The remanent magnetisation recorded in the Chesapeake Bay impact crater, Virginia

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Abstract. During impact events, planetary crusts experience high pressures that can impart rocks with shock remanent magnetisation (SRM) if an ambient magnetic field or demagnetise rocks if a field is absent. If rocks experience substantial impact heating or are pressurised above ~40 GPa (inducing melting and recrystallisation) they may instead record a thermo-viscous remanent magnetisation (TVRM) as they cool below their Curie temperatures. Understanding impact re-magnetisation is crucial for studying terrestrial impact craters, but also unraveling the history of long-lived core dynamo fields on other planetary bodies. In this research we studied impact-related re-magnetisation recorded in natural rock samples from the Chesapeake Bay impact crater, Virginia. As a case study, here we discuss the natural remanent magnetisation (NRM) of two samples of different rock types: a suevite (sample I9-UI, depth 1.40 km beneath the ground) and a schist (sample S32, depth 1.67 km beneath the ground) using thermal and alternating field demagnetisation. The suevite represents a sample that contains material that experience impact remelting, whereas the schist represents an unmelted rock. From the NRM spectra, we found that the sample ITH9-UI was remagnetised by TVRM due to impact-related heating, while the sample STH32 shows the indication of shock deformation of magnetic minerals.

1. Introduction

Hypervelocity impact events on the planets drive Earth scientists to explore the effects of impacts on rocks. During impact events, shock-induced remanent magnetisation (SRM) can record the ambient field such as the Earth's magnetic field throughout geological time when the field is presence [1]. If an ambient field is absent, the shock pressure rearranges the magnetic moments in rocks randomly, in a process known as shock demagnetisation [1]. The SRM is crucial in palaeomagnetism as it is a key to understand long-lived core dynamo magnetic field of the planets, and also transient magnetic fields generated and amplified by impact plasmas.

There are several experiments designed in laboratories to understand SRM (e.g., [1, 2]). However, many of these studies are conducted using hydrostatic analogs of SRM. Laboratory experiments show that SRM is preferentially recorded in low-coercivity ferromagnetic grains [i.e., SRM can easily be removed by low alternating magnetic field (e.g., 10 mT)]. In a natural setting, SRM may be overprinted by thermoviscous remanent magnetisation from impact-related heating (TVRM), viscous remanent magnetisation (VRM) from long-term exposure to a planetary magnetic field after an impact and isothermal remanent magnetisation (IRM) from effects such as lightning strikes. Therefore, SRM may not survive in nature after the impact events. With regards to the relationship between SRM and magnetic unblocking temperatures, SRM seems to occupy grains spanning nearly the entire unblocking temperature spectrum of rocks up to the Curie temperature. As natural craters on both terrestrial and extraterrestrial crusts experience shock level pressures in the order of ~1-50 GPa, samples from impact craters are ideal to study the SRM. Therefore, in this research we sought to explore the nature of impact remagnetisation at the Chesapeake Bay impact crater, Virginia and determine whether SRM was recorded in rock samples there.

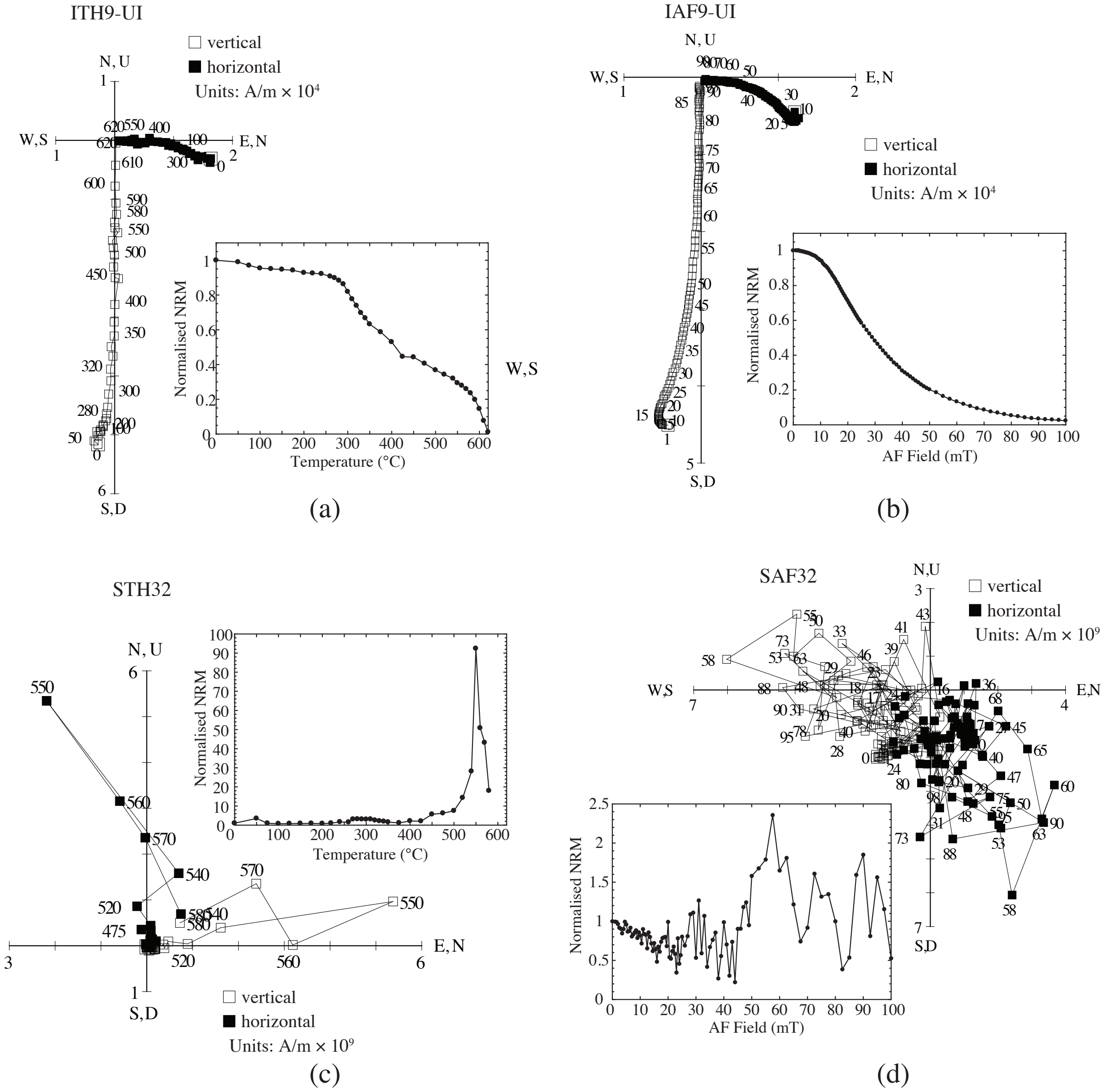

Figure 1. Zijderveld diagrams showing the declination (black square, vertical field) and inclination (open square, horizontal field) of the palaeomagnetic field. Inset diagrams show the normalised NRM spectrum. (a) and (b) show thermal and AF demagnetisation of sister specimens from a suevite sample from the impact layer. (c) and (d) represent the thermal and AF demagnetisation of a schist sample from the schist-pegmatite layer.

2. Sample collection and palaeomagnetic measurements

2.1. Chesapeake Bay impact crater and sample collections

The Chesapeake Bay impact crater was formed during the late Eocene (~35.5 Ma) by a meteorite crashing onto Earth [3]. The International Continental Scientific Drilling Program (ICDP) held a scientific drilling campaign to sample this impact structure in 2005 at the Eyreville farm, Virginia and successfully obtained three cores: core A (depth 124.6-940.9 m), core B (depth 737.6-1766.3 m) and core C (depth 0-140.2 m). These cores are stored at the ICDP core repository at Rutgers University. In our effort to determine the nature of impact remagnetisation at the crater, we focus on the Eyreville core B as this core contains an impact-melt-containing breccia (suevite) layer (depth ~1,393-1,550 m) containing materials that experienced a shock pressure in the order of 35-50 GPa during the impact [4], and a schist-pegmatite layer (~1,550-1,766 m depth) which represents the impact target rocks. We collected 19 samples from the impact breccia layer and 30 samples from the schist-pegmatite layer. Samples were cut into a 2×2 cm squares with a thickness of ~0.5 cm, yielding ~2-6 specimens for each sample.

2.2. Palaeomagnetic measurements

Palaeomagnetic measurements were performed in the Palaeomagnetism Laboratory at Rutgers University. Standard demagnetisation experiments including thermal demagnetisation and alternating field (AF) demagnetisation were performed on 19 specimens from the impact layer and 30 specimens from the schist-pegmatite layer. For the thermal demagnetisation, the specimens were stepwise heated from 50 °C to 620 °C using an ASC TD48-SC thermal demagnetiser to isolate natural remanent magnetisation (NRM) directions. The remaining NRM and directions were measured using a 2G Cryogenic SQUID magnetometer after each heating step. During AF demagnetisation experiments, peak ac fields of 1-100 mT were applied to gradually demagnetise the NRM, and the remaining NRM and magnetisation directions was measured after each AF demagnetising field. The palaeomagnetic data were illustrated and interpreted on Zijderveld diagrams [5] and NRM decay plots (figure 1).

3. Results and discussion

Here we present palaeomagnetic data from a suevite sample (sample I9-UI, depth 1.40 km) from the impact layer and a schist sample from the schist-pegmatite layer (sample S32, depth 1.67 km). Samples with the AF and TH codes in front of the numbers are referred to as AF-demagnetised and thermal demagnetised samples.

3.1. Impact layer

The thermal demagnetisation data show that two magnetisation components are recorded in the suevite: A high-temperature (HT) component likely attributable to primary cooling after the impact is blocked between 620 °C and 350 °C (figure 1(a)). Curvature of the Zijderveld diagram connects the HT component to a second low-temperature (LT) magnetisation component with a somewhat different direction blocked between 350 °C and room temperature. It is possible that the LT component was acquired during prolonged cooling accompanied by block rotation within the crater but further work is necessary to explore that hypothesis. To determine the magnetic mineralogy of our samples, we consider the NRM spectrum (figure 1(a) inset). Our data show two phases of magnetic minerals: pyrrhotite (Curie temperature ~320 °C) and oxidised titanomagnetite (Curie temperature ~580 °C). It is clear that the impact layer acquires the TVRM.

AF demagnetisation revealed the same two magnetisation components observed in the thermal data: a high coercivity (HC) component with a direction matching the HT direction from the sister specimen was present in grains with coercivities between 50-100 mT. A low coercivity (LC) component matching the LT direction was blocked between 1-50 mT. The NRM spectrum (figure 1(b) inset) shows the median destructive field (MDF, the field required to remove half of the NRM) was ~29.1 mT.

3.2. Schist-pegmatite layer

Thermal demagnetisation of the schist sample (figure 1(c)) reveals significant scatter on the Zijderveld diagram during the heating steps between 50-400 °C. The sample acquires a spurious magnetisation from heating in the thermomagnetic oven above 400 °C due to thermochemical alteration of the sample (figure 1(c) inset). Therefore, data points above 400 °C are not considered here. Unlike the impact layer, the characteristic component of the NRM for low temperature steps (50-400 °C) cannot be determined from the Zijderveld diagram. AF demagnetisation data from the sister specimen also exhibit scattered magnetisation directions (figure 1(d)). The NRM spectrum is not smooth, precluding determination of the MDF (figure 1(d) inset). The data from both experiments indicate that the schist-pegmatite layer apparently did not acquire any stable SRM as a result of the impact but may in fact have experienced a net demagnetisation effect.

A full shock demagnetisation of intact magnetic minerals may be excluded because there is an ambient magnetic field on Earth. Pyrrhotite is the primary magnetic mineral in the schist sample while magnetite is the minor magnetic mineral [6]. The pyrrhotite grains are single domain grain with medium coercivity [6]. Experimental studies on shock pressure effecting on pyrrhotite grains show that pressures exceeding the Hugoniot elastic limit of 3.5 GPa of pyrrhotite causes the fracturing and deformation of pyrrhotite grains, forming amorphous domains [7]. The high shock pressures may also reduce magnetic grain sizes to the superparamagnetic range that cannot preserve stable magnetisation over geological time [7]. The amorphous domains reduce the ability of remanent acquisition in pyrrhotite [7]. We tentatively conclude that the schist sample may have lost its ability to acquire a stable magnetisation due to fracturing and deformation of the pyrrhotite grains. However, further studies to measure the magnetic domain grains and mineral phases, e.g., measurements of hysteresis, backfield curve and Curie temperature should be performed to provide better conclusions.

4. Conclusions

Paleomagnetic study of samples from the Chesapeake Bay impact crater indicates that different forms of magnetisation are recorded by different rock types within the crate. Melt-bearing breccias (suevites) containing pyrrhotite and titanomagnetite recorded TVRM as they cooled following the impact event. The schist target rocks show signs of impact-related demagnetisation due to the fracturing and deformation of pyrrhotite. We did not detect any evidence of SRM in our rocks, supporting prior observations that this form of magnetisation is not well-preserved in nature.

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