Y. F. Li, A. Y. Peskov, S. L. Sun, A. S. Karetnikov, and Y. H. Zhou (2016), Closure of the Solonker Basin: Paleomagnetism of the Linxi and Xingfuzhilu Formations (Inner Mongolia, China), Russian Journal of Pacific Geology, 10(5), 317-336.

Dossing, A., A. R. Muxworthy, R. Supakulopas, M. S. Riishuus, and C. Mac Niocaill (2016), High northern geomagnetic field behavior and new constraints on the Gilsa event: Paleomagnetic and Ar-40/Ar-39 results of similar to 0.5-3.1 Ma basalts from Jokuldalur, Iceland, Earth and Planetary Science Letters, 456, 98-111.

Eyster, A. E., R. R. Fu, J. V. Strauss, B. P. Weiss, C. F. Roots, G. P. Halverson, D. A. D. Evans, and F. A. Macdonald (2017), Paleomagnetic evidence for a large rotation of the Yukon block relative to Laurentia: Implications for a low-latitude Sturtian glaciation and the breakup of Rodinia, Geological Society of America Bulletin, 129(1-2), 38-58.

Ezquerro, L., M. Moretti, C. L. Liesa, A. Luzon, E. L. Pueyo, and J. L. Simon (2016), Controls on space-time distribution of soft-sediment deformation structures: Applying palaeomagnetic dating to approach the apparent recurrence period of paleoseisms at the Concud Fault (eastern Spain), Sedimentary Geology, 344, 91-111.

Fattaruso, L. A., M. L. Cooke, R. J. Dorsey, and B. A. Housen (2016), Response of deformation patterns to reorganization of the southern San Andreas fault system since ca. 1.5 Ma, Tectonophysics, 693, 474-488.

Fedorova, N. M., M. L. Bazhenov, J. G. Meert, and N. B. Kuznetsov (2016), Ediacaran-Cambrian paleogeography of Baltica: A paleomagnetic view from a diamond pit on the White Sea east coast, Lithosphere, 8(5), 564-573.

Finn, D. R., R. S. Coe, E. Brown, M. Branney, M. Reichow, T. Knott, M. Storey, and B. Bonnichsen (2016), Distinguishing and correlating deposits from large ignimbrite eruptions using paleomagnetism: The Cougar Point Tuffs (mid-Miocene), southern Snake River Plain, Idaho, USA, Journal of Geophysical Research-Solid Earth, 121(9), 6293-6314.

Fozing, E. M., T. Njanko, S. Naba, M. Kwekam, E. Njonfang, and P. Rochette (2016), Structural characterization of the Misaj, granitic pluton (NW Cameroon): constraints from magnetic and field observations, International Journal of Earth Sciences, 105(8), 2285-2309.

Galli, C. I., B. L. Coira, R. N. Alonso, M. P. I. Llanos, C. B. Prezzi, and S. M. Kay (2016), Tectonostratigraphic history of the Neogene Maimara basin, Northwest Argentina, Journal of South American Earth Sciences, 72, 137-158.

Garces, M., J. Garcia-Senz, J. A. Munoz, B. Lopez-Mir, and E. Beamud (2016), Timing of magnetization and vertical-axis rotations of the Cotiella massif (Late Cretaceous, South Central Pyrenees), in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 213-232.

Garcia-Quintana, A., A. Goguitchaichvili, J. Morales, M. Cervantes-Solano, S. Osorio-Ocampo, J. L. Macias, and J. Urrutia-Fucugauchi (2016), Magnetic dating of Holcene volcanic rocks: case of the lava flows around Patzcuaro Lake (Michoacan-Guanajuato volcanic field), Revista Mexicana De Ciencias Geologicas, 33(2), 209-220.

Grabowski, J., I. Lakova, S. Petrova, K. Stoykova, D. Ivanova, P. Wojcik-Tabol, K. Sobien, and P. Schnabl (2016), Paleomagnetism and integrated stratigraphy of the Upper Berriasian hemipelagic succession in the Barlya section Western Balkan, Bulgaria: Implications for lithogenic input and paleoredox variations, Palaeogeography Palaeoclimatology Palaeoecology, 461, 156-177.

Greve, A., G. M. Turner, C. E. Conway, D. B. Townsend, J. A. Gamble, and G. S. Leonard (2016), Palaeomagnetic refinement of the eruption ages of Holocene lava flows, and implications for the eruptive history of the Tongariro Volcanic Centre, New Zealand, Geophysical Journal International, 207(2), 702-718.

Heslop, D., and A. P. Roberts (2016), Analyzing paleomagnetic data: To anchor or not to anchor?, Journal of Geophysical Research-Solid Earth, 121(11), 7742-7753.

Japas, M. S., G. H. Re, S. Oriolo, and J. F. Vilas (2016), Palaeomagnetic data from the Precordillera fold and thrust belt constraining Neogene foreland evolution of the Pampean flat-slab segment (Central Andes, Argentina), in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 81-105.

Jokat, W., P. Lehmann, D. Damaske, and J. B. Nelson (2016), Magnetic signature of North-East Greenland, the Morris Jesup Rise, the Yermak Plateau, the central Fram Strait: Constraints for the rift/drift history between Greenland and Svalbard since the Eocene, Tectonophysics, 691, 98-109.

Kidane, T. (2016), Strong clockwise block rotation of the Ali-Sabieh/Aisha Block: evidence for opening of the Afar Depression by a 'saloon-door' mechanism, in Magmatic Rifting and Active Volcanism, edited by T. J. Wright, A. Ayele, D. J. Ferguson, T. Kidane and C. VyeBrown, pp. 209-219.

Kiss, D., E. Marton, and A. K. Tokarski (2016), An integrated paleomagnetic and magnetic anisotropy study of the Oligocene flysch from the Dukla nappe, Outer Western Carpathians, Poland, Geologica Carpathica, 67(6), 595-605.

Klein, R., L. J. Pesonen, I. Manttari, and J. S. Heinonen (2016), A late Paleoproterozoic key pole for the Fennoscandian Shield: A paleomagnetic study of the Keuruu diabase dykes, Central Finland, Precambrian Research, 286, 379-397.

Klootwijk, C. (2016), Paleomagnetism of the Carboniferous Rouchel Block, Tamworth Belt, and pole path revision for the New England Orogen, eastern Australia, Australian Journal of Earth Sciences, 63(5), 513-549.

Marton, E., J. Grabowski, A. K. Tokarski, and I. Tunyi (2016), Palaeomagnetic results from the fold and thrust belt of the Western Carpathians: an overview, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 7-36.

Mattei, M. (2016), Palaeomagnetism in Fold and Thrust Belts: New Perspectives Foreword, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia.

Moore, D. H., P. G. Betts, and M. Hall (2016), Constraining the VanDieland microcontinent at the edge of East Gondwana, Australia, Tectonophysics, 687, 158-179.

Mullender, T. A. T., T. Frederichs, C. Hilgenfeldt, L. V. de Groot, K. Fabian, and M. J. Dekkers (2016), Automated paleomagnetic and rock magnetic data acquisition with an in-line horizontal "2G" system, Geochemistry Geophysics Geosystems, 17(9), 3546-3559.

Neres, M., P. F. Silva, M. Ikenne, S. Martins, A. Hafid, J. Mata, F. Almeida, N. Youbi, and M. A. Boumehdi (2016), Evidences for multiple remagnetization of Proterozoic dykes from Iguerda inlier (Anti-Atlas Belt, Southern Morocco), Studia Geophysica Et Geodaetica, 60(4), 700-730.Ri

Palamakumbura, R. N., A. H. F. Robertson, T. C. Kinnaird, P. van Calsteren, D. Kroon, and J. A. Tait (2016), Quantitative dating of Pleistocene deposits of the Kyrenia Range, northern Cyprus: implications for timing, rates of uplift and driving mechanisms, Journal of the Geological Society, 173(6), 933-948.

Pedersen, L. B., and M. Bastani (2016), Estimating rock-vector magnetization from coincident measurements of magnetic field and gravity gradient tensor, Geophysics, 81(3), B55-B64.

Plado, J., U. Preeden, A. Joeleht, L. J. Pesonen, and S. Mertanen (2016), Palaeomagnetism of Middle Ordovician Carbonate Sequence, Vaivara Sinimaed Area, Northeast Estonia, Baltica, Acta Geophysica, 64(5), 1391-1411.

Pueyo, E. L., F. Cifelli, A. J. Sussman, and B. Oliva-Urcia (2016), Introduction: Palaeomagnetism in fold and thrust belts: new perspectives, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 1-6.

Pueyo, E. L., A. J. Sussman, B. Oliva-Urcia, and F. Cifelli (2016), Palaeomagnetism in fold and thrust belts: use with caution, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 259-276.

Qin, H. F., Y. X. Pan, H. Y. He, L. K. Yang, and R. X. Zhu (2016), Paleomagnetism of Early Cretaceous volcanic rocks at Huangya section in Jiaodong Peninsula and implications for tectonics, Acta Petrologica Sinica, 32(10), 3205-3213.

Ramon, M. J., E. L. Pueyo, G. Caumon, and J. L. Briz (2016), Parametric unfolding of flexural folds using palaeomagnetic vectors, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 247-258.

Rapalini, A. E., J. Peroni, T. Luppo, A. Tassone, M. E. Cerredo, F. Esteban, H. Lippai, and J. Franciscovilas (2016), Palaeomagnetism of Mesozoic magmatic bodies of the Fuegian Cordillera: implications for the formation of the Patagonian Orocline, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 65-80.

Salminen, J. M., D. A. D. Evans, R. I. F. Trindade, E. P. Oliveira, E. J. Piispa, and A. V. Smirnov (2016), Paleogeography of the Congo/Sao Francisco craton at 1.5 Ga: Expanding the core of Nuna supercontinent, Precambrian Research, 286, 195-212.

Sato, T., N. Nakamura, H. Nagahama, and K. Minoura (2016), Stretched exponential relaxation of viscous remanence and magnetic dating of erratic boulders, Journal of Geophysical Research-Solid Earth, 121(11), 7707-7715.

Schettino, A., C. Macchiavelli, P. P. Pierantoni, D. Zanoni, and N. Rasul (2016), Recent kinematics of the tectonic plates surrounding the Red Sea and Gulf of Aden, Geophysical Journal International, 207(1), 457-480.

Shang, L. M., X. H. Zhang, R. L. Du, Y. G. Jia, Z. X. Tian, B. Han, and C. S. Yang (2016), New magnetic data of the southern East China Sea and some geological interpretations, Studia Geophysica Et Geodaetica, 60(4), 679-699.

Symons, D. T. A., K. Kawasaki, F. Tornos, F. Velasco, and I. Rosales (2017), Temporal constraints on genesis of the Caravia-Berbes fluorite deposits of Asturias, Spain, from paleomagnetism, Ore Geology Reviews, 80, 754-766.

Valcarcel, M., R. Soto, E. Beamud, B. Oliva-Urcia, J. A. Munoz, and C. Biete (2016), Integration of palaeomagnetic data, basement-cover relationships and theoretical calculations to characterize the obliquity of the Altomira-Loranca structures (central Spain), in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 169-188.

Villalain, J. J., A. M. Casas-Sainz, and R. Soto (2016), Reconstruction of inverted sedimentary basins from syn-tectonic remagnetizations. A methodological proposal, in Palaeomagnetism in Fold and Thrust Belts: New Perspectives, edited by E. L. Pueyo, F. Cifelli, A. J. Sussman and B. OlivaUrcia, pp. 233-246.

Stratigraphy

Llanos, M. P. I., D. A. Kietzmann, M. K. Martinez, and R. M. Palma (2017), Magnetostratigraphy of the Upper Jurassic-Lower Cretaceous from Argentina: Implications for the J-K boundary in the Neuquen Basin, Cretaceous Research, 70, 189-208.

Menshov, O., R. Kuderavets, S. Vyzhva, V. Maksymchuk, I. Chobotok, and T. Pastushenko (2016), Magnetic studies at Starunia paleontological and hydrocarbon bearing site (Carpathians, Ukraine), Studia Geophysica Et Geodaetica, 60(4), 731-746.

Pueyo, E. L., A. Munoz, C. Laplana, and J. M. Pares (2016), The Last Appearance Datum of Hipparion in Western Europe: magnetostratigraphy along the Pliocene-Pleistocene boundary in the Villarroya Basin (Northern Spain), International Journal of Earth Sciences, 105(8), 2203-2220.

Puspoki, Z., et al. (2016), Magnetic susceptibility as a possible correlation tool in Quaternary alluvial stratigraphy, Boreas, 45(4), 861-875.

Rodionov, V. P. (2016), Magnetostratigraphy of the Middle-Upper Cambrian Verkhnyaya Lena Group and Lower Ordovician Ust-Kut formation in the southern Siberian Platform, Stratigraphy and Geological Correlation, 24(5), 464-485.

Turner, D. G., B. C. Ward, D. G. Froese, M. Lamothe, J. D. Bond, and N. H. Bigelow (2016), Stratigraphy of Pleistocene glaciations in the St Elias Mountains, southwest Yukon, Canada, Boreas, 45(3), 521-536.

Vazquez, G., B. Solis, E. Solleiro-Rebolledo, A. Goguitchaichvili, and J. J. Morales (2016), Mineral magnetic properties of an alluvial paleosol sequence in the Maya Lowlands: Late Pleistocene-Holocene paleoclimatic implications, Quaternary International, 418, 10-21.

Wang, Z. F., et al. (2016), Preliminary results of rock magnetism and magnetostratigraphy for Late Miocene to Pliocene biogenetic reefs in the Xisha Islands, South China Sea, Chinese Journal of Geophysics-Chinese Edition, 59(11), 4178-4187.

Other

Strehlau, J. H., B. M. Toner, W. A. Arnold, and R. L. Penn (2017), Accessible reactive surface area and abiotic redox reactivity of iron oxyhydroxides in acidic brines, Geochimica Et Cosmochimica Acta, 197, 345-355.

Zhang, L., et al. (2017), Magnetic susceptibility of WFSD-2 borehole cores from the Longmenshan thrust belt and its implications for great seismic activity, Chinese Journal of Geophysics-Chinese Edition, 60(1), 225-239.

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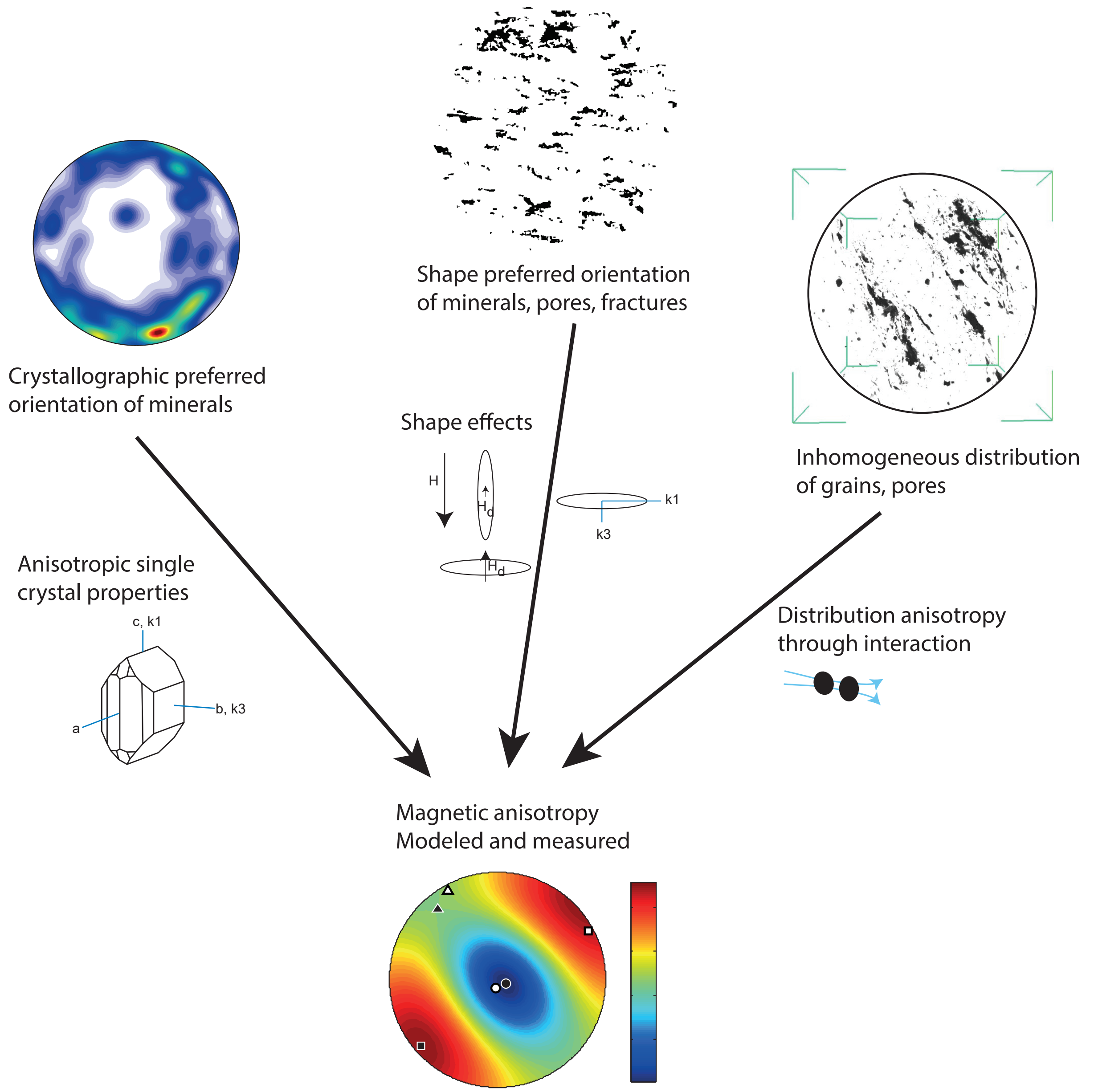

Fig. 1. Conceptual sketch of petrofabric properties influencing magnetic anisotropy in rocks. Please refer to online version for color.

relate to the more complicated rock texture.

Because the magnetic anisotropy ellipsoid is a simplified representation of the rock texture, challenges arise when interpreting the resulting fabrics, as in the case of inverse or complex fabrics. However, with a better understanding of factors controlling magnetic anisotropy, and improved experimental techniques that allow for isolating contributions of specific mineral groups, magnetic fabrics are now an even more reliable proxy for rock texture. Magnetic anisotropy is a direct consequence of (1) magnetocrystalline anisotropy in combination with CPO, (2) shape anisotropy together with SPO, and (3) distribution anisotropy and non-uniform spatial distribution of grains (Figure 1; Cañon-Tapia, 1996; Grégoire et al., 1995; Hargraves et al., 1991; Mainprice et al., 1994). Thus it is essential to understand (1) which mineral carries the anisotropy, (2) whether it possesses a magnetocrystalline, shape or distribution anisotropy, and (3) how the CPO, SPO and spatial distribution relate to geodynamic processes, before any interpretation of magnetic fabric data. Minerals carrying the magnetic anisotropy can be identified by (1) experimental separation techniques, e.g. measurements in various temperatures and fields, and anisotropy of ARMs and IRMs, to isolate the anisotropy carried by the paramagnetic and different types and grainsizes of ferromagnetic minerals (e.g. Martín-Hernández and Ferré, 2007; and references therein), and (2) comparison between the orientation and degree of the AMS ellipsoid to the properties of either CPO or SPO of a specific mineral. The latter is especially suited for samples whose magnetic fabric is dominated by one mineral. For example, AMS in phyllosilicate-bearing rocks has been found to directly reflect the CPO of the phyllosilicates (Chadima et al., 2004; Hirt et al., 1995; Lüneburg et al., 1999; Richter et al., 1993; Siegesmund et al., 1995). Ferré et al. (2005) investigated fabrics in a dunite and compared high-field AMS to olivine CPO. Other studies show AMS correlating with the SPO of magnetite grains (Archanjo et al., 1995, 2002; Grégoire 1995, 1998; Launeau and Cruden, 1998). If several minerals contribute to the magnetic fabric, detailed and systematic characterization of single crystal susceptibility tensors as well as physical models for magnetocrystalline, shape and distribution anisotropy are necessary for a reliable interpretation.

Modeling magnetic anisotropy and the contribution of individual minerals

A relatively new approach was adapted from a method used to compute seismic anisotropy, and focuses on modeling contributions of individual rock-forming minerals to the magnetocrystalline anisotropy (Mainprice and Humbert, 1994). These models are based on CPO data and single crystal susceptibility tensors, and can be used to predict (1) the contribution of specific minerals to the whole-rock anisotropy, or (2) the sum of contributions for a group of minerals or all minerals in the rock that possess magnetocrystalline anisotropy. The simulated components of anisotropy can then be compared to the measured AMS, or any experimentally isolated component of the AMS measured on the same rock. In any case, well-defined susceptibility tensors of single crystals for each mineral in the rock are necessary for reliable models. Whereas the first studies on single crystal magnetic anisotropy were published over a century ago (e.g. Faraday, 1846; Finke, 1909; Tyndall, 1851), recent works have systematically characterized magnetocrystalline anisotropy as a function of chemical composition for many common rock-forming minerals from both the carbonate and silicate groups (e.g. Biedermann et al., 2014a, 2015a; Schmidt et al., 2006, 2007). Schmidt et al. (2009) compared the paramagnetic and diamagnetic components of the AMS in synthetic quartz-muscovite aggregates to those modeled based on muscovite and quartz CPO, respectively. Biedermann et al. (2015b) modelled the paramagnetic component of AMS in amphibolites, peridotite and pyroxenite, nicely matching the isolated paramagnetic component of AMS (Figure 2). Additionally, modeling allows to investigate the interplay between fabrics of different paramagnetic minerals which cannot yet be separated experimentally. Furthermore, using synthetic fabrics, it is possible to simulate under which circumstances the anisotropies of two minerals interfere positively, creating a stronger whole-rock magnetic fabric, or negatively, leading to an overall weaker fabric (Figure 3). Such modeling is clearly beneficial when interpreting complex fabrics.

Summary

Experimental separation techniques and understanding which minerals carry the anisotropy have significantly increased the reliability of the interpretation of magnetic fabrics. Together with new single crystal data, modelling of the anisotropy contribution carried by different minerals in a rock allows to take magnetic fabric interpretation one step further, particularly in the case of complex fabrics. A more detailed understanding of the interplay of different minerals to form the whole-rock magnetic anisotropy will provide a deeper insight into different AMS components, and eventually lead to improved interpretation of magnetic fabrics in rocks.

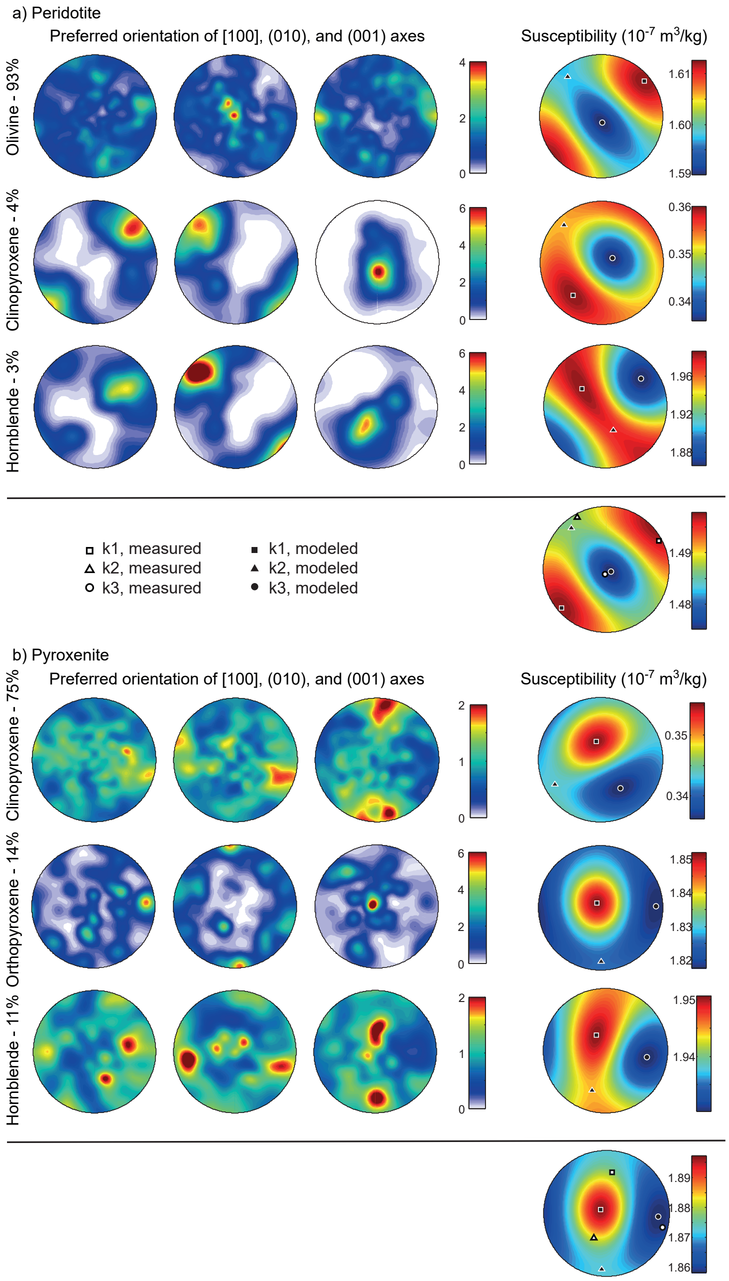

Fig. 2.(a) Peridotite with negative interference between olivine and hornblende AMS, and (b) pyroxenite with positive interference between orthopyroxene and hornblende AMS. Modified after Biedermann et al., 2015b.

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References

Archanjo, C.J., Araujo, M.G.S., Launeau, P., 2002. Fabric of the Rio Ceara-Mirim mafic dike swarm (northeastern Brazil) determined by anisotropy of magnetic susceptibility and image analysis. Journal of Geophysical Research, 107, EPM1-1-1-13.

Archanjo, C.J., Launeau, P., Bouchez, J.L., 1995. Magnetic fabric vs. magnetite and biotite shape fabrics of the mag-

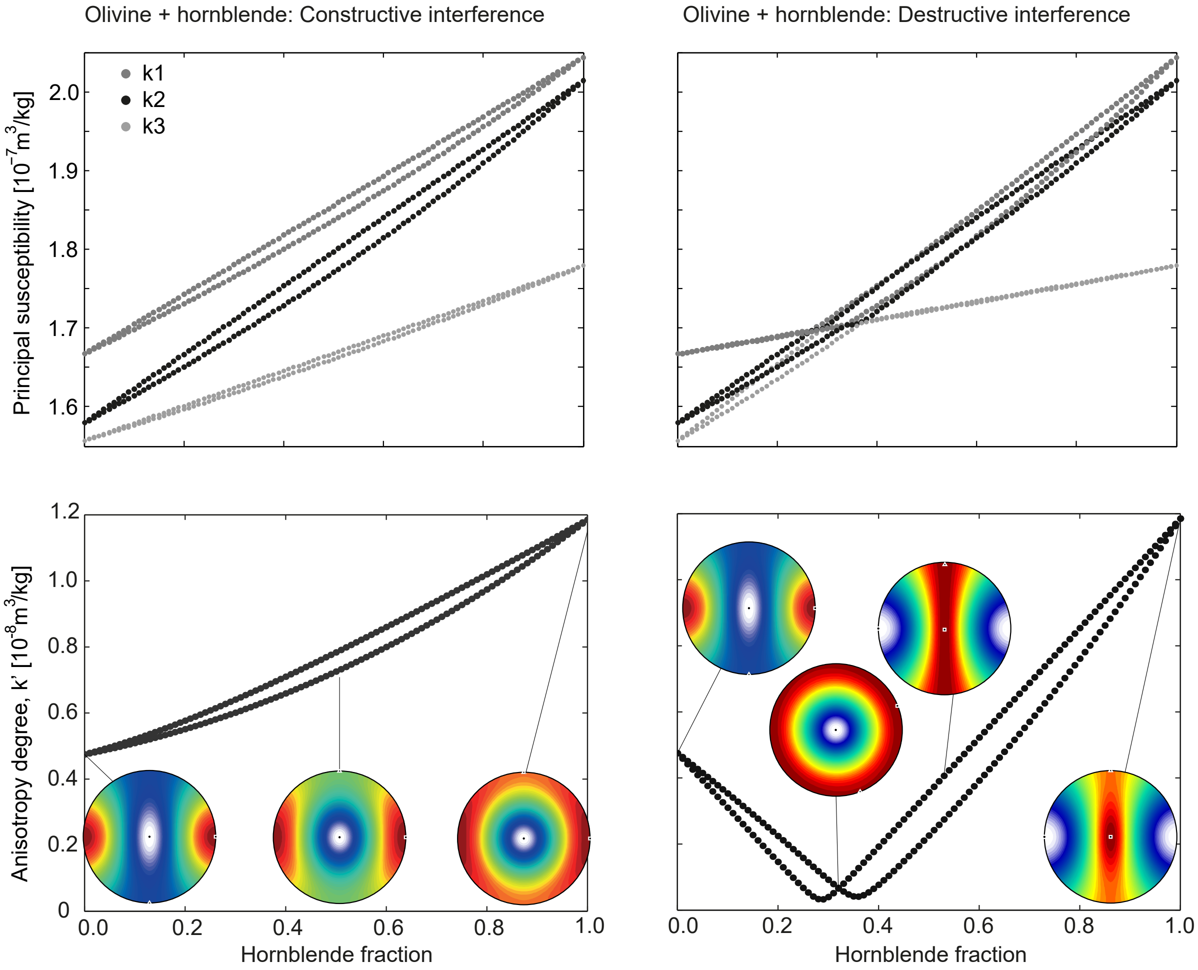


Fig. 3. Synthetic example for positive and negative interference between olivine and hornblende AMS. Modified after a conference presentation by Biedermann et al. (2014b): Upper and lower dotted lines show Voigt and Reuss averages, respectively, for the modelled principal axes and anisotropy degree (Reuss, 1929; Voigt, 1928).

netite-bearing granite pluton of Gameleiras (Northeast Brazil). Physics of the Earth and Planetary Interiors, 89, 63-75.

Balsley, J.R., Buddington, A.F., 1960. Magnetic susceptibility anisotropy and fabric of some Adirondack granites and orthogneisses. American Journal of Science 258-A, 6-20.

Biedermann, A.R., Kunze, K., Zappone, A.S., Hirt, A.M., 2015b. Origin of magnetic fabric in ultramafic rocks. IOP Conference Series: Materials Science and Engineering, 82(1).

Biedermann, A.R., Kunze, K., Zappone, A.S., Hirt, A.M., 2014b. Origin of magnetic fabrics in ultrabasic rocks. ICOTOM 2014, Dresden, Germany.

Biedermann, A.R., Pettke, T., Bender Koch, C., Hirt, A.M., 2015a. Magnetic anisotropy in clinopyroxene and orthopyroxene single crystals. Journal of Geophysical Research - Solid Earth, 120, 1431-1451.

Biedermann, A.R., Pettke, T., Reusser, E., Hirt, A.M., 2014a. Anisotropy of magnetic susceptibility in natural olivine single crystals. Geochemistry, Geophysics, Geosystems, GC005386.

Borradaile, G.J., Henry, B., 1997. Tectonic applications of magnetic susceptibility and its anisotropy. Earth-Science Reviews 42, 49-93.

Borradaile, G.J., Jackson, M., 2010. Structural geology, petrofabrics and magnetic fabrics (AMS, AARM, AIRM). Journal of Structural Geology 32, 1519-1551.

Cañón-Tapia, E., 1996. Single-grain versus distribution anisotropy: a simple three-dimensional model. Physics of the Earth and Planetary Interiors 94, 149-158.

Chadima, M., Hansen, A., Hirt, A.M., Hrouda, F., Siemens, H., 2004. Phyllosilicate preferred orientation as a control of magnetic fabric: Evidence from neutron texture goniometry and low and high-field magnetic anisotropy (SE Rhenohercynian Zone of Bohemian Massif), in: Martín-Hernández, F., Lüneburg, C.M., Aubourg, C., Jackson, M. (Eds.), Magnetic Fabric: Methods and Applications. The Geological Society, London UK, pp. 361-380.

Cogné, J.P., Perroud, H., 1988. Anisotropy of magnetic susceptibility as a strain gauge in the Flamanville granite, NW France. Physics of the Earth and Planetary Interiors 51, 264-270.

Engler, O., Randle, V., 2009. Introduction to Texture Analysis: Macrotexture, Microtexture, and Orientation Mapping. CRC Press, Boca Raton, US.

Faraday, M., 1846a. Experimental researches in electricity. Twentieth series. Philosophical Transactions of the Royal Society London 136, 21-40.

Ferré, E.C., Tikoff, B., Jackson, M., 2005. The magnetic anisotropy of mantle peridotites: Example from the Twin Sisters dunite, Washington. Tectonophysics 398, 141-166.

Finke, W., 1909. Magnetische Messungen an Platinmetallen und monoklinen Kristallen, insbesondere der Eisen-, Kobalt- und Nickelsalze. Annalen der Physik 336, 149-168.

Gialanella, P.R., Heller, F., Incoronato, A., 1994. Rock magnetism of deformed upper Triassic limestones from the Lagonegro Basin (southern Apennines, Italy). Geophysical Research Letters 21, 2665-2668.

Graham, J.W., 1954. Magnetic susceptibility anisotropy, an unexploited petrofabric element. Geological Society of America Bulletin 65, 1257-1258.

Grégoire, V., Darrozes, P., Gaillot, P., Nédélec, A., 1998. Magnetite grain shape fabric and distribution anisotropy vs rock magnetic fabric: a three-dimensional case study. Journal of Structural Geology, 20, 937-944.

Grégoire, V., De Saint-Blanquat, M., Nédélec, A., Bouchez, J.-L., 1995. Shape anisotropy versus magnetic interactions of magnetite grains: experiments and application to AMS in granitic rocks. Geophysical Research Letters, 22, 2765-2768.

Hargraves, R.B., Johnson, D., Chan, C.Y., 1991. Distribution anisotropy: the cause of AMS in igneous rocks? Geophysical Research Letters 18, 2193-2196.

Heilbronner, R., Barrett, S., 2014. Image Analysis in Earth Sciences: Microstructures and Textures of Earth Materials. Springer, Heidelberg, Germany, 520pp.

Hirt, A.M., Evans, K.F., Engelder, T., 1995. Correlation between magnetic anisotropy and fabric for Devonian shales on the Appalachian Plateau. Tectonophysics 247, 121-132.

Housen, B.A., van der Pluijm, B.A., 1990. Chlorite control of correlations between strain and anisotropy of magnetic susceptibility. Physics of the Earth and Planetary Interiors 61, 315-323.

Housen, B.A., Richter, C., van der Pluijm, B.A., 1993. Composite magnetic anisotropy fabrics: experiments, numerical models, and implications for the quantification of rock fabrics. Tectonophysics, 220, 1-12.

Hrouda, F., 1982. Magnetic anisotropy of rocks and its application in geology and geophysics. Geophysical Surveys 5, 37-82.

Hrouda, F., and Jezek, J., 2017. Role of single-domain magnetic particles in creation of inverse magnetic fabrics in volcanic rocks: A mathematical model study, Studia Geophysica Et Geodaetica, 61, 1, 145-161.

Kligfield, R., Lowrie, W., Dalziel, W.D., 1977. Magnetic susceptibility anisotropy as a strain indicator in the Sudbury Basin, Ontario. Tectonophysics 40, 287-308.

Kligfield, R., Owens, W.H., Lowrie, W., 1981. Magnetic susceptibility anisotropy, strain, and progressive deformation in Permian sediments from the Maritime Alps (France). Earth and Planetary Science Letters 55, 181-189.

Kneen, S.J., 1976. The relationship between the magnetic and strain fabrics of some haematite-bearing slates. Earth and Planetary Science Letters 31, 413-416.

König, W., 1887. Magnetische Untersuchungen an Krystallen. Annalen der Physik 267, 273-302.

Launeau, P., Cruden, A.R., 1998. Magmatic fabric acquisition mechanisms in a syenite: Results of a combined anisotropy of magnetic susceptibility and image analysis study. Journal of Geophysical Research: Solid Earth, 103, 5067-5089.

Lüneburg, C.M., Lampert, S.A., Lebit, H.D., Hirt, A.M., Casey, M., Lowrie, W., 1999. Magnetic anisotropy, rock fabrics and finite strain in deformed sediments of SW Sardinia (Italy). Tectonophysics 307, 51-74.

Mainprice, D. and Humbert, M., 1994. Methods of calculating petrophysical properties from lattice preferred orientation data. Surveys in Geophysics, 15, 575-592.

Martín-Hernández, F., Ferré, E.C., 2007. Separation of paramagnetic and ferrimagnetic anisotropies: A review. Journal of Geophysical Research-Solid Earth 112.

Martín-Hernández, F., Lüneburg, C.M., Aubourg, C., Jackson, M., 2004. Magnetic Fabrics: Methods and Applications. The Geological Society, London, UK.

Owens, W.H., Bamford, D., 1976. Magnetic, seismic, and other anisotropic properties of rock fabrics. Philosophical Transactions of the Royal Society A 283, 55-68.

Pares, J., van der Pluijm, B.A., 2004. Correlating magnetic fabrics with finite strain: Comparing results from mudrocks in the Variscan and Appalachian Orogens. Geologica Acta 2, 2004, 213-220.

Prior, D.J., Boyle, A.P., Brenker, F., Cheadle, M.C., Day, A., Lopez, G., Peruzzo, L., Potts, G.J., Reddy, S., Spiess, R., Timms, N.E., Trimby, P., Wheeler, J., Zetterström, L., 1999. The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. American Mineralogist 84, 1741-1759.

Reuss, A., 1929. Berechnung der Fliessgrenze von Mischkristallen auf Grund der Plastizitätsbedingung für Einkristalle. Zeitschrift für angewandte Physik 9, 49-58.

Richter, C., Ratschbacher, L., Frisch, W., 1993. Magnetic fabrics, crystallographic preferred orientation, and strain of progressively metamorphosed pelites in the Helvetic Zone of the Central Alps (Quartenschiefer Formation). Journal of Geophysical Research – Solid Earth 98, 9557–9570.

Rochette, P., Aubourg, C., Perrin, M., 1999. Is this magnetic fabric normal? A review and case studies in volcanic formations. Tectonophysics 307, 219-234.

Schmidt, V., Günther, D., Hirt, A.M., 2006. Magnetic anisotropy of calcite at room-temperature. Tectonophysics 418, 63-73.

Schmidt, V., Hirt, A.M., Hametner, K., Gunther, D., 2007. Magnetic anisotropy of carbonate minerals at room temperature and 77 K. American Mineralogist 92, 1673-1684.

Schmidt, V., Hirt, A.M., Leiss, B., Burlini, L., Walter, J.M., 2009. Quantitative correlation of texture and magnetic anisotropy of compacted calcite–muscovite aggregates. Journal of Structural Geology 31, 1062-1073.

Siegesmund, S., Ullemeyer, K., Dahms, M., 1995. Control of magnetic rock fabrics by mica preferred orientation - a quantitative approach. Journal of Structural Geology 17, 1601-1613.

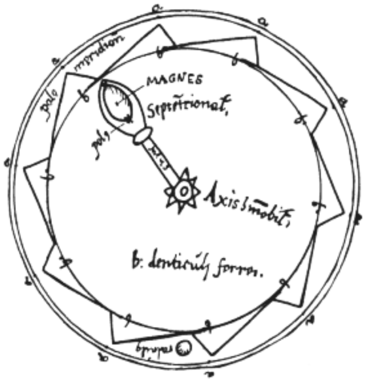
Tarling, D.H., Hrouda, F., 1993. The magnetic anisotropy of rocks. Chapman and Hall, London, UK.

Tyndall, J., 1851. Ueber Diamagnetismus und magnekrystallinische Wirkung. Annalen der Physik 159, 384-416.

Ullemeyer, K., Braun, G., Dahms, M., Kruhl, J.H., Olesen, N.Ø., Siegesmund, S., 2000. Texture analysis of a muscovite-bearing quartzite: A comparison of some currently used techniques. Journal of Structural Geology, 22, 1541-1557.

Voigt, W., 1928. Lehrbuch der Kristallographie. Teubner-Verlag, Leipzig, Germany.

Weil, A.B., Yonkee, A., 2009. Anisotropy of magnetic susceptibility in weakly deformed red beds from the Wyoming salient, Sevier thrust belt: Relations to layer-parallel shortening and orogenic curvature. Lithosphere 1, 235-256.



University of Minnesota
291 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5274
fax: (612) 625-7502
e-mail: irm@umn.edu
www.irm.umn.edu

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Dario Bilardello
Institute for Rock Magnetism
University of Minnesota
291 Shepherd Laboratories
100 Union Street S. E.
Minneapolis, MN 55455-0128
phone: (612) 624-5274
fax: (612) 625-7502
e-mail: dario@umn.edu
www.irm.umn.edu

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