PALEOMAGNETISM IN COMPLEX IMPACT STRUCTURES: EXAMPLES FROM THE HAUGHTON AND WEST CLEARWATER IMPACTS, CANADA.

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Introduction: Hypervelocity impacts of solid bodies with the Earth's surface result in a variety of geological and physical processes that are still incompletely understood. For example, the existence of a shock-induced natural remanent magnetization (SRM) [1] is still debated and has never been clearly observed on terrestrial impact craters. Therefore, measuring the natural remanent magnetization (NRM) of impactites has implications for our understanding of impact cratering processes and high-pressure effects in rocks and materials [2].

An important application of paleomagnetism is the dating of the impacts. In fact, the precise datation of impacts is a required step to estimate the frequency of large impact events on Earth [3]. It therefore has consequences for our understanding of their potential environmental effects such as mass extinctions and ore genesis, as well as risk assessment. Unfortunately, only about 21 out of the 188 confirmed impact structures [4] are accurately and precisely dated today [5].

In this work, we present two new case studies to show possible applications of paleomagnetism to impact structures: (A) dating of the impact, and (B) understanding the geological impact processes.

Methods: Field missions to Haughton and Clearwater Lakes impact structures were conducted in 2010, 2013 and 2014. Each time, small oriented core samples (3-8 cm long and 2.5 cm diameter) from different locations and lithologies were drilled within the impact craters. The NRM of the samples is measured using a SQUIDs magnetometer at the laboratory of rock magnetism of the CEREGE and demagnetized using alternating-field and thermal demagnetization techniques, respectively up to 110 mT and 600 °C. The resulting data is analyzed with the Paleomac software [6], allowing the calculation of the different components of the paleomagnetic directions recorded by magnetic minerals in the samples. We obtained an estimation of the West Clearwater impact age (A) by calculating the virtual geomagnetic pole (VGP) of impact-melt rocks (IMR) and comparison with the apparent polar wander path (APWP) for North America. To identify impact processes (B), we compare the paleomagnetic directions of samples inside and around the Haughton crater in order to establish a simple model of how the magnetization is acquired in Haughton's rocks.

Results: *A) Paleomagnetic dating*. The West and East Clearwater Lakes in Québec, Canada, are two eroded mid-size impact structures of respectively 36 and 26 km diameters. Due especially to their proximity, they are interpreted as a typical "impact doublet". The age of the West structure is now well-defined to ~280 Ma, but it is not the case of the East structure which is still debated, questioning the impact doublet theory [7,8].

The calculated VGP of 40 IMR cores and some remagnetized basement at West Clearwater correlates well with the magnetic paleopole at ~240-260 Ma (Fig.1). This result needs to be aged of ~20 Ma due to recent update of the database [9], which gives a final dating of 270 ± 10 Ma. This result is compatible with a recent $^{40}Ar/^{39}Ar$ dating that yielded an Early Permian age of 286.2 ± 2.2 Ma for the West Clearwater Lake impact [8]. The differences between the two ages could be explained by the precision of the paleomagnetic database as well as possibly the secular variation of the geomagnetic field during cooling of the impact-melt sheet. Additionally, our data indicates that the impact happened during a reverse polarity period and that the IMR are formed at relatively high-temperature, due to same paleomagnetic directions in both clasts and groundmass within the IMR.

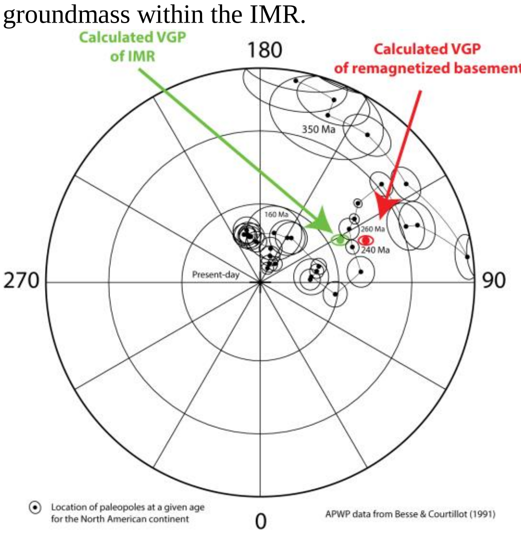

Fig. 1: Polar-projection showing the mean paleomagnetic direction of impact-melt rock (IMR) cores and remagnetized basement from the West Clearwater Lake impact structure, compared with the APWP for North America.

B) Impact-cratering processes. The Haughton impact structure is located on Devon Island in the Canadian High Arctic Archipelago. It is a mid-size (~23 km diameter) complex impact structure dated ~23.5 Ma [10].

The study of rocks forming the target sequence (carbonaceous rocks) outside the crater show two distinct components of the paleomagnetic directions: a low-temperature direction acquired in the present-day Earth's ambiant magnetic field, and a high-temperature component matching with the Ordovician paleomagnetic direction, indicating the age of formation of the limestones. Thus, we observe that the rocks outside the crater have largely preserved their primary magnetization in their high-temperature paleomagnetic components.

Inside the crater, two distinct processes occur (Fig.2): (1) Remagnetization of impact-tilted target-sequence blocks: The blocks sampled in the field have different dips. However, the magnetization measured in the laboratory is constant. This means that the blocks have been remagnetized after tilting by the impact; (2) remagnetization of clasts within IMR formed at high-temperature: As the blocks of target-sequence rocks are tilted by the impact, they must have endured shock-metamorphism. Therefore, if these blocks are remagnetized by the impact, their paleomagnetic directions should be the same to those of clasts in melt rocks. However, we see that the direction of tilted blocks deviates slightly from the direction of clasts within IMR (Fig.2).

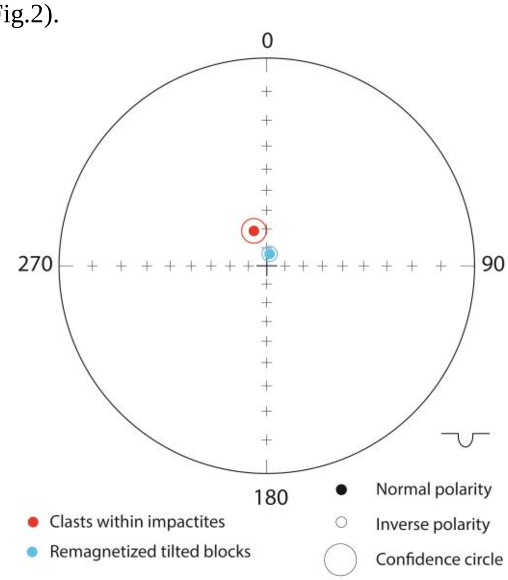

Fig. 2: Comparison between clasts' and tilted blocks paleomagnetic directions.

Discussion: The two case studies show totally different applications of paleomagnetism to impact craters:

(A) The datation of impacts, which is critical to estimate the flux of large meteorite falls on Earth and their relationships with mass extinctions, as well as for risk assessment. Here, we confirm the age of the West Clearwater impact structure. We also show that the impact-melt breccias at West Clearwater are formed at high-temperature, because the paleomagnetic directions are the same both in clasts and matrix of breccias. A future paleomagnetic dating of the adjacent 26 km-diameter East Clearwater Lake impact structure may help answer the question of the possibility of an impact doublet at Clearwater. This perspective is of great interest as the existence of an impact doublet on Earth has never been proved while "false doublets" seem more common than previously thought.

(B) How the magnetization can be acquired during and soon after an impact. We show that the melt-bearing rocks at Haughton are formed at high-temperature and that the rocks from the target sequence inside the crater are remagnetized after tilting. We formulate the hypothesis that this remagnetization is due to impact-induced hydrothermalism soon after the impact, but so far we do not explain why only some of the intra-crater rocks are remagnetized. This can be due to different lithologies that are more or less sensitive to alteration and/or remagnetization.

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