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Rock Magnetic Studies of the Neuschwanstein EL6 Chondrite – Implications on the Origin of its Natural Remanent Magnetization

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Abstract

We report magnetic properties of the Neuschwanstein enstatite chondrite (EL6). Low magnetic coercivity of the Neuschwanstein samples indicates presence of multidomain magnetic grains. Thermomagnetic and microprobe investigations reveal kamacite with 6% Ni to be the main magnetic phase, but there is also an indication for the presence of a low-Ni phase in thermomagnetic curves. However, this low-Ni phase was not observed in microprobe analysis. The natural remanent magnetization (NRM) of Neuschwanstein interior has low stability against alternating demagnetization field (median destructive field ~ 3 mT) while the samples containing fusion crust have NRM of higher coercivity (median destructive field ~ 17 mT). The NRM of the meteorite was tested for presence of isothermal remanent magnetization (IRM) overprint. The results indicate that the NRM of Neuschwanstein was most likely overprinted by a strong IRM during the meteorite handling. Thus, the Neuschwanstein meteorite is not suitable for paleointensity studies. Such a test for the presence of the artificial IRM overprint should be always done prior interpreting NRM in meteorites.

Key words: Neuschwanstein meteorite, enstatite chondrite, magnetism, paleomagnetism, remagnetization

1. Introduction

The meteorites are the richest source of extraterrestrial material on Earth and bring valuable information about their parent bodies – asteroids and various magnetic events in the Solar System and on early planetesimals like the presence of magnetic dynamo, shock effects or interplanetary magnetic fields. Thus, chondritic meteorites are often subject to paleointensity studies. As an example, most recent ones using reliable methodology are *Acton et al*. (2007), *Kletetschka et al*. (2003), *Gattacceca and Rochette* (2004), *Gattacceca et al.* (2003). A detailed paleomagnetic study on Abee EH4 enstatite chondrite was done by *Sugiura and Strangway* (1983), where a stable natural remanent magnetization (NRM) component of extraterrestrial origin and paleointensity estimates are reported.

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Enstatite chondrites are the most reduced among chondrites with abundant metal phase and almost no iron in silicate phase (*Norton*, 2004, 115-116). They have formed most likely close to the Sun, and thus experienced high temperatures accompanied by large solar magnetic fields during formation.

The Neuschwanstein meteorite fall occurred on April 6, 2002, close to Neuschwanstein castle in Bavaria, Germany (*Oberst et al*., 2004). The fall was captured by camera stations of the European Fireball Network and become the 4th photographically documented fall and 7th fall with determined orbit (*Spurny et al*., 2003). The orbit originates in asteroid belt and is identical to that of Pribram meteorite (*Spurny et al*., 2003). Three individual meteorite bodies were subsequently recovered and are identified in literature as Neuschwanstein I (Fig. 1), II and III respectively. The chemical and mineralogical properties of the meteorite were reported by *Bischoff and Zipfel* (2003) and *Zipfel and Dreibus* (2003), and the meteorite was classified as enstatite chondrite of petrographic type 6 (EL6), shock level S2 (peak shock pressure 5–10 GPa according to the scale by *Stöffler et al*. (1991)).

Fig. 1. The Neuschwanstein 1750g fragment found on July 14, 2002. The dark cover is the fusion crust while the fresh interior is exposed on the cut. The samples used in this study are coming from the separated edge.

The Neuschwanstein I. (found on July 14, 2002; 1750 g total mass) is the source of our study material. Two unoriented fragments (~1 cm size) of the Neuschwanstein I. body were obtained. First fragment contains fusion crust on one side and the second fragment consists entirely of interior material. The fragments were subsequently cut to smaller samples (2–3 mm in size) and subjected to magnetic studies.

The relatively short time between the fall and recovery of the Neuschwanstein meteorite (3 months) gives us a unique opportunity to study fresh, unweathered extraterrestrial material. In this study we will characterize physical and rock magnetic properties of the Neuschwanstein meteorite and define the possible origin of the Neuschwanstein's NRM.

2. *Instruments and methods*

Basic petrophysical parameters of the Neuschwanstein meteorite were determined in the Solid Earth Geophysics Laboratory at the Department of Physics, University of Helsinki (HU), Finland. Density and volume were determined through the Archimedean method based on weighing the sample in air and suspending in water using the AND HF-300G digital balance. Bulk susceptibility measurements were done on a RISTO 5 kappa-bridge (operating at 1025 Hz frequency and 48 A/m RMS field intensity). For remanence measurements an AGICO JR-6 spinner, RISTO 5 fluxgate magnetometer and a 2G Model 755 superconducting rock magnetometer (SRM) were used.

Subsequent detailed magnetic and magneto-mineralogical investigations were done in order to verify the stability and origin of NRM and to identify the main magnetic minerals. The hysteresis parameters were measured on a Princeton Measurements Model 3900 VSM (Vibrating Sample Magnetometer) at HU and on a Quantum Designs MPMS-5S cryogenic susceptometer installed at the National Institute for Standards and Technologies (NIST), Maryland, USA. Temperature dependence of magnetic susceptibility was measured using a KLY-3S kappa-bridge (operating at 875 Hz and 300 A/m RMS field intensity) equipped with CS-3 and CS-L temperature control units installed at HU. Isothermal remanent magnetization (IRM) acquisition was done on a Princeton Measurements Model 7500 VSM and an AGICO PUM-1 pulse magnetizer, both at HU. Alternating field demagnetization (AFD) was done using an AGICO LDA-3, a 2G Model 600 and a Schoenstedt GSD-1 demagnetizers at HU.

3. *Basic physical parameters*

Average values of bulk density 3500 kg/m^3 and magnetic susceptibility 25900 × 10^8 m^3/kg or 0.9 SI (shape corrected by using method in *Osborn* (1945) measured on fresh interior samples are consistent with E chondrite values in meteorite petrophysics database by *Kohout et al*. (2008) (density and susceptibility, Fig. 2), *Rochette et al*. (2008) (apparent susceptibility values) and *Britt and Consolmagno* (2003) (bulk density). There is a ~ 3% variation in density and up to 50% variation in magnetic susceptibility observed in the studied samples (Table 1) caused by inhomogenity in the metal distribution on millimeter scale (size of our samples).

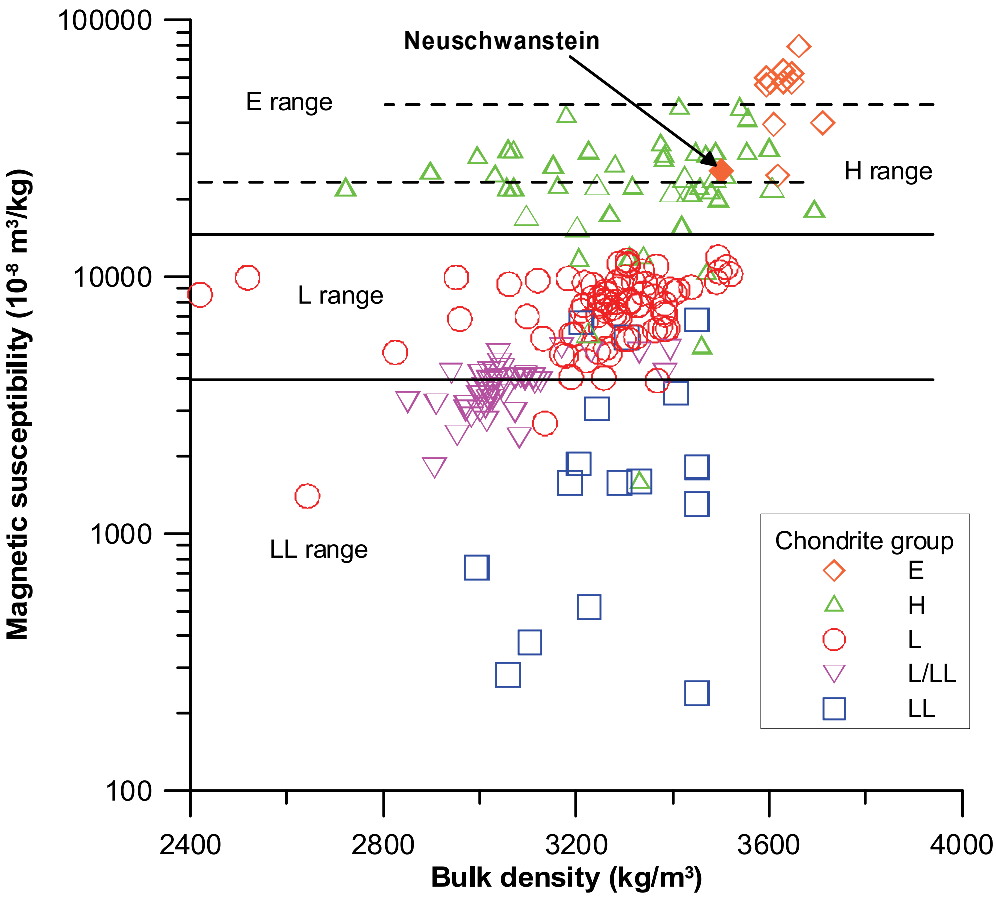

Fig. 2. Magnetic susceptibility (shape corrected) versus bulk density of various chondritic meteorites from *Kohout et al*. 2008. Only unweathered falls are displayed. Approximate range of susceptibility values for each chondrite type are outlined by horizontal lines. The Neuschwanstein EL6 chondrite is denoted with solid diamond.

Table 1. List of interior and edge samples with their mass, shape-corrected susceptibility, NRM intensity, saturation magnetization (M_{rs}) and REM ratio.

Sample	**Mass (mg)**	**Susc. (10^{-8} m^3/kg)**	**NRM (mAm^2/kg)**	**M_{rs} (mAm^2/kg)**	**REM**
D3-3A (interior)	24	16300	8.7	89	0.1
D3-4A (interior)	34	33300	10.4	200	0.05
NE1A (5 mm below fusion crust)	35	36800	10.0	95.0	0.11
NE1B (5 mm below fusion crust)	18	38200	24.6	88.9	0.28
NE2B (5 mm below fusion crust)	33	20700	8.2	96.7	0.085
NE3 (1/3 of surface is fusion crust)	150	30600	14.9	116.7	0.13
NE4 (1/4 of surface is fusion crust)	120	27200	29.6	198.3	0.15

4. *Hysteresis properties*

Room temperature magnetic hysteresis properties are characterized by low coercivity (Bc ~ 0.5 mT) typical for the presence of multi domain (MD) grains. The saturation is achieved between 1 and 1.5 T. The saturation magnetization (M_s) of Neuschwanstein interior samples is ~ 40 Am^2/kg while the saturation remanence (M_{rs}) is in order of 10^1 Am^2/kg. Similar variations to those in magnetic susceptibility are also observed in M_s and M_{rs} (again caused by the inhomogenity of metal distribution within our millimeter sized samples). The comparison of hysteresis properties of the two Neuschwanstein interior samples to the earlier chondrite data by *Pesonen et al.* (1993), and *Sugiura* (1977), reveal a good agreement with other E chondrites (Fig. 3).

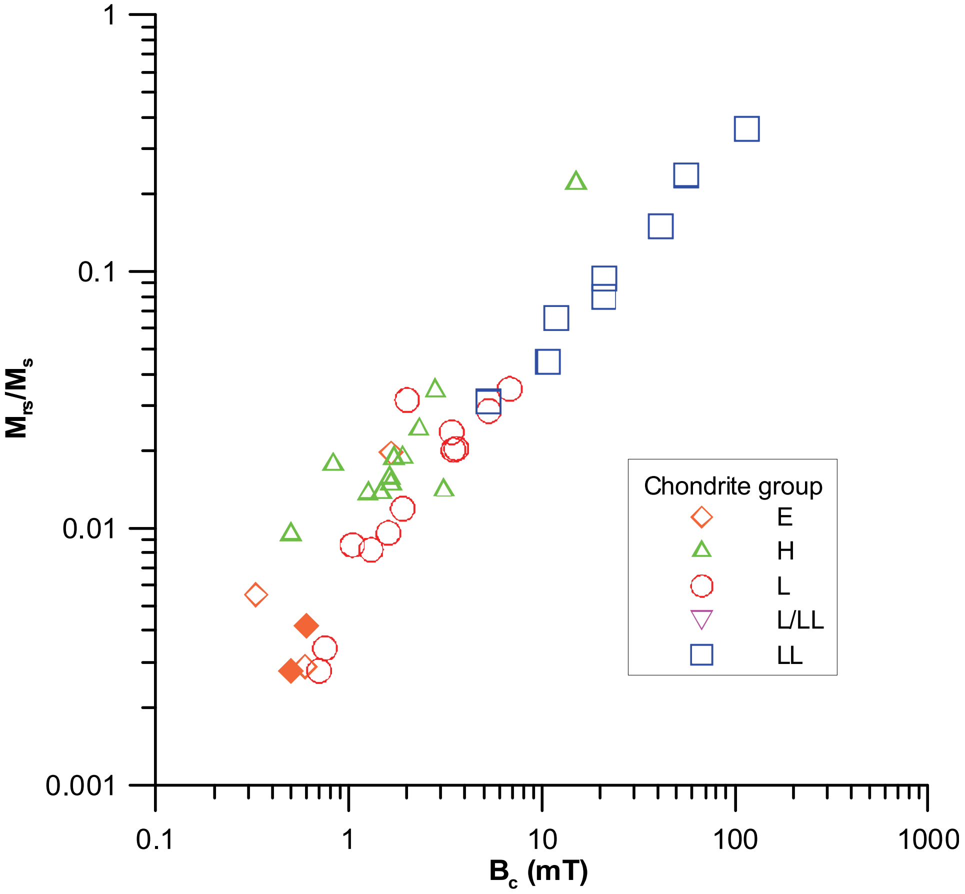

Fig. 3. The comparison of hysteresis properties (M_{rs}/M_s vs. B_c) to the data by *Pesonen et al.* (1993) and *Sugiura* (1997). The two Neuschwanstein interior samples are denoted with solid diamonds.

5. *Thermomagnetic investigations*

Previously, the presence of daubreelite ($FeCr_2S_4$), trolite (FeS) and kamacite (α-FeNi) were identified in Neuschwanstein's Mössbauer spectra (*Hochleitner et al.*, 2004). Daubreelite was also detected by *Kohout et al.* (2007) in low temperature magnetic measurements through its Curie temperature, (T_c ~ 150 K) and structural magnetic transition (T_m ~ 70 K).

To gather more detailed information on the magnetic minerals within Neuschwanstein meteorite, the temperature dependence of the magnetic susceptibility of the Neuschwanstein interior sample was studied from room temperature to ~ 800°C under argon atmosphere. Fig. 4 shows the results of three high temperature thermomagnetic measurements of a Neuschwanstein interior sample with subsequently increasing maximum temperatures (T_{max} 707ºC, 777ºC, and 806ºC respectively). The curves show three main features consistent with the FeNi phase diagram with 6 wt% Ni (*Reuter et al.*, 1989).

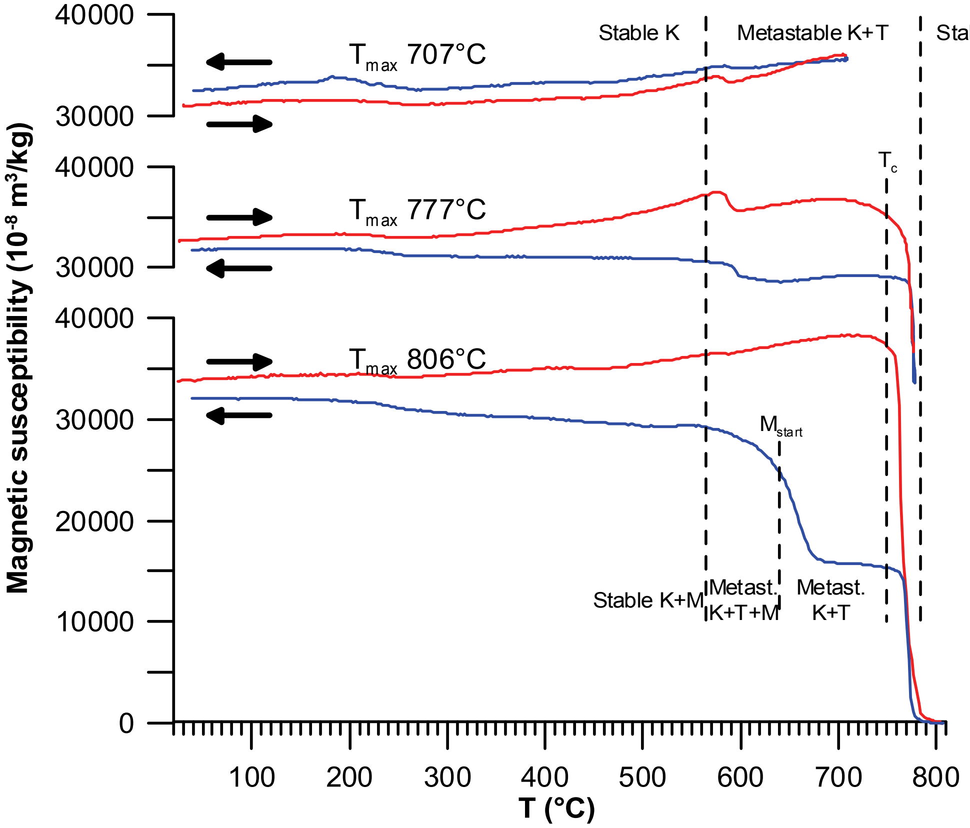

Fig. 4. Thermal dependence of apparent magnetic susceptibility measured under argon atmosphere at different maximum temperatures (T_{max}). Typical transition temperatures for 6 wt% Ni kamacite (*Reuter et al.*, 1989) are indicated by vertical lines. K – kamacite, T – taenite, M – martensite, M_{start} – martensite start temperature, T_c – Curie temperature.

All heating and cooling curves show variation in susceptibility at ~ 580ºC. This might correspond to the transition temperature of stable kamacite (565ºC for 6 wt% Ni) to metastable kamacite and taenite mixture (kamacite → kamacite + taenite). The small drop in the susceptibility indicates that only a limited portion of taenite (γ-FeNi, paramagnetic at this temperature) was formed by this reaction.

The curves of $T_{max} \geq 777$ºC show a clear transition at 760–775ºC, which probably corresponds to the T_c of kamacite. This is higher than expected for 6 wt% Ni kamacite (~ 740°C). Since the low Ni metals have higher T_c (e.g. 760ºC for 2 wt% Ni), the metal in Neuschwanstein can be a mixture of 6 wt% Ni phase and a low-Ni phase. Another explanation for this transition is reduction of ferrous/ferric iron to metallic iron with graphite present in the meteorite.

The higher T_{max} curves show different irreversible patterns depending on T_{max}. The 806ºC T_{max} cooling curve shows a stepped feature with two transition temperatures (775ºC and 645ºC), whereas the 777ºC T_{max} curve does not show any change at 645ºC. This 645ºC transition corresponds to the martensite onset temperature (M_{start}) of 6 wt% Ni taenite. The taenite → martensite diffusionless transformation started reaching this M_{start} temperature (at 8ºC/min cooling rate in our case), because the diffusion controlled taenite → taenite + kamacite reaction is suppressed during 5ºC/min or faster cooling (*Kaufman and Cohen*, 1956). The 806ºC T_{max} curve exceeded taenite to taenite + kamacite solvus that is 785ºC for 6 wt% Ni alloy, forming a stable taenite phase, whereas the 777°C T_{max} curve did not exceeded this line. Thus, the 806ºC T_{max} curve shows a transition at the M_{start} temperature, whereas the 777ºC T_{max} curve does not.

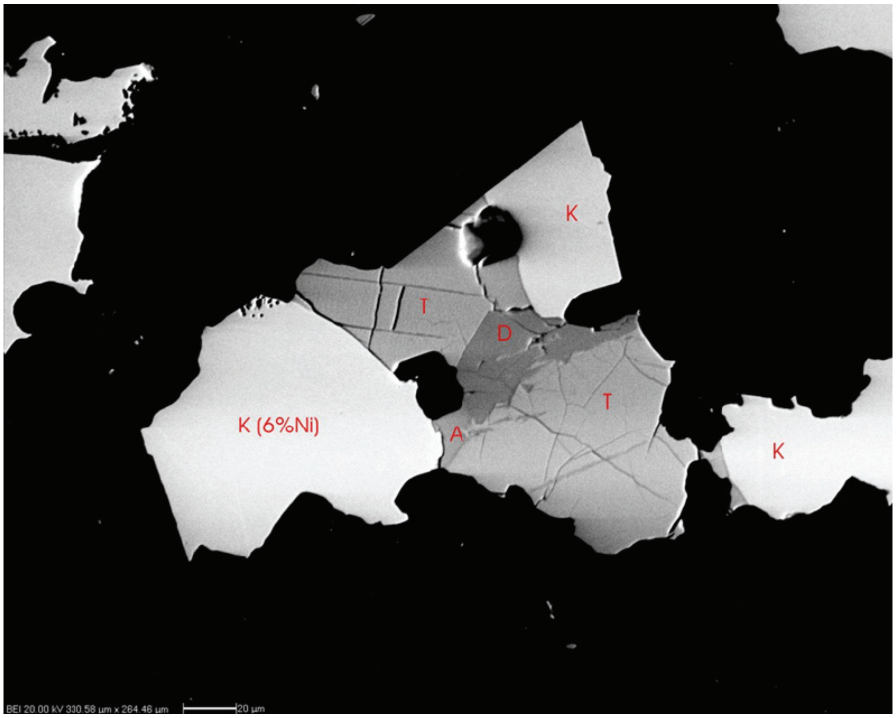

Fig. 5. SEM backscattered electron image of the Neuschwanstein meteorite showing the major metal and sulphide phases. A – alabandite (Fe, Mn)S, D – daubreelite $FeCr_2S_4$, K – kamacite FeNi, T – troilite FeS. The horizontal dimension of the image is 330.58 µm.

This series of thermomagnetic measurements clearly indicate that the dominant magnetic mineral of Neuschwanstein meteorite is 6 wt% Ni kamacite. This was verified at the Czech Geological Survey, Prague, Czech Republic using a CamScan 3200 scanning electron microscope (SEM) with an Oxford Instruments Link ISIS300 energy-dispersive spectrometry (EDS) analyzer (Fig. 5) and at the Institute for Planetology, University of Münster (Addi Bischoff, personal communication) using a JEOL JXA-8600 S electron microprobe. Both instruments revealed FeNi grains with a Ni amount of 5–7 wt%. As apparent in Fig. 7, the kamacite grains are ~ 100 µm what is consistent with their MD properties. Data measured on the Neuschwanstein I interior sample is also consistent with the analysis published by *Hochleitner et al*. (2004) on the Neuschwanstein II fragment.

However, the thermomagnetic data indicates also the presence of a small amount of Ni-poor kamacite (possibly due to a Ni-zonation in the metal) or a reduction of ferrous/ferric iron to metallic iron. We cannot draw definite conclusions from the current data and further research has to be done to resolve these issues.

6. NRM of Neuschwanstein meteorite

Due to the abundance of kamacite, enstatite chondrites are capable of carrying strong remanent magnetization. The NRM of Neuschwanstein interior samples ranges between 8.7 and 10.4 mAm^2/kg. The NRM of samples containing fusion crust is slightly higher, ranging between 14.9 and 29.6 mAm^2/kg (Table 1). In Fig. 6 the NRM vs. magnetic susceptibility is plotted for Neuschwanstein (EL6) as well as for Abee EH4 chondrite meteorite and for Hvittis and Pillistfer EL6 chondrite meteorites (data from *Terho et al*., 1993). Neuschwanstein's NRM is in the same order of magnitude that other enstatite chondrites (Fig. 6).

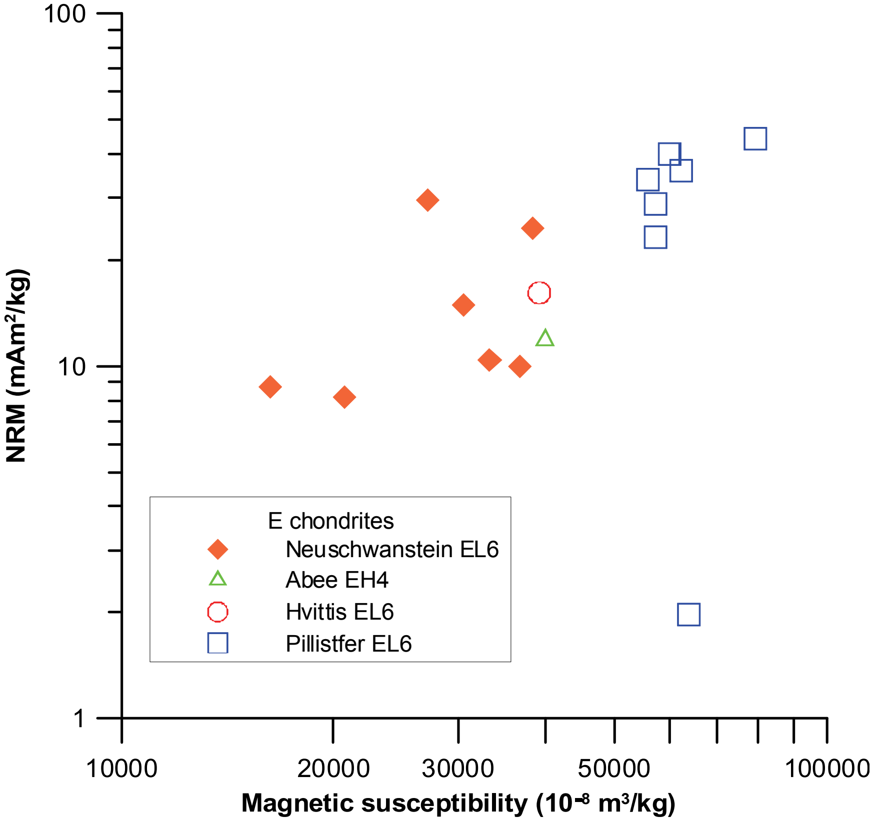

Fig. 6. NRM vs. magnetic susceptibility (both in log scale) of Neuschwanstein meteorite compared to Abee, Hvittis and Pillistfer meteorites (data from *Terho et al*., 1993).

The remanent magnetization efficiency ratios (REM = NRM/M_{rs}) calculated from Neuschwanstein interior and edge samples (~ 10^{-1}, Table 1) are relatively high for thermal remanent magnetization (TRM) and thus may be a result of the IRM overprint (*Wasilewski and Dickinson*, 2000; *Wasilewski*, 1977).

To characterize the NRM (stability and components) the samples were demagnetized in an AF field. The results of 6 samples from both meteorite interior and edge are displayed in Fig. 7.

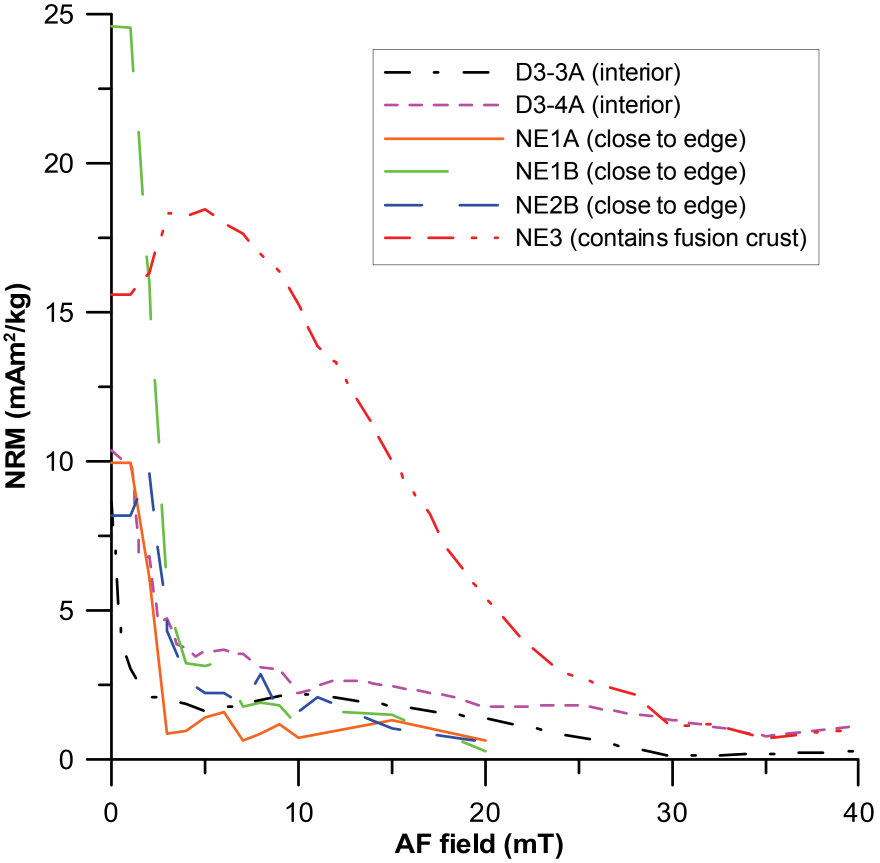

Fig. 7. AF demagnetization curves of NRM of Neuschwanstein interior and edge samples.

The NRM of samples from the meteorite interior is of low stability (major fraction of the NRM is removed by 5 mT demagnetizing field, median destructive field (MDF) is ~ 3 mT), what suggest MD kamacite to be the remanence carrier. Fig. 8 shows the Zijdervelt diagram and stereoplot of the interior sample D3-3A. In the figure, one main component (0-5 mT) of the NRM can be identified. The 5 mT AF field is sufficient to demagnetize most of the NRM (Fig. 7). Thus, the signal beyond the 5 mT AF field is directionally unstable due to a noise introduced by the MD grains.

The NRM directions of neighboring Neuschwanstein interior samples are mostly similar, but sometimes show scatter of several tenth of degrees. This result must be considered with caution since large MD grains have significant local fields and shape anisotropy which can easily influence the directions of the acquired remanent magnetization.

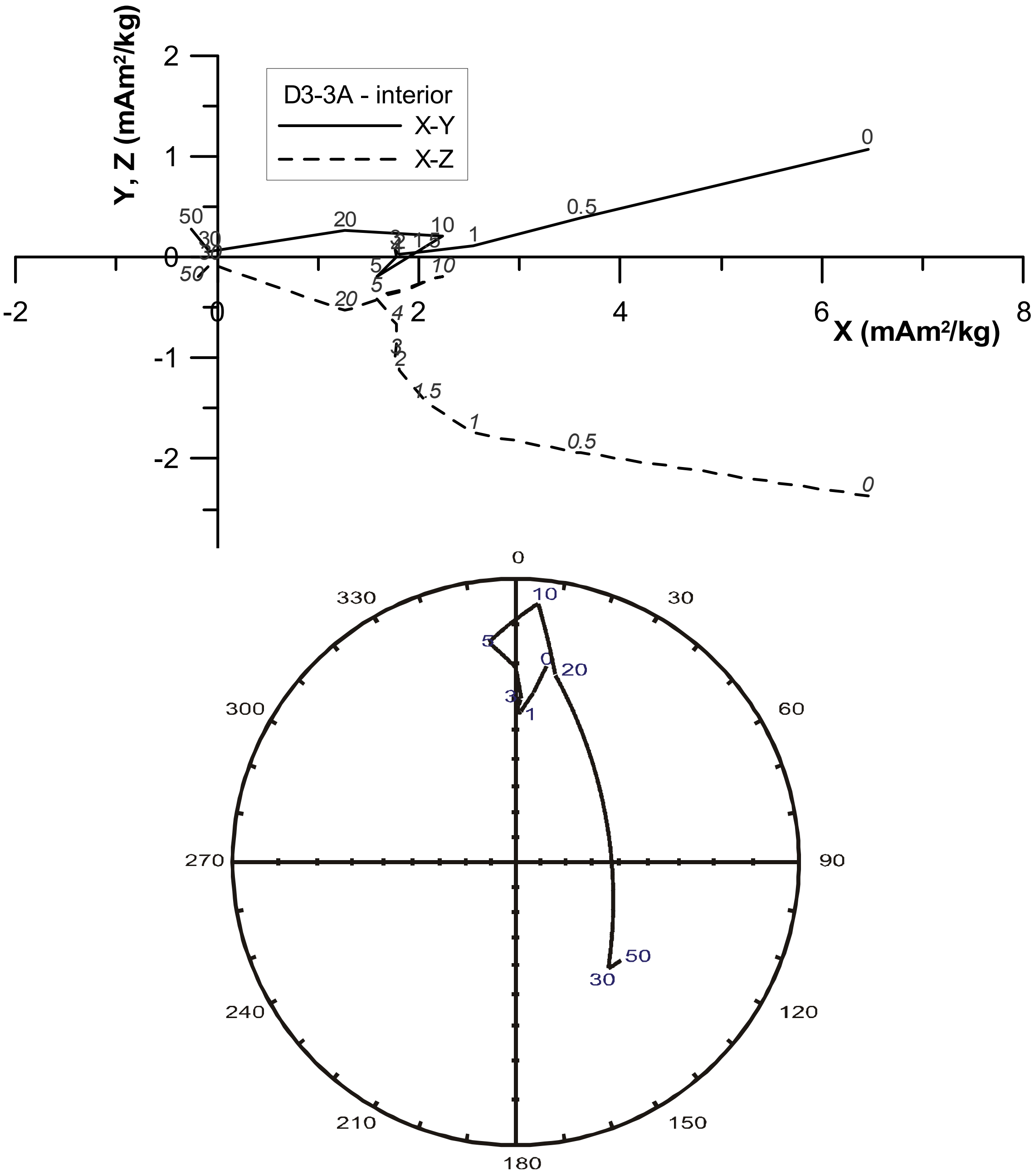

Fig. 8. Zijdervelt diagram and stereographic projection (equal area) of D3-3A interior sample (non-oriented sample). The labels indicate AF demagnetization fields in mT. All steps in stereographic projection are of negative inclination.

Contrastingly, the NE3 sample covered with the largest area of fusion crust (1/3 of the surface is covered by a fusion crust, see Table 1) has three directionally distinct components (0–2 mT, 2–6 mT and 6–30 mT; Fig 9). The higher stability of NRM (MDF ~ 17 mT) can be related to the new magnetic minerals developed as the result of melting and rapid cooling during the atmospheric entry. Since the sample NE3 contains both fusion crust and non-affected interior material, the remanence components may represent distinct lithologies (magnetically soft fresh interior and harder fusion crust).

These findings are consistent with previous studies of fusion crust (*Kohout et al.*, 2004, *Nagata*, 1979). The remanence of the D3-3A and NE3 samples was measured on an Agico JR-6 spinner mangetometer and was two orders of magnitude stronger than the instrument noise. The samples are from different Neuschwanstein I fragments and are not mutually oriented.

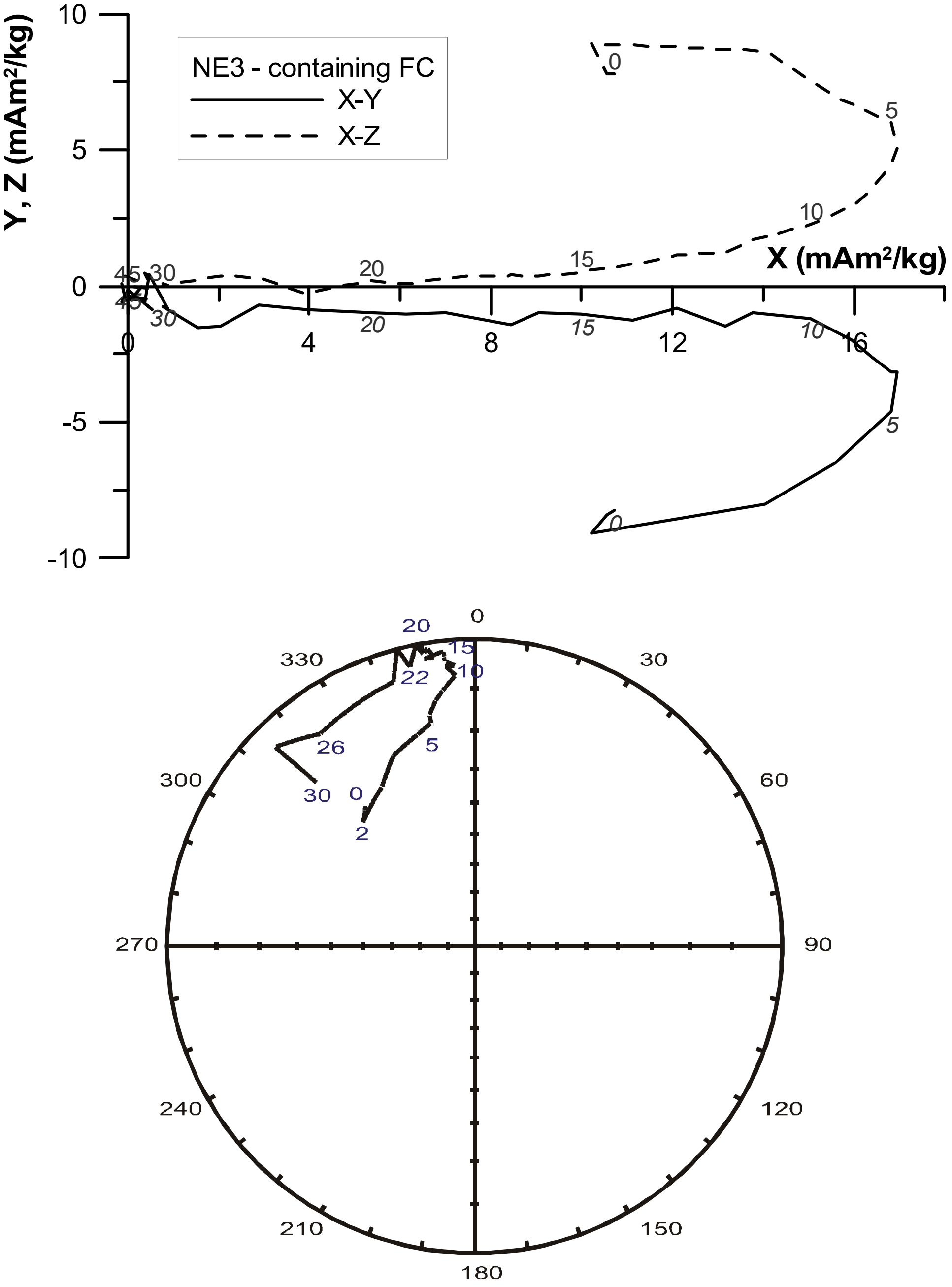

Fig. 9. Zijdervelt diagram and stereographic projection (equal area) of NE3 sample containing the fusion crust (non-oriented sample). The labels indicate AF demagnetization fields in mT. All steps in stereographic projection are of positive inclination except 22 mT step what is of negative inclination (indicated by italics).

7. IRM acquisition

As discussed above, the NRM resides in MD kamacite grains and thus is extremely susceptible to viscous decay, artificial IRM overprints and shock related remagnetizations (*Cisowski and Fuller*, 1978).

To test the NRM of Neuschwanstein interior samples for presence of magnetic overprint, the REM(AF) (*Kohout et al*., 2008) or REM' (*Gattacceca and Rochette*, 2004) method could not be reliably applied due to the fast decay of NRM during AF demagnetization (MDF is only 3 mT). Due to this reason an alternative approach was applied. The IRM acquisition curve was measured up to 1 T at room temperature (Fig. 10). The IRM saturates around 300 mT, which is consistent with the kamacite properties. The results indicate that laboratory fields between 3 and 4 mT are sufficient to produce IRM of similar intensity as the original NRM (Fig. 10).

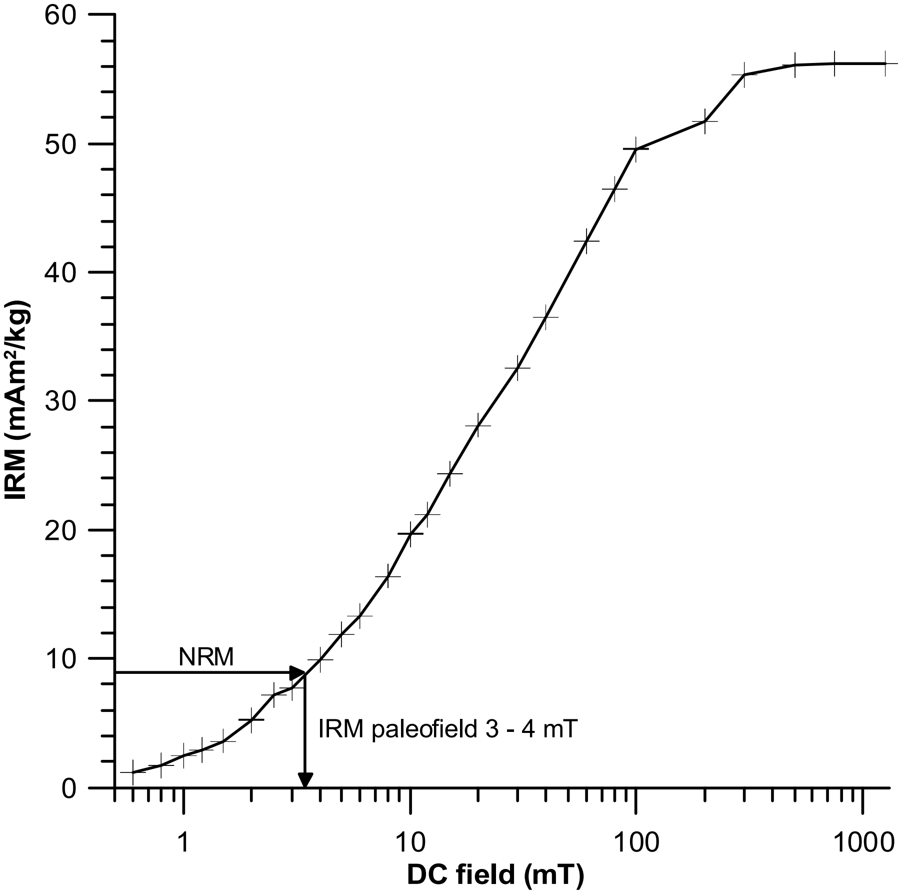

Fig. 10. IRM acquisition of the D3-3A interior up to 1.3 T. The magnetic fields between 3 and 4 mT are sufficient to produce the IRM of the similar intensity than NRM.

8. *Discussion about the origin of Neuschwanstein's interior NRM*

The Neuschwanstein meteorite has a long and interesting thermal and shock history. After accretion of the parent body, it was exposed to a high degree of thermal metamorphism (petrographic grade 6 corresponds to peak temperatures in the 750°C–950°C range, thus exceeding the Curie temperature of kamacite) and shocked to a S2 level (peak pressure 5–10 GPa, most likely associated with local reheating), which might have caused partial or complete overprint of any previous remanence.

As discussed above, the carrier of Neuschwanstein's remanence is MD kamacite. In general, MD grains are not reliable paleomagnetic recorders and are sensitive to viscous decay and overprints. Comparing our results to those of *Sugiura and Strangway* (1981 and 1983), on Abee EH4 meteorite, we did not observe any stable NRM component in Neuschwanstein interior samples. The NRM directions of neighboring Neuschwanstein samples are scattered, which may be explained by the presence of large MD grains with significant shape anisotropy resulting from their irregular shapes, partly controlling the remanent magnetization directions. *Sugiura and Strangway* (1983), identified through thermal treatment a stable NRM component most likely associated with the presence of cohenite (Fe_3C). We applied thermal demagnetization and the Thellier Thellier method on one of the Neuschwanstein interior samples. However, our Thellier Thellier results are of poor quality due to abundance of MD grains and chemical alterations (*Westphal*, 1986). Nevertheless, our AF demagnetization results of Neuschwanstein's NRM are similar to the AF demagnetization of Abee (*Sugiura and Strangway*, 1981), where they observed an extremely low stability of the NRM, due to presence of MD kamacite. Thus, it seems the abundance of MD kamacite and the absence of abundant cohenite, or other stable phases, is the reason why we were unable to isolate a stable NRM component in Neuschwanstein interior samples.

An artificial origin of Neuschwanstein's interior NRM is one possibility we must take into account. Based on the correspondence with Dieter Heinlein, meteorite curator, it is clear that all recovered Neuschwanstein meteorite bodies were tested by their finders with a strong hand magnet for the presence of iron what produced a strong IRM overprint. To evaluate the effect of the artificial magnet contamination, we used a similar hand magnet and mapped its magnetic field with a laboratory magnetometer. Fields higher that 2 mT were found up to 5 cm from the magnet's edge, which is half of the diameter of the Neuschwanstein I meteorite body (~10 cm, Fig. 1). Thus, a significant portion of the Neuschwanstein I meteorite body may have been remagnetized due to the exposure to such a magnet. To prove this, we experimentally exposed one of the previously demagnetized interior samples (D3-4A) to a magnetic field of the hand magnet at a 5 cm distance. This resulted in a strong IRM overprint. The stability of this artificially produced IRM against alternating field (the 2G SRM was used for the AFD and remanence measurements) is similar to the original NRM (Fig. 11). Due to this similarity, the NRM of the Neuschwanstein meteorite interior is most likely of an artificial origin produced during the meteorite handling, which is also supported by high REM values typical for a strong IRM.

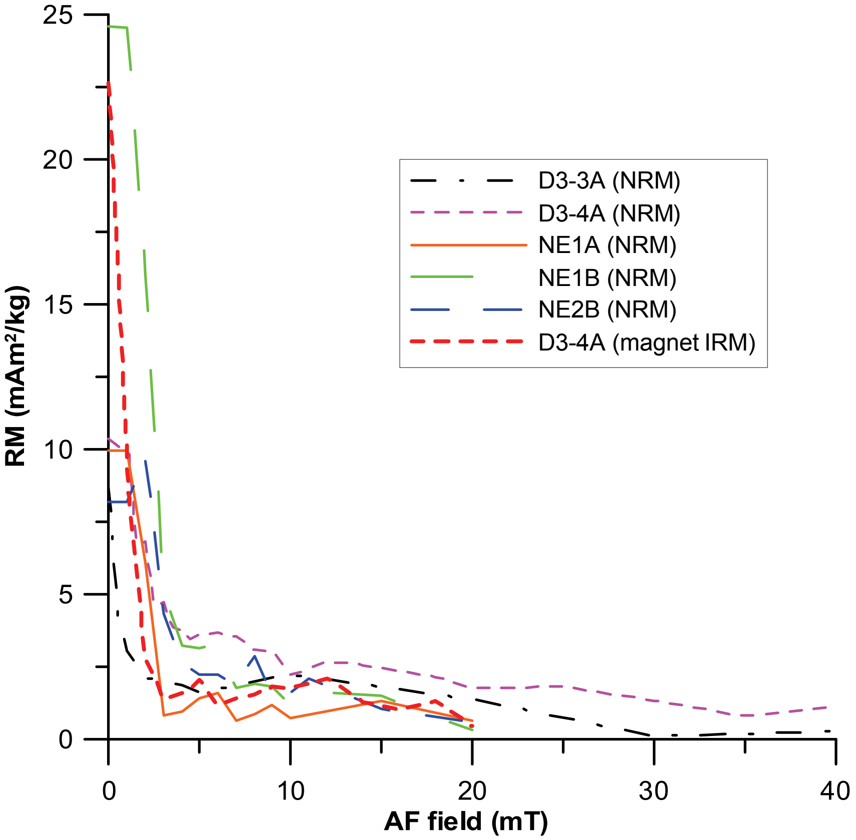

Fig. 11. Comparison of the stability of artificially produced (by exposure to hand-magnet) IRM (bold, red, dashed line) of D3-4A sample to the NRM of Neuschwanstein samples (excluding fusion crust samples). The magnitude and stability of those remanent magnetizations (RM) is similar. Thus, it is most likely that the NRM was generated by a similar hand magnet during meteorite handling and thus is of artificial origin.

The possibility of such a contamination is likely in many chondritic meteorites with MD kamacite grains (*Westphal*, 1999). Earlier paleointensity investigations published without contamination tests should be approached with caution. One of the most promising paleointensity work on primitive meteorite material is by *Weiss et al.* (2008) on Angrite achondrites (basaltic primitive meteorites with no shock features present). The results suggest paleofields on the surface of Angrite parent body to be ~ 10 μT. However, the results contain uncertainty due to the methodology based on NRM/IRM ratios, where it was not shown whether IRM used reached or approached saturation, and NRM/ARM (Anhysteretic Remanent Magnetization) ratios where the paleofield calibration is strongly material dependent and thus of limited reliability.

9. Conclusions

As tested through various methods, the rock-magnetic properties of Neuschwanstein at room temperature are dominated by the presence of 6 wt% Ni kamacite in MD form. MD kamacite is also a carrier of the remanent magnetization. Additionally, there is evidence in the thermomagnetic data that a minor amount of low-

Ni kamacite might be present. However, this was not observed in the SEM-EDS observations.

The fusion crust NRM of Neuschwanstein meteorite contains a component stable up to 30 mT AF field. This component likely originates from meteorite heating during meteorite atmospheric entry. Contrastingly, the NRM of the Neuschwanstein meteorite interior is of a soft nature. Due to a high susceptibility of the MD kamacite to the IRM acquisition, the Neuschwanstein I meteorite body has been most likely completely remagnetized during meteorite handling, and thus does not carry an extraterrestrial magnetic signal. This is further supported by relatively high REM values.

Fig. 6, where the NRM of Neuschwanstein is compared to other meteorites, demonstrates that the NRM of Neuschwanstein is similar to other enstatite chondrites. It is possible that also other enstatite chondrites have been contaminated to a similar extent due to testing for presence of iron using a strong hand-magnet. Thus, extraterrestrial samples should be tested for artificial magnetic contamination prior any paleomagnetic or paleointensity studies.

The habit of testing for a presence of iron using a strong hand-magnet is quite common among meteorite collectors. Such an approach results in significant IRM overprints and limits the future use of the meteorite for paleomagnetic or paleointensity studies. The simple measurement of magnetic susceptibility provides information about the iron presence and does not harm the remanent magnetization of the meteorites.

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