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# Paleomagnetism and Relative Paleointensity of two stalagmites from the Estremenho Limestone Massif, Portugal

***Paleomagnetismo e paleointensidade relativa de duas estalagmites do Maciço Calcário Estremenho, Portugal***

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## Resumo
O magnetismo de espeleotemas tem sido usado para o estudo de variações do campo magnético terrestre (CMT) de curta duração, e do clima. Neste trabalho, dois espeleotemas do Maciço Calcário Estremenho de Portugal foram estudados, com o objetivo de obter informação acerca da variação do CMT. Foram obtidos dados paleomagnéticos (magnetização remanescente natural), medição das propriedades magnéticas (FORC), e datação U-Th, assim como o cálculo da paleointensidade relativa, através do método de Pseudo-Thellier. Resultados paleomagnéticos indicam que as estalagmites registaram uma magnetização remanescente estável de origem primária (contemporânea à precipitação das estalagmites), e indicam a magnetite como o principal portador da magnetização nas estalagmites. A datação U-Th forneceu um intervalo de idades em uma das estalagmites (114.7 ±1.5 ky BP; 109.6 ±1.7 ky BP; 106.3 ±1.6 ky BP) compatível com a idade de excursão geomagnética Blake. A curva de paleointensidade relativa mostra um padrão de variação muito semelhante à das curvas de referência para este intervalo de tempo, contudo, os dados magnéticos obtidos não indicam a presença da ocorrência da excursão Blake. Isto sugere uma idade mais antiga para esta excursão geomagnética ou uma origem secundária para a magnetização. Futuras investigações contribuirão para clarificar esta discrepância.

## Abstract
Speleothems magnetism has been used for the study of short-lived variations in the Earth's magnetic field (CMT) as well as climate. In this work, two speleothems from the Estremenho Limestone Massif of Portugal were studied, to obtain information about the variation of the CMT. Paleomagnetic data (natural remanent magnetization), measurement of magnetic properties (FORC), and U-Th dating were performed, as well as the calculation of relative paleointensity, through the Pseudo-Thellier method. Paleomagnetic results indicate that stalagmites recorded a stable remnant magnetization of primary origin (contemporaneous with stalagmite precipitation) and indicate magnetite as the main carrier of magnetization in stalagmites. U-Th dating provided an age range in one of the stalagmites (114.7 ±1.5 ky BP; 109.6 ±1.7 ky BP; 106.3 ±1.6 ky BP), compatible with the Blake geomagnetic excursion age. The relative paleointensity curve shows a pattern of variation very similar to the reference curves for this time interval, however, the magnetic data obtained do not indicate the presence of the occurrence of the Blake excursion. This suggests an older age for this geomagnetic excursion, or a secondary magnetization origin. Further research is needed to unravel this discrepancy.

**Palavras-chave:** *Espeleotemas, Paleomagnetismo, Clima, Mineralogia Magnética, Excursão Geomagnética Blake*
**Keywords:** *Speleothems, Paleomagnetism, Climate, Magnetic Mineralogy, Blake Geomagnetic Excursion*

## Introduction
The magnetism of speleothems is currently a growing area, with numerous advantages compared to classical geological data archives, as it provides continuous recording and better resolution. Since speleothems are consolidated mineral deposits and allow to avoid problems related to compaction or bioturbation. Moreover, speleothems can be dated with

high precision using radioactive series of U-Th. In the last two decades, researchers have tested and consolidated the field of investigation of speleothems magnetism (Latham *et al.*, 1979; Openshaw *et al.*, 1997; Perkins *et al.*, 1993; Osete *et at.*, 2012; Lascu *et al.*, 2016; Trindade *et al.*, 2018; Font *et al.*, 2014; Ponte *et al.*, 2017; Ponte *et al.*, 2018). These studies illustrate the potential of speleothems to register short-term variations of CMT, with diverse implications for geosciences and geophysics. One of the best-studied geomagnetic excursions is the Blake event, which has been reported in numerous works, and identified in different records, such as continental sediments (Shier et al., 2011), oceanic sediments (Tric *et al.*, 1991; Thouveny *et al.*, 2004; Lund *et al.*, 2006), and loess deposits (Zhu *et al.*, 1994; Fang *et al.,* 1997). More recently, the Blake excursion has been identified in a stalagmite from Spain (Osete et al., 2012).
Although its occurrence age interval is debatable, many authors suggest that the Blake excursion is characterized by two reversed polarity zones (Denham, 1996), and that occurred between 138 ky BP and 100 ky BP, making a duration range between 20 and 35 ky. Osete *et al.* (2012) suggest an occurrence between 116.5 ± 0.7 ky BP and 112.0 ± 1.9 ky BP, results that show consistency with other age results published before (Zhu *et al.,* 1994; Lund *et al.*, 2006; Thouveny *et al.,* 2004). This way, Osete *et al.* (2012) uphold a duration of approximately 5.5 ky, also compatible with results previously published (Tucholka *et al.*, 1987; Fang *et al.*, 1997). Here we investigated the paleomagnetism and obtained the age of two stalagmites from the Estremenho Karst Massif in Portugal, from which age encompass the Blake excursion.

## Geological Setting and Sampling

We collected two stalagmites from the Estremenho Limestone Massif (ELM) in Portugal, located in the central region of Portugal. The Estremenho massif is part of the Montejunto-Estrela Mountain system, encompassing also the Sicó-Condeixa and Alvaiázere mountain ranges, as well as the Porto de Mós Massif. The ELM is part of the Western Meso-Cenozoic Rim and corresponds to a super-elevated geomorphological unit, due to compressive tectonic efforts that occurred in the Cenozoic, which led to the reactivation of ancient tectonic accidents, delimiting the ELM in three preferred directions: NNE-SSW, NE-SW, and WNW-ESE (Carvalho *et al.*, 2012). The rocks present in the ELM include Early Jurassic to Cretaceous carbonates.
The stalagmite FI-IB was oriented in the field using a magnetic compass. It was further cut into ~2cm thick slices. Specimens of ~2.5x2.5x0.5 cm were then cut along the vertical growing axis, to avoid the possible influence of stalagmite's morphology on the orientation of magnetic minerals (Ponte *et al.*, 2017).

## Methodology

Magnetic analyses were conducted at USPMag lab at Instituto de Astronomia, Geofísica e Ciências Atmosféricas (IAG) at Universidade de São Paulo (USP), and consist of alternate-field demagnetization (AF) of the natural remnant magnetization and the acquisition of anystheretic remanent magnetization curves. The magnetization was measured using a 2G cryogenic magnetometer. The paleomagnetic data were analyzed from principal component analysis using Fisher's statistics. U-Th dating was conducted at CENIEH's laboratory in Burgos. Relative Paleointensity was measured based on the Pseudo-Thellier method. Data were treated using the Paleointensity.org tool (Béguin *et al.*, 2020). This method consists of the calculation of the slope of the Arai plots, obtained with the demagnetized NRM versus the acquired anhysteretic remanent magnetization (ARM).

## Results

Radiometric dating of the stalagmites FI-VII provides ages of 114.7 (±1.5) ky for the point located near the base of the stalagmite, and 109.6 ±1.7 ky BP and 106.3 (±1.6) ky for the points located in the middle of the stalagmite. The results of the alternating field demagnetizations show a stable low-coercivity magnetic component with mean destructive field of 25 mT. NRM intensities measured are comprised of between 1.02 x $10^{-5}$ and 2.55 x $10^{-8}$ A/m. Orthogonal projections show a viscous magnetization removed below 10 mT, followed by a primary magnetization pointing to the origin. Directions obtained in the FI-IB stalagmite oriented in the field are consistent with the directions of the present-day Earth magnetic field at this locality. The presence of a reversal at the top of FI-II is suggested by a rapid variation of the declination (200º) and the magnetic inclination (from -60º to 60º). The non-oriented stalagmite, FI-VII, shows a consistent and high-resolution secular variation of the declination from the base to the top. However, no geomagnetic reversal has been identified in this stalagmite despite the fact that the age should include the Blake excursion dated at 116.5 ± 0.7 ky BP and 112.0 ± 1.9 ky BP by Osete et al. (2012). Such discrepancy questions the accuracy of the U-Th ages obtained here or the primary character of the magnetization, or even suggests that the age of the Blake excursion is older than previously thought. In order to check for the accuracy of our U-Th dating, we conducted measurement of the relative paleointensity

(RPI) and compared our data with the reference curve of Thouveny et al (2004). The results of the Pseudo-Thellier method show a strong correlation between the NRM and the ARM, suggesting that the calculation of the RPI is trustworthy in our case. In the FI-VII stalagmite, the RPI curve exhibits a consistent and gradual increase from the base to the top of the stalagmite. Once calibrated with U-Th ages, this RPI curve shows a strong correlation with RPI published by Thouveny *et al.* (2004), who provide a variation between 0-400 ky BP based on clay-carbonate sedimentary sequences from the Portuguese margin (Northeast Atlantic Ocean). Therefore, it is possible that the age of the Blake geomagnetic excursion is older than 116.5 kyr BP. More radiometric dating and magnetic mineralogical data are needed to confirm the age of the stalagmite FI-VII and the primary character of the magnetization.

## Conclusions

The results show a stable remaining magnetization, consistent with the directions of the present-day Earth magnetic field in Portugal. The stalagmite FI-IB shows reverse and antipodal directions at the top. Radiometric dating of the FI-VII stalagmite shows an age interval of 114.7 (±1.5) ky BP - 106.3 (±1.6) ky BP. Relative paleointensity (RPI) calibrated based on U-Th is consistent with reference RPI curves shown by Thouveny *et al.* (2004) from the Portuguese marine sedimentary sequences. The absence of the Blake excursion record suggested that the latter is older than previously thought, or that paleomagnetic data and/or U-Th dating are questionable.

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