CHARACTERIZATION OF MAGNETIC CARRIERS IN A SPELEOTHEM FROM MOROCCO

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ABSTRACT

Recent studies have reported the great potential of speleothems as a paleomagnetic archive. The remanence acquisition is almost instantaneous, unaffected by post-depositional effects, and can be combined with high accuracy radiometric dating. Despite their great efficiency to record the geomagnetic field, more efforts are needed to detail the origin of the natural remanent magnetization (NRM). In order to better understand it, a stalagmite (WIN1) from Wintimdouine cave in the Agadir region (Morocco) was submitted to paleomagnetic analyses. Our results indicate a strong correlation between detrital input and magnetic signal strength, where two main magnetic carriers are present: magnetite and hematite. Their orientation, determined by detailed thermal and alternating field demagnetization, present the same magnetic orientation. The average inclination observed for magnetite is 37.0° with A_{95} equal to 2.8°, whereas for hematite the inclination has a value of 34.9° and 5.5° for A_{95}, expressing the consistency of the magnetic record of this stalagmite within both treatments.

Keywords: Speleothem, Rock Magnetism, Paleomagnetism

RESUMEN

Estudios recientes han revelado el gran potencial de los espeleotemas como archivo paleomagnético. La adquisición de remanencia es casi instantánea, no se ve afectada por efectos posteriores a a su deposito y se puede combinar con datación radiométrica de alta precisión. A pesar de su gran eficiencia para registrar el campo geomagnético, se necesitan más esfuerzos para detallar el origen de la magnetización remanente natural (NRM). Para entenderlo mejor, una estalagmita (WIN1) de la cueva Wintimdouine en la región de Agadir (Marruecos) fue sometida a análisis paleomagnéticos. Nuestros resultados indican una fuerte correlación entre los inputs detríticos y la intensidad de la señal magnética, donde están presentes dos portadores magnéticos principales: magnetita y hematita. Su orientación, determinada por desmagnetización térmica y por campo alterno, presenta la misma orientación magnética. La inclinación promedio observada para magnetita es 37.0° con A95 igual a 2.8°, mientras que para hematita la inclinación tiene un valor de 34.9° y 5.5° para A95, expresando la consistencia del registro magnético de esta estalagmita en ambos métodos.

Keywords: Espelotemas, Magnetismo de Roca, Paleomangetismo

1. Introduction

Speleothems have some relevant advantages when compared to other "traditional" archives in paleomagnetism, their continuous growth; accurate U-Th dating and nearly instantaneous magnetization lock-in time (of severals 100 s) (Perkins, Maher, 1993; Lascu, Feinberg, 2011; Dreybodt, Scholz, 2011). Recent studies have shown that magnetic minerals present in stalagmites, despite their low magnetic intensity, can be used to successfully understand some important features of the geomagnetic field (*e.g.* paleosecular variation, geomagnetic excursions, magnetic anomalies – Osete *et al.*, 2012; Lascu *et al.*, 2016; Chou *et al.*, 2018;

Trindade *et al.*, 2018; Zanella *et al.*, 2018). Even with a growing number of publications in speleothem magnetism, the mechanisms responsible for the remanence acquisition in speleothems is poorly understood (Ponte *et al*., 2017).

Speleothems can accumulate detrital material originated by dripping or running water during flood events (Lascu, Feinberg, 2011), and also transported by air currents if caves morphology and airflow patterns allow (White, 1988). In these two cases, the detrital material (usually containing magnetic minerals) is deposited on the surface of the speleothems and immediately encapsulated by the precipitation of new layers of calcite. In addition to detrital particles, there is evidence of *in situ* precipitation of iron oxyhydroxides from dripwater solution (Strauss *et al*., 2013). Therefore, the natural remanence acquisition in speleothems occurs by a combination of two mechanisms: chemical precipitation of magnetic minerals (*e.g.* fine grains of goethite) and deposition of particles on the surface of speleothems (*e.g.* magnetite and hematite).

Here, we evaluate the reliability of different magnetic carriers as geomagntic field recorders in a stalagmite from Morocco, which was submitted to routines used in paleomagnetic studies. The knowledge about the magnetic carriers behavior in this speleothem is important to conduct future investigations and thus improve the database for Northern Africa.

2. Materials and methods

The WIN1 stalagmite was collected at Wintimdouine cave (30°40'48'' N, 09°20'24'' W), located at the Western High Atlas Mountains in southwestern Morocco. This stalagmite presents intervals with a high content of detrital material observed as dark layers with more concentrations of clay minerals, oxides, and hydroxides (Jaqueto *et al*., 2016). WIN1 sample has 200 mm long and presents large intervals with detrital content (Figure 1).

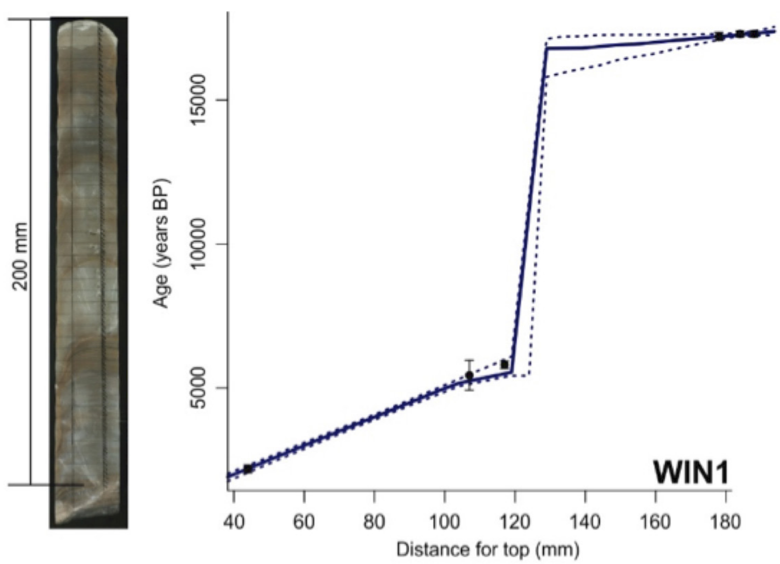

Figure 1 – WIN1 sample from Wintimdouine karts system (Morocco) and chronological models based on StalAge algorithm. Dashed lines represent 95% confidence intervals

The U-Th analyses for radiometric dating were carried out at the Isotope Laboratory in the University of Minnesota (USA) and at the Institute of Global Environmental Change of Xi'an Jiaotong University (China), using a multi-collector inductive plasma mass spectrometer (ICP-MS) (Cheng *et al*., 2013). The age models and corresponding 95% confidence limits were determined with the StalAge algorithm (Scholz, Hoffmann, 2011). The final age-model of WIN1 sample is based on 6 U-Th dating points (Figure 1), whereas other samples from the same cave ("WIN2" and "WIN3") are based on 33 and 21 ages, respectively. WIN1 sample has few U-Th ages due to its higher detrital content (^{232}Th).

The WIN1 stalagmite was collected without azimuth orientation, the specimens were prepared with a thin saw blade (0.4 mm) to avoid loss of material and have an average height (z-axis) of 5 mm. Magnetic remanent measurements were performed at the Laboratório de Paleomagnetismo of Universidade de São Paulo (USPmag), using a SQUID magnetometer with coupled alternating field (AF) in a RAPID system – 2G Enterprises. A total of 40 specimens were submitted to stepwise alternating field (AF) demagnetization along 47 steps up to 100 mT. After AF treatment, 20 specimens (intercalated samples) were submitted to a detailed thermal demagnetization protocol consisting of 33 steps up to 700 °C, designed to unravel the high coercivity magnetic minerals content. Directions were calculated based on principal component analysis (Kirschvink, 1980) using the *Remasoft 3.0* software (AGICO Ltd.).

3. Results

The magnetic moment of natural remanent magnetization (NRM) vary up to 2 orders of magnitude (from 5.4 x10^{-10} to 1.6 x10^{-8} Am²). Higher magnetic moment values are found at intervals with more detrital material (dirty layers), while lower values are associated with intervals of clean calcite (Figure 2). The magnetic vector during the AF treatment (blue dots - Fig. 2) is stable and better defined in the range between 30 and 90 mT. Intensity decrease of up 30 mT (low coercivity minerals contribution - magnetite) and preservation of the magnetic signal in ~50%, which indicates the presence of high coercivity minerals (*e.g.* hematite or goethite).

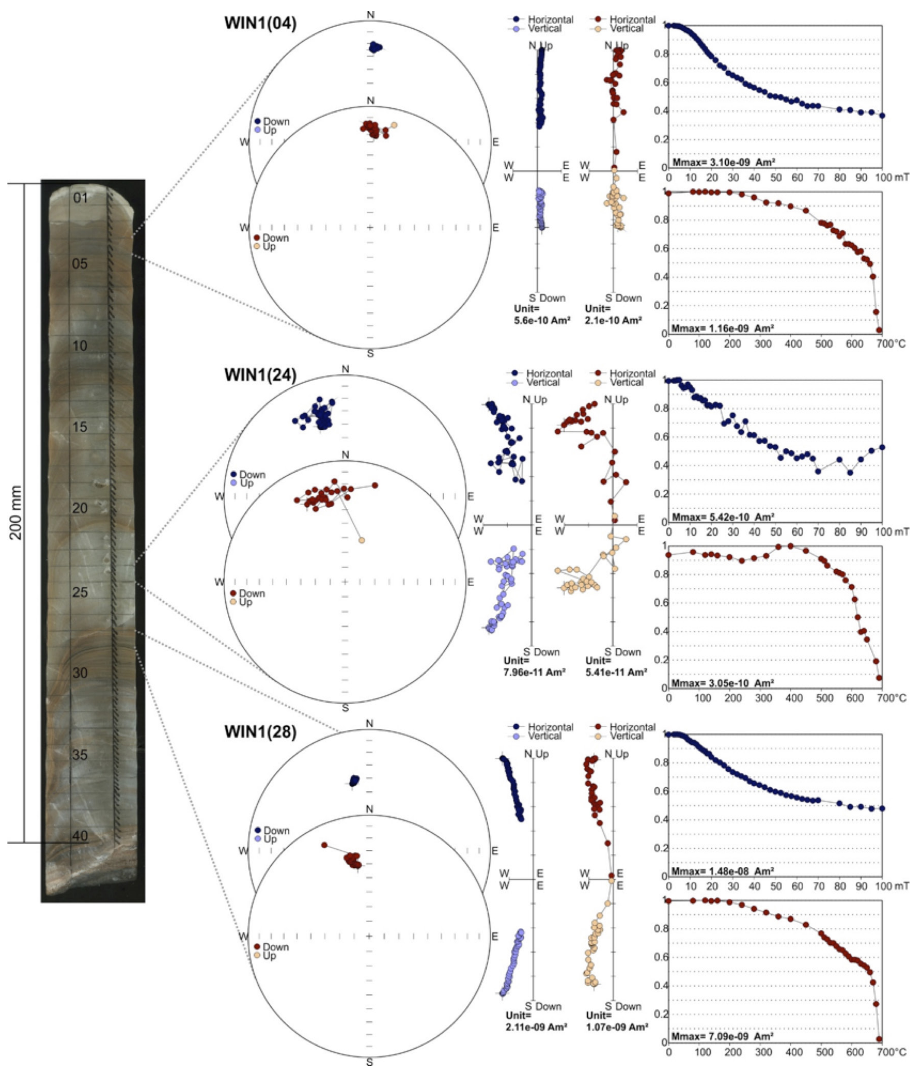

Figure 2 – WIN1 sample and paleomagnetic data of WIN1(4), WIN1(24) and WIN1(28) specimens. Stereographic and orthogonal projections and remanence intensities during alternating field demagnetization (blue dots) and thermal demagnetization (red dots).

The twenty specimens submitted to the thermal demagnetization (red dots - Fig. 2) present magnetic moment values between 3.1 x10^{-10} and 7.1 x10^{-9} Am². The magnetic signal is stable for 75% of specimens (correlated with magnetic moment higher than 9.5 x10^{-10} Am²). Thermal demagnetization curves of 90% of samples show similar behavior followed by a gradual intensity decrease above 200° C, an abrupt decrease after 660° C and a total remanence loss at 680° C, supporting strong evidence of the presence of hematite. Seven specimens show a slight loss of intensity up to 120° C, perhaps a possible presence of goethite (it needs to be confirmed).

Two main directional components in AF data can be discriminated: a weak viscous remanence between 2.5 and 10 mT (Figure 2) and the interpreted characteristic remanent magnetization (ChRM), which usually points to the origin of the orthogonal projection (Zijderveld, 1967). The ChRM directions for the thermal demagnetization are defined between 590 and 670 °C. In this case, about 50% of the samples shows a ChRM that points towards the center of the Zijderveld diagrams, the determination of "clean" samples is not achieved due to the weakening of remanence in the last steps of demagnetization, that is close to the sensitivity of the RAPID system (1 x10^{-11} Am²).

The inclinations determined from AF demagnetization vary from 29.4° to 48° (maximum angular deviation (MAD) from 2.4° to 16.6°), the average inclination calculated for WIN1 stalagmite is 37° and A_{95} equal to 2.8°, which is close to the site modern values of 40.7°. The thermal demagnetization has inclinations varying from 31.8° to 38.7° (MAD between 6.5° and 12.2°), and the average inclination value is 34.9° with A_{95} equal to 5.5°. Both calculated directions (interpreted as magnetite and hematite) are compatible with each other, showing that the stalagmite has strong reproducibility and that the depositional mechanism is reliable for determination of the past geomagnetic field.

4. Conclusion

The results obtained with WIN1 stalagmite from southwest Morocco shows a strong correlation between detrital input and magnetic moment, where the layers with a high concentration of detrital material are great for paleomagnetism studies, but usually have the drawback of low accuracy in age determination. The magnetic mineral assembly in WIN1 sample is interpreted as composed of magnetite and hematite along the whole speleothem, and more tests are needed to confirm the presence of goethite. Remanent magnetization in WIN1 is stable and coherent for both magnetic carriers, the calculated inclination values with the alternating field and thermal analyses agrees in average with modern values, expressing the excellent reliability of this type of material as geomagnetic recorder.

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References

Cheng, H., Edwards, R.L., Shen, C.C., Polyak, V.J., Asmerom, Y., Woodhead, J., Hellstrom, J., Wang, Y., Kong, X., Spötl, C., Wang, X., Alexander Jr., E.C., 2013. Improvements in ^{230}Th dating, ^{230}Th and ^{234}U half-life values, and U–Th isotopic measurements by multi-collector inductively coupled plasma mass spectrometry. *Earth and Planetary Science Letters 371*, 82-91

Chou, Y.M., Jiang, X., Liu, Q., Hu, H.M., Wu, C.C., Liu, J., Jiang, Z., Lee, T.Q., Wang, C.C., Song, Y.F., Chiang, C.C., Tan, L., Lone, M.A., Pan, Y., Zhu, R., He, Y., Chou, Y.C., Tan, A.H., Roberts, A.P., Zhao, X., Shen, C.C., 2018. Multidecadally resolved polarity oscillations during a geomagnetic excursion. *Proceedings of the National Academy of Sciences 115*, *36*, 8913-8918

Dreybrodt, W., Scholz, D., 2011. Climatic dependence of stable carbon and oxygen isotope signals recorded in speleothems: From soil water to speleothem calcite. *Geochimica et Cosmochimica Acta 75*, *3*, 734-752

Jaqueto, P., Trindade, R.I., Hartmann, G.A., Novello, V.F., Cruz, F.W., Karmann, I., Strauss, B.E., Feinberg, J.M., 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

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. *Geophysical Journal International 62*, *3*, 699-718

Lascu, I., Feinberg, J.M., 2011. Speleothem magnetism. *Quaternary Science Reviews 30, 23-24*, 3306-3320

Lascu, I., Feinberg, J.M., Dorale, J.A., Cheng, H., Edwards, R. L., 2016. Age of the Laschamp excursion determined by U-Th dating of a speleothem geomagnetic record from North America. *Geology*, *44, 2*, 139-142

Osete, M.L., Martín-Chivelet, J., Rossi, C., Edwards, R.L., Egli, R., Muñoz-García, M.B., Wang, X., Pavón-Carrasco, F.J., Heller, F., 2012. The Blake geomagnetic excursion recorded in a radiometrically dated speleothem. *Earth and Planetary Science Letters 353*, 173-181

Perkins, A.M., Maher, B.A., 1993. Rock magnetic and palaeomagnetic studies of British speleothems. *Journal of geomagnetism and geoelectricity 45, 2*, 143-153

Ponte, J.M., Font, E., Veiga-Pires, C., Hillaire-Marcel, C., Ghaleb, B., 2017. The effect of speleothem surface slope on the remanent magnetic inclination. *Journal of Geophysical Research: Solid Earth 122*, *6*, 4143-4156

Scholz, D., Hoffmann, D.L. (2011). StalAge – An algorithm designed for construction of speleothem age models. *Quaternary Geochronology 6*, *3-4*, 369-382

Strauss, B.E., Strehlau, J.H., Lascu, I., Dorale, J.A., Penn, R.L., Feinberg, J.M., 2013. The origin of magnetic remanence in stalagmites: Observations from electron microscopy and rock magnetism. *Geochemistry, Geophysics, Geosystems 14*, *12*, 5006-5025

Trindade, R.I., Jaqueto, P., Terra-Nova, F., Brandt, D., Hartmann, G.A., Feinberg, J.M., Strauss, B.E., Novello, V.F., Cruz, F.W., Karmmann, I., Cheng, H., Edwards, R.L., 2018. Speleothem record of geomagnetic South Atlantic Anomaly recurrence. *Proceedings of the National Academy of Sciences 115*, *52*, 13198-13203

White, W.B., 1988. Geomorphology and hydrology of karst terrains, Oxford University Press., New York, 464 pp.

Zanella, E., Tema, E., Lanci, L., Regattieri, E., Isola, I., Hellstrom, J.C., Costa, E., Zanchetta, G., Drysdale, R.N., Magrì, F., 2018. A 10,000 yr record of high-resolution Paleosecular Variation from a flowstone of Rio Martino Cave, Northwestern Alps, Italy. *Earth and Planetary Science Letters 485*, 32-42

Zijderveld, J.D.A., 1967. AC demagnetization of rocks: Analysis of results, in Runcorn, S.K., Creer, K.M., and Collinson, D.W., eds., Methods in Palaeomagnetism: New York, Elsevier, 254-286 pp.