Evidence of Matuyama-Brunhes transition in the cave sediment in Central Europe

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Abstract

In this study, we offer a significant improvement over previous results that identified the Matuyama-Brunhes magnetic reversal in cave sediments in Central Europe, Czech Republic. We collected discrete samples from the sedimentary profile in the Za Hajovnou cave located in the eastern part of the Czech Republic. Novel use of characteristic remanent magnetization (ChRM) directions and VGP (Virtual Geomagnetic Pole) path of the data revealed the Matuyama-Brunhes transition boundary within 5.7 cm located in the upper part of the sampled sedimentary section of the cave. This result showed a new, more detailed behavior of the polarity transition from the central European location. The migration of the paleopole between east of Africa and west of North America is a significant marker for the central European paleomagnetic record in terms of global magnetic data. The precursor of the reversal occurred 4±0.2 kyr before the transition. The rock magnetism measurements showed that the magnetic carrier of most of the samples is maghemite. Also, we estimated the sedimentation rate of the studied section (~35 cm) in the cave as 0.7±0.2 cm/kyr.

Keywords: Paleomagnetism; Matuyama-Brunhes; magnetic reversal; cave; sediments

1. Introduction

Matuyama-Brunhes magnetic reversal occurred approximately 773 kyr ago (Cohen and Gibbard, 2019) as several recent studies have shown (Channell et al., 2010 (773 ± 0.4 ka); Suganuma et al., 2015 (770.2 ± 7.3 ka); Singer et al., 2019 (773 ± 2 ka); Valet et al., 2019 (772.4 ± 6.6 ka); Haneda et al., 2020 (772.9 ± 5.4 ka)). Published studies (Channel et al., 2010; Sagnotti et al., 2010, 2014; Suganuma et al., 2010; Jin and Liu, 2011; Giaccio et al., 2013; Kitaba et al., 2013; Pares et al., 2013; Valet et al., 2014; Liu et al., 2016; Okada et al., 2017; Bella et al., 2019) reported that this event is well recorded by sediments that had sufficient sedimentation rate and could be analyzed, in detail, by paleomagnetism.

Sediments acquire remanent magnetization during their deposition. The alignment of magnetic moments of the grains occurs in the direction of the Earth's magnetic field, and acquisition of primary magnetization due to this sedimentation process is called depositional or detrital remanent magnetization (DRM) (Gubbins and Herrero, 2017). Remanent magnetization protected by potential energy barriers can last over geologic time scales. Nevertheless, due to thermal and/or chemical processes such as reheating, oxidation, and iron hydroxide formation during time, secondary magnetizations can be acquired by crossing potential energy barriers or the generation of chemical remanences. The new secondary magnetization has an orientation in the direction of the Earth's field at the time of alteration rather than the time of original deposition. Then rocks can acquire a viscous remanent magnetization (VRM) a long time after their formation due to exposure to the geomagnetic field. VRM contributes to noise in paleomagnetic data (Butler, 1992; Lanza and Meloni, 2006).

Lock-in-depth affects the nature of the paleomagnetic recording process in sediments. It is defined as the depth at which the remanent magnetization is stabilized. Lithology, grain-size distribution of the sediment matrix, sedimentation rate, and bioturbation influence the position of the lock-in-depth in the sediments (Bleil and von Dobeneck, 1999; Sagnotti et al., 2005).

When assuming the steady sedimentation rate, the result of lock-in-depth is a delay of magnetization that corresponds to the time required to accumulate a sediment layer equal to the lock-in-depth. For example, if the sediment has an accumulation speed of 1 mm/kyr and lock-in-depth is 10 mm, the magnetization age is 10 kyr younger than the sediment itself (Sagnotti et al., 2005).

Paleomagnetic analysis of magnetic reversals from cave sediments was carried out in different locations around the world such as in Western Europe (Parés et al., 2018), South Africa (Nami et al., 2016), South America (Jaqueto et al., 2016), North America (Stock et al., 2005), Southern Europe (Pruner et al., 2010), and Eastern Asia (Morinaga et al., 1992). Kadlec et al. (2005, 2014) already reported that the Central European cave (local name "Za Hajovnou") in the Moravia region of the Czech Republic records the Matuyama-Brunhes transition. The aim of the present study is to analyze the reversal using more detailed paleomagnetic methods and to identify the magnetic carrier of the cave sediment. Here, we obtained a new paleomagnetic dataset from three vertical sediment profiles in this cave. Contribution of the central European paleomagnetic record from the cave sediment will be valuable for investigating the characteristic behavior of the Earth's magnetic field during the Matuyama-Brunhes magnetic reversal. Because the sedimentation rate in the cave is not well understood, details of the timing of the transition are not yet known. It makes our estimation even more crucial in this study.

1.1 Geology of the Cave

The Za Hájovnou Cave (49° 40´ N, 16° 55´E) is a former sinkhole located in Javoricko Karst, Moravia Region of the Czech Republic (Lundberg et al., 2014; Musil, 2014) (Fig. 1). The Javoricko Karst is formed by light-grey-colored massive Devonian limestone that overlies Pre-Cambrian phyllite (Lundberg et al., 2014; Musil, 2014). Spranek and Javoricka are two rivers that flow through the karst. While the Za Hájovnou Cave is situated on the north-western bank of the Javoříčka river, on the southern slope of the Pani Hora hill (Lundberg et al., 2014; Žák et al., 2018), both Spranek and Javoricka watershed may have contributed to the sediment development in this cave (Fig. 1).

The Za Hajovnou cave is approximately a 500 m long system (Musil, 2005; Bábek et al., 2015). The cave was explored previously in a total length of ~200 m and currently consists of two main parallel corridors with a slightly different sedimentological record (Musil, 2014; Musil et al., 2014) (Fig. 2). The first corridor (local name is "Excavated Corridor" which used to be a sinkhole entrance) and the other corridor (local name is "Birthday Corridor") have a separate entrance, and are connected by the Connecting Passage Corridor (Fig. 2). Sediments from the Excavated Corridor continue to the Birthday Corridor and partially fill the Connecting Passage Corridor (Musil et al., 2014) (Fig. 2).

Upper sediments of the cave were dated by U/Th dating of flowstones from 118 ± 1 to 267 ± 3 ka, and the sediment spans the time of the Cromerian Interglacial Complex in north-western Europe, which begins with the interglacial period of the marine isotope stage (MIS 19; 773 ka; Cohen and Gibbard, 2019), and the Matuyama-Brunhes reversal (Kadlec et al., 2005, 2014; Musil, 2005, 2014; Musil et al., 2014; Lundberg et al., 2014; Bábek et al., 2015; Žák et al., 2018).

The Matuyama-Brunhes boundary (773 ka) was identified (by Kadlec et al., 2005, 2014) in the upper part of the backwater fine sediments, deposited from suspension (total thickness up to 4.3 m) in the flooded cave. These sediments underlay mostly non-fluvial deposits that entered the cave through a steep passage and fill the Connecting Passage Corridor (Kadlec et al., 2014; Lundberg et al., 2014; Musil et al., 2014).

Sedimentary sections studied by Kadlec et al. (2005, 2014) in the Excavated Corridor of the Za Hajovnou cave were composed of two parts. The first part, 0.8 m thick (Section No. 1, in Fig. 2), about 28 m from the cave entrance, was interpreted to contain the Matuyama-Brunhes transition from reversed to normal polarity by Kadlec et al. (2014). Section No. 2 (Fig. 2), ~3.3 m thick, underlays Section No. 1. Kadlec et al. (2014) indicated that this section had sediment with just reversed polarity except for the upper part of the sediment where the magnetization was difficult to interpret, because the sediments had weak magnetization for which the sensitivity of the Agico JR-5A spinner magnetometer was insufficient. This difficulty was the motivation for the present research. Here we collected new 44 oriented discrete sedimentary samples from the Excavated Corridor near the upper backwater sedimentary Section No. 1 (Fig. 2, 3).

2. Materials and Methods

2.1. Preparation of the Samples

We had prior indication where the reversed polarity is from Kadlec et al. (2014). Our sample collection took the larger part before the transition and the smaller part above the transition. We chose three sets of overlapping boxes (Fig. 3) to characterize the transition completely. The 35.1 cm of exposed sediment at the base of Section No. 1 was planed to a clean vertical face, and the samples for the paleomagnetism measurements were taken by pushing the plastic boxes (2x2x2 cm; 8cc) into the sediment (Fig. 3). We used a Brunton geological compass to measure the azimuth and tilt of the boxes. In addition, another 4 samples were collected for rock magnetism measurements (Fig. 3c), which corresponded with the paleomagnetic samples (13_0P, 7_7P, 17_2M, 22_0M). The upper part of the section, from 0 cm to ~12 cm (Fig. 3), called Bed No. 1 (Kadlec et al. 2014), is made up of fine backwater sediment of brown clayey silt with white angular clasts of weathered limestone and bone fragments (Bed No. 1) (Kadlec et al., 2014). The lower part of the section, from ~12 to ~35 cm, consisted of the brown silty clay without white clasts (Bed No. 2) (Kadlec et al., 2014). Although our "Section 2" is the same as "Profile 2" of Kadlec et al. (2005) and "Section 2" of Kadlec et al. (2014), our "Section

1" is not the same as "Profile 1" of Kadlec et al. (2005) but is the same as "Section 1" of Kadlec et al. (2014). The depths in the present study are not the same as those in Kadlec et al. (2014). We examined the sediment structure near the walls of the plastic sediment holder and observed that the process of pushing the box into the sediment caused deformation structures along the walls of the boxes. The structure was on the order of 0.05 mm thick. Providing the volume of the box is 8000 mm^3 (20x20x20 mm), and the volume of the structurally modified layers is 80 mm^3 (4x 0.05x20x20 mm), we have a volume that may be modified by the pushing as 1/100 fraction of the unmodified volume. Even if this moment would be organized in (e.g., perpendicular direction), it would only deflect the magnetic remanence by <5%.

2.2. Demagnetization Measurements

To clean the secondary magnetizations from the sedimentary samples, we applied a stepwise alternative field (AF) demagnetization method in the Pruhonice Paleomagnetism Laboratory of the Czech Academy of Sciences. This method was carried out using a 2G Enterprises Cryogenic Magnetometer on 44 samples divided into 3 different sequences. The first sequence of 17 samples (shown in the leftmost column of Fig. 3c) were demagnetized at 1 mT intervals from 0 to 49 mT and 10 mT intervals from 50 to 100 mT. The second sequence of 14 samples (shown in the middle column of Fig. 3c) were demagnetized at 2 mT intervals from 0 to 48 mT and 10 mT intervals from 50 to 100 mT. The third sequence of 13 samples (shown in the rightmost column of Fig. 3c) were demagnetized at 0.5 mT intervals from 0 to 39.5 mT and 10 mT intervals from 40 to 100 mT. Demagnetization data were interpreted with Remasoft software (Agico Company; Martin Chadima and Frantisek Hrouda).

ChRM directions and maximum angular deviation (MAD) values were determined from principal component analysis (PCA) (Kirschvink, 1980) on the Zijderveld diagram (Zijderveld, 1967). Virtual geomagnetic pole's (VGP's) latitudes and longitudes were calculated using

PMGSC software (Randy Enkin). Table 1 shows the data of alternative field demagnetization for each sample. Examples of AF demagnetization results for the Matuyama and Brunhes intervals (two examples each) are shown in Fig. 4. The rest of the samples are in the Supporting Information Tables S1 and Supporting Information Figs S2.

2.3. Rock Magnetism Measurements

To determine the magnetic minerals in the samples, High Temperature Magnetic Susceptibility measurements ((χ) mass normalized) were done up to 635 °C using an Agico Kappabridge MFK1-FA susceptibility meter. Isothermal remanent magnetization (IRM) acquisition was done at 25 mT intervals from 0 to 100 mT, 50 mT intervals from 100 to 400 mT, and 100 mT intervals from 400 to 1000 mT using a Magnetic Measurements MMPM10 pulse magnetizer. Stepwise AF demagnetization of IRM was done at 5 mT intervals from 0 to 40 mT and 10 mT intervals from 40 to 50 mT using an Agico LDA 5 AF demagnetizer. All the remanent magnetizations were measured using an Agico JR-6 spinner magnetometer after each step. The samples for the rock magnetism measurements were chosen according to the paleomagnetic data.

3. Results

3.1. Paleomagnetic Results

The samples were generally demagnetized up to 20 mT (for details, see Supporting Information Figs S2), which removed the VRM component causing a change in the direction of remanent magnetization. This soft VRM component has a mean D: 13.8° and I: 56.8° value, which is close to the present day's Earth's magnetic field direction for the Czech Republic (D: 4.4° and I: 66.8°) (see Supporting Information Figs S3). Some samples (01_8M, 04_2M, 17_2M, 17_9M, 22_0M) could not be demagnetized even to 100mT.

The intensity of the natural remanent magnetization (NRM) of the samples varies between 8.5e-3 and 34.1e-3 A/m. Median destructive field (MDF) values where samples lost half of their magnetization range between 5 and 8 mT. NRM intensity and MDF values of the samples are shown in Supporting Information Figs S3. MAD values for the Matuyama and Brunhes sections are between 0.3° and 5.4° (Fig. 5a). These values for the transition section are between 0.7° and 5.3°, which is relatively reliable for detecting the migration of the paleomagnetic vector from reversed to normal polarity (Fig. 5a). The trend of the MAD values in our data increases before and during the transition (shown with dashed lines in Fig. 5a-c) between 23.1 and 7.1 cm depth. This increase can also be seen in other studies (Muttoni et al., 2017 (Bulgaria, cave sediments, 1 cm/kyr sedimentation rate); Ge et al., 2021 (China, cave sediments, 0.2 cm/kyr sedimentation rate); Sagnotti et al., 2014 (Italy, lacustrine sediments, 20 cm/kyr sedimentation rate); Okada et al., 2017 (Japan, marine sediments, 61 cm/kyr sedimentation rate)) while these values are higher than those in our study. (Fig. 5b,c).

Fig. 6 shows the data in comparison with published studies that consisted of cave sediments (brownish silty clay) (Bella et al., 2019 (Slovakia, 0.6 cm/kyr sedimentation rate); Ge et al., 2021 (China, 0.2 cm/kyr sedimentation rate); Shaar et al., 2021 (South Africa, 0.13 cm/kyr sedimentation rate)), marine sediments (Liu et al., 2016 (China, 9 cm/kyr sedimentation rate); Okada et al., 2017 (Japan, 61 cm/kyr sedimentation rate); Valet et al., 2014 (Indian Ocean, 5cm/kyr sedimentation rate)), and other types of sediments (Giaccio et al., 2013 (Italy, lacustrine sediments, 26 cm/kyr sedimentation rate); Sagnotti et al., 2014 (Italy, lacustrine sediments, 20 cm/kyr sedimentation rate); Jin and Liu, 2011 (China, loess sediments, 100 cm/kyr sedimentation rate)). Depth of the datasets was normalized considering the transition zone and differences of sedimentation rate for each study and is not given in Fig. 5, 6. Our paleomagnetic data showed inclination values changing by approximately 90° (shown with empty and full arrows in Fig. 6a-d) from 12.8 to 7.1 cm depth (Fig. 6a). This revealed the transition nature of the Matuyama-Brunhes magnetic reversal in the Za Hajovnou cave. The change can be seen in other datasets from negative to positive inclination (Fig. 6b-d). Between 12.8 and 11.8 cm depth, inclination gets a positive value (shown with circle arrows in Fig. 6a-d) just before the transition in our data. It is also observed in other studies, even though the change is larger in other types of sediments (Fig. 6d) than cave and marine sediments (Fig. 6b,c). Below this depth, the Matuyama section has inclination fluctuations (shown with dashed lines in Fig. 6a-d) between -6.3° and -89.3°. These fluctuations in other datasets (Fig. 6b-d) have less frequency in other types of sediments (Fig. 6d). Above the transition, inclination angle changes between 25.2° and 65.9° for the Brunhes section in our data (Fig. 6a).

Our declination data show more frequent fluctuations for the whole sediment section (Fig. 6e). The change between 3.0 and 9.2 cm depth (shown with empty and full arrows in Fig. 6e-h) can be seen in other studies with a larger difference. Below the transition, the frequent fluctuations (shown with dashed lines in Fig. 6e-h) with a large declination change (shown with square arrows in Fig. 6e-h) between 25.3 and 23.1 cm depth are observed in other studies. These fluctuations in cave sediments (Fig. 6b) are more frequent than marine and other types of sediments (Fig. 6c,d).

Despite the fluctuations, the intensity values of ChRM, which can depend on the concentration variation of magnetic carriers of every individual sample, were decreasing for the Matuyama section from the bottom to the transition between 35.1 and ~15 cm depth in our data (Fig. 6i). After the transition from reversed to normal polarity, these values increased in the Brunhes section between 7.1 and 0 cm depth (Fig. 6i). Even though there are some differences in absolute values due to the changes of the paleomagnetic data depending on the location and sediment type, comparisons of this dataset with other studies showed that fluctuations and frequency of fluctuations in our data are consistent with other datasets and serves as a supporting argument for the Matuyama-Brunhes magnetic reversal in the Za Hajovnou cave.

3.2. VGP's and Pole Migration

VGP shows the position of the geomagnetic paleopole (Lanza and Meloni, 2006). VGP's latitudes from this dataset show fluctuations ranging from -64° to -1° before the transition in the Matuyama section, which are similar to the data from Haneda et al. (2020) (Japan, marine sediments, 89 cm/kyr sedimentation rate) having fluctuations from -85° to -32° (Fig. 7a, b). These values indicate a 90° change between 7.1 and 12.8 cm depth (5.7 cm thickness) during the transition due to pole migration (Fig. 7a). 75° change in VGP values at 11.8 cm depth (Fig. 7a) shows the precursor of the reversal according to Valet et al. (2012) (Fig. 7c). In addition, we plotted the VGP path using VGP latitudes and longitudes based on ChRM directions of our data (Fig. 8). VGP locations for the Matuyama section are in the southern hemisphere (Fig. 8). During the transition from reversed to normal polarity, the magnetic pole fluctuates east of Africa in the southern hemisphere and then migrates to the west of North America in the northern hemisphere (Fig 8a). The same occurrence of this migration of the paleopole compares well with the M/B transition section from Okada et al. (2017) recorded in marine sediments near Japan (Fig. 8b). After the geomagnetic transition, paleopoles fluctuate around the geographic north pole (Fig. 8a).

3.3. Rock Magnetism Results

According to the High Temperature Magnetic Susceptibility measurements, the transition of maghemite to magnetite can be seen with an increase in susceptibility values at approximately 250-350 °C (Fig. 9). The samples have Curie temperatures between 530 and 550 °C, which may be a sign of titanium in the minerals and a new sulphite phase created from decomposing the maghemite and incorporation of the sulfur from the surrounding clay. The increase of susceptibility values in the cooling curves corresponds to the percentage of maghemite decrease after the heating (Fig. 9a, c, d). Two different drops in susceptibility values at 410 °C and 530 °C in Fig. 9c show the existence of maghemite and magnetite together in the sample. IRM results show that samples in Fig. 10a-d were saturated at 400-500 mT and demagnetized at 50-60 mT, indicating low coercivity. Samples in Fig. 10e-h are those that could not be AF demagnetized up to 100 mT in section 2.2. These samples did not reach saturation up to 1000 mT and were not demagnetized up to 100 mT, indicating high coercivity (e.g., hematite). Two of them (17_2M and 22_0M) have a Curie temperature of about 540° (Fig. 9c,d) that shows the presence of low and high coercivity minerals together in these samples.

3.4. Sedimentation Rate Estimation

To estimate the sedimentation rate of the studied part (~35 cm) of Section No. 1, we compared the thickness of the transition section of our study (cm) (5.7 cm section from 7.1 cm to 12.8 cm depth) with the duration of the transition of published studies (kyr) from European cave sediments (Pares et al., 2013, Spain, brownish silty clay; Muttoni et al., 2017, Bulgaria, brownish clayey sand; Bella et al., 2019, Slovakia, brownish silty clay; Zupan Hajna et al., 2021, Slovenia, brownish silty clay and speleothem; Gibert et al., 2016, Spain, reddish clay, and speleothem). In equation 1.1, *tso* is the transition section thickness from our study (in cm), *tsd* is the transition duration of the published study (in kyr), *and sro* is the sedimentation rate of our study (in cm/kyr).

Equation;

$$tso\ (cm)\ /\ tsd\ (kyr)\ =\ sro\ (cm) \qquad (1.1)$$

Then, the sedimentation rate ranges between 0.5 and 1.1 cm/kyr. Thus, the average sedimentation rate is 0.7±0.2 cm/kyr. Sedimentation rate estimates compared with other studies are shown in Table 2.

4. Discussion

Our data indicate that the Matuyama-Brunhes transition boundary constitutes 5.7 cm between 7.1 and 12.8 cm depth of the sampled sedimentary section of the Za Hajovnou cave. The magnetic reversal is characterized and represented by frequent fluctuations of inclination angle (Fig. 6a) and VGP latitude (Fig. 7a). We think that fluctuations in declination data indicate the instability in the Earth's magnetic field and remanent magnetization. On the other hand, similarities seen in the previous studies (Fig. 6) show the reliability of the data.

Even though some samples could not be demagnetized up to 100 mT, the data show that minerals with low coercivity are responsible for the magnetization of the cave sediment in our study. This is supported with rock magnetism results that indicate the behavior of maghemite for most of the samples.

The migration of the magnetic North pole from the east of Africa to the west of North America is a key point for the behavior of the magnetic field during the transition. Although the data in this study and Okada et al. (2017) belong to geographically different locations and sediment types, the similarity during polar migration (Fig. 8) shows that the reversal was a dipole transition, and the non-dipole field component was less significant (Oda et al., 2000; Mochizuki et al., 2011; Simon et al., 2019).

Note that most of the sediment section contains samples from the polarity transition. The data shows that the magnetic field was already unstable for our oldest sample in reversed polarity. This observation goes well with Haneda et al. (2020), where they show the magnetic pole was unstable a long time before the reversal boundary (Fig. 7b), and the magnetic field started to fluctuate almost 20 kyr before the actual transition (Fig. 11). We think that our data illustrate the same instability, and this is why no paleomagnetic samples have VGP latitudes that deviate less than 25° from the reversed position. We provide a more detailed explanation of the reversed

VGP behavior in our data showing reversed polarity unrest well before the actual magnetic reversal.

4.1. Precursor Event

Valet et al. (2012) showed a 90° change in VGP during reversed polarity before the transition (Fig. 7c). According to this model, the precursor prior to the magnetic reversal has a 2.5 kyr duration, and it occurs ~3.5 kyr before the actual transition (mid-point) which has a 1 kyr duration (Fig. 7c). The model showed another 90° change as the rebound with 2.5 kyr duration after the transition (Fig. 7c). Sagnotti et al. (2014) reported Valet et al. (2012)'s precursor with 140° change in VGP, 0.7 kyr duration, and 5 kyr prior to the actual transition. In our VGP data (Fig. 7a), ~75° change between 13.6 and 11.8 cm depth shows 2.6±0.2 kyr duration (according to 0.7±0.2 cm/kyr average sedimentation rate estimation) that can be interpreted as the precursor of the Matuyama-Brunhes magnetic reversal. The pick point of the precursor (11.8 cm depth) is 4±0.2 kyr before the actual transition (9.0 cm depth). The actual transition duration is 0.6±0.2 kyr between 9.2 and 8.8 cm. These values are consistent with Valet et al. (2012)'s model and show the unique behavior of the Earth's magnetic field during the reversal time. The rebound after the transition in the model is not seen in our study since VGP change between 7.1 and 3.2 cm is not enough to interpret it as the rebound.

4.2. Sediment Deposition and Sedimentation Rate

The M/B event has occurred during the interglacial period (MIS 19) following the glacial period (MIS 20) (Cohen and Gibbard, 2019). In the case of the cave sediment, we see coarser grains deeper (below 12 cm depth; Bed No. 2 in Fig. 3; Matuyama section) and finer grains at a shallower depth. Since the cave sedimentation was taking place at the time of glaciation, the cave itself was not frozen solid. This means that seasonal variation was inducing thaw-freeze cycle that generally generates physical weathering and source of coarser sediment. This phenomenon is observed in our cave. The change from glacial to interglacial is supported by finer grain size sediment due to the smaller influence of the thaw-freeze cycle. Therefore, our observations support frozen surface and later warming with smaller sediment availability for sedimentation, supporting the transition from glacial to interglacial period.

According to Lundberg et al. (2014), the cave was filled with water during the sedimentation, which was continuously active without any significant color change or hiatus with the exception of a slight change towards finer grains. This provides the continuous magnetic record of the reversal in the cave sediment and allows the sediment to acquire and keep the primary magnetization without the possibility of secondary mineralization. Furthermore, there are no obvious signs of breaks in deposition (e.g., lithological boundaries, desiccation cracks) in the studied sediment section, other than a slight change in grain size.

Our sedimentation rate estimation (0.7±0.2 cm/kyr) seems to be similar to the sediments from other European cave studies (Table 2). While the duration of the M/B transition was reported to last between 4 and 13 kyr (Suganuma et al., 2010; Valet et al., 2014; Okada et al., 2017), the average sedimentation rate of 0.7±0.2 cm/kyr in this study suggests a transition duration of 8.1±0.2 kyr (7.1-12.8 cm transition section) and thus supports the reliability of our sedimentation rate and paleomagnetic record estimates. King and Channell (1991) suggested that large "lock-in" depths are associated with interparticle rigidity and strength, characteristic of clayey low accumulation rate sediments (<1 cm/kyr), which results in delays of magnetic acquisition. This shows that magnetic polarity reversal could have a large (25 kyr) apparent age offset between sediments with high and very low accumulation rates (King and Channell, 1991).

5. Conclusions

We compared our paleomagnetic data with the published magnetic reversal record, used the detailed magnetic characteristic of the cave sediment, and inferred the specific magnetic reversal (Matuyama-Brunhes). This is possible due to the nature of the magnetic reversal. Note that the paleopole was residing east of Africa and then quickly reappeared west of North America. We consider this an important marker signature for dating the central European paleomagnetic record from this time period.

The precursor event in our data is a significant anomaly to identify the behavior of the Matuyama-Brunhes magnetic reversal. Additionally, we were able to estimate the accumulation rate of the studied section (~35 cm) in the Za Hajovnou cave.

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Author contributions

HU and GK designed research and wrote the paper, JK contributed to the fieldwork, gave detailed information about the cave sediment, and commented significantly.

Data Availability Statement

All data are incorporated into the article and its online supplementary material.

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List of Figure/Table Captions

Fig. 1. Location of the study area in (a) Central Europe, (b) in the Czech Republic. Map in (c) shows regional detail of the Za Hajovnou cave placement (modified after Lundberg et al., 2014; Musil, 2014).

Fig. 2. Map of the Za Hajovnou cave (modified after Kadlec et al., 2014; Lundberg et al., 2014; Musil, 2014) (m a.s.l.: meter above sea level).

Fig. 3. The Za Hajovnou cave sediments. (a) Age diagram of the Za Hajovnou cave, (b) sampled sedimentary Section No. 1, and (c) discrete samples for the paleomagnetism measurements and the rock magnetism samples (numbers show the sample name) (orange dashed lines show the boundary between Bed No. 1 and 2).

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Fig. 5. MAD changes during the Matuyama-Brunhes magnetic reversal (a) from this data, (b,c) from published studies in cave and other types of sediments, respectively. Note: MAD values

are not available for two of the studies on cave sediments (Bella et al., 2019; Shaar et al., 2021) presented in Fig. 6.

Fig. 6. Comparisons of inclination and declination data with previous studies. Data shows inclination (a) from this study, (b-d) from published studies in cave, marine, and other types of sediments, respectively. Declination data is from (e) this study and (f-h) published studies in cave, marine, and other types of sediments. (i) shows intensity of ChRM of the samples from this study. Note: declination data from Giaccio et al. (2013) and Liu et al. (2016) are not available. Also, declination and inclination data are not available for one of the studies on cave sediments (Muttoni et al., 2017) presented in Fig. 5b.

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Fig. 11. NRM/ARM data (relative paleointensity (RPI)) from Haneda et al. (2020). Dashed lines show the M/B reversal.

Table 1. AF demagnetization, VGP data, and the Matuyama-Brunhes magnetic reversal scale for this study. Minus (-) values for VGP latitudes and longitudes indicate the southern and western hemispheres. MAD: maximum angular deviation, φ_p: VGP latitude, λ_p: VGP longitude.

Table 2. Sedimentation rate estimations for Za Hajovnou from the previous studies.

Supporting Information

Supplementary data are available online.

Supporting Information Tables S1: Demagnetization data for the samples.

Supporting Information Figures S2: Zijderveld diagrams, Wulf stereonets, and demagnetization curves of the rest of the samples for the AF demagnetization method.

Supporting Information Figures S3: NRM intensity, MDF values, and VRM data