Historical climatic record from flood sediments deposited in the interior of Spirálka Cave, Czech republic

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Abstract

Magnetic susceptibility (χ) was measured on more than four hundred samples collected from a 5 m high section of fine grained sediments deposited during flood events in the interior of Spirálka Cave. Spirálka Cave is located in the northeastern portion of the Moravian Karst, Czech Republic. In the upper 1.5 m of this profile, mineral magnetic (χFe, ARM/SIRM, S-ratio, χ(T)) and other non-magnetic measurements heavy mineral concentration, loss on ignition and particle grain size) indicate that χ variations are controlled by the concentration of magnetite and by magnetic grain size, i.e. increased magnetic susceptibility results from increased concentration of coarse grained magnetite. A positive correlation with Ti and Zr concentrations in this part of the profile with our magnetic susceptibility record is a detrital signal responding to changing environmental conditions in the catchment area. Furthermore, a comparison of our susceptibility record to the record of winter temperature anomalies constructed from both instrumental and historical records collected at the Klementinum Observatory in Prague shows a remarkable correlation. The most probable explanation of these correlations is that during years with warmer winters (positive winter temperature anomalies) and less snow cover the floods were less intensive but probably had access to larger tracts of cultivated land as agriculture tended to expand during these warmer periods. Cultivation of the land provided flood waters with greater access to coarser grained magnetite-like materials exposed by tilling of soils. Lower in the profile, interpreting the environmental significance of magnetic susceptibility variations is more complex as remobilization of iron has occurred. Nevertheless the magnetic susceptibility record when coupled with non-magnetic measurements can be shown to correlate to known environmental conditions present in Central Europe during the deposition of the lower portion of the profile.

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1. Introduction

1.1. Cave sediments and paleoenvironmental reconstructions

Cave sediments can be divided into entrance facies and interior facies. Entrance facies sediments either
form directly in the cave (e.g. roof collapse) or are transported into the cave from the Earth’s surface (wind, mass wasting, fluvial processes). The cave entrance acts as a trap in which the sediments are well protected from erosion. The entrance facies provides a wealth of material suitable for paleoclimatic/paleoenvironmental interpretation including its fossil and archeological artifacts (e.g. Sutcliffe, 1985; Horáček and Ložek, 1988; Valoch, 1988; Campy and Chaline, 1993; Goodfriend and Mitterer, 1993), clastic detritus (Kukla and Ložek, 1958; Trudgill, 1985; Campy et al., 1992; Farrand, 2001) and paleosols (e.g. Wattez et al., 1989; Courty et al., 1991; Maggi et al., 1991). Interior facies cave sediments found deeper in the cave are genetically divided into chemogenic and clastic. The latter, which typically range from clays to gravel, are transported into the cave interior by fluvial processes while chemogenic sediments, i.e. speleothems, form as precipitates from drip-water. Chemogenic and clastic sediments can be found “sandwiched” between each other. This alteration is often climatically controlled; clastic material being deposited during periods of increased availability of sediments during cold periods and chemogenic sediments typically forming during periods of climatic amelioration (Lauritzen and Lundberg, 1999). Many researchers have attempted to create climatic reconstructions from interior facies cave sediments. These attempts were based principally on oxygen isotope records obtained from datable stalagmites and flowstones (e.g. Atkinson et al., 1986; Schwarcz, 1989; Lauritzen, 1990; Kashiwaya et al., 1991; Gascoyne, 1992; Sturchio et al., 1994; Lauritzen, 1995).

1.2. Environmental magnetism and its application to the cave environment

Environmental magnetism is the study of environmental (including paleoenvironmental) processes based on measurement of magnetic properties of the studied materials. Iron-containing minerals are extremely sensitive to environmental processes occurring on Earth’s surface which modify their phase, concentration, and grain size. Laboratory measurements of the magnetic signature of sediment samples allow rapid characterization of ferrimagnetic minerals and subsequent determination of environmental processes operating on the Earth’s surface. Excellent reviews illustrating the wide range of environmental magnetic applications used to solve paleoclimatic/environmental problems can be found in e.g. Thompson and Oldfield (1986), Maher and Thompson (1999) and Evans and Heller (2003).

Environmental magnetic techniques which have been successfully used for climatic reconstruction not only from lake sediments but also from loess deposits and deep sea sediments, have been scarcely applied in the cave environment. Only Ellwood et al. (1996) and Šroubek et al. (1998, 2001) attempted climatic reconstructions from mineral magnetic properties of clastic sediments deposited in caves. Ellwood and co-authors produced a paleoclimatic record for the Mediterranean region spanning the time interval between 9000 and 3500 years B.P. using magnetic susceptibility highs as indicators of climatic improvement and susceptibility lows suggesting deterioration. Šroubek et al. (2001) used a similar approach for their climatic reconstruction obtained from the sediments of Kůlna Cave, Czech Republic, spanning the entire Last Glacial Stage. Similar to Ellwood et al., these authors measured magnetic susceptibility throughout several profiles in fine-grained clastic sediments found in the cave entrance. Variations in the magnetic susceptibility record were explained by growth of extremely fine-grained magnetite and/or maghemite formed by pedogenic processes during warm and humid climatic periods and redeposition into the cave.

1.3. Importance of paleoenvironmental studies

Unforced natural variability of the climate system is very important on multi decadal and century time scales. Knowing both the spatial and temporal variations of climate change over the past several centuries remains a key to assessing possible human impact on the post-industrial climate. A more confident estimate of this impact is possible, if a faithful empirical description of climate variability over several past centuries can be obtained (Grove, 1988; Kukla and Gavin, 1992; Oeschger, 1992; Rind and Overpeck, 1993). Because widespread climate data determined from instrumentation are available for only about one century we must use available climate proxy indicators combined with instrumental records to obtain an empirical description of large scale climate variability during past centuries. Currently, there is a lack of available data not only from oceans and remote parts of the world but also from areas with a long history of habitation and richness of climatic information from instrumental measurements and historical written records (Bradley, 1985).

To test the suitability of cave deposits to record a high resolution environmental magnetic signal we chose to study the sediments of Spiráľka Cave. Spiráľka Cave is located in the eastern part of the Czech Republic; an area where there are only few suitable sedimentary
environments from which paleoclimatic reconstructions are possible. At our sampling locality in the cave, the deposits are significantly thick, show only one depositional hiatus, no obvious erosional events and contain material suitable for radiocarbon dating. The deposition at the location is currently ongoing and thus the mineral magnetic environmental proxy record can be calibrated by comparison with instrumental data. The character of

Fig. 1. Location of the Moravian Karst and superimposed topographical and geological plan showing the catchment of the Bílá Voda River which supplies sediments to the Spirálka Cave. Crosses indicate position of samples collected in the catchment area.
recent flood deposition can also be directly assessed by
in-situ observations. Finally, the catchment of the Bílá
Voda River providing sediments to the cave is litho-
logically uniform and thus the changing character of
sediments should reflect climate variability and human
impact rather than a changing source region.

2. Description of the studied area

2.1. Description of the Spirálka Cave

Spirálka Cave is located in the northeastern segment
of the Moravian Karst (Fig. 1), which is a part of a larger
geomorphological complex of the Drahkaný Upland. The
entrance of the cave is situated 471 m a.s.l. approxi-
mately 1 km south of the Holštejn Village in the
Hradský žleb Valley. Spirálka Cave (Fig. 2) consists of a
series of entrance shafts totaling a depth of 40 m from
which it continues both northward and eastward. The
northern continuation is terminated by a sump that
connects Spirálka Cave with Piková Dama (Queen of
Spades) Cave. To the east a narrow passage named
Tunelová (Tunnel) Passage continues for 60 m where it
terminates in the Odtokový (Outflow) Sump. Spirálka
Cave continues for 500 m past the Odtokový Sump
where it ends in the Macošský Sump. Passages between
the Odtokový and Macošský Sumps are the riverbed of
the Bílá Voda (White Water) River. The overall length of
the cave is 1691 m.

2.2. Hydrology and topography of the studied area

Spirálka Cave System belongs hydrographically to
the Northern Part of the Moravian Karst, an area drained
by the Bílá Voda River (Fig. 1), which is a tributary to
the Punkva River. The Bílá Voda River flows 22.2 km
on the surface until it reaches the Holštejn half-blind
valley, where it sinks in the Nová Rasovna (Knacker’s
House) Cave (443 m a.s.l.) and continues underground
until it enters Spirálka Cave through Macošský Sump
and several other minor sumps. The altitude of Bílá
Voda in Spirálka Cave during normal-flow conditions is
approximately 400 m a.s.l. Throughout most of its lower
flow, between the villages of Rozstání and Holštejn, the
Bílá Voda Stream flows through a broad valley with
gentle slopes. The valley’s width ranges from 50 to
150 m and its depth is no larger than 60 m. The valley
floor, i.e. the floodplain of the stream, is covered by
meadows whereas the slopes are typically forested. The
undulating terrain of the upland in the vicinity of
Holštejn is forested, higher upstream cultivated fields
dominate. Fields also typically cover the gently sloping
landscape along the stream north of the village of
Rozstání, where the maximum elevation reaches 670 m.

2.3. Clastic sediments in the Spirálka Cave

Spirálka Cave is rich in clastic and chemogenic se-
diments most of which are recent, however older
(probably Eemian) deposits are also present (Vít,
1998). One of the more extensive sedimentary profiles
includes a 4 m thick gravel bed located in the vicinity of
the Macošský Sump. The upper part of this profile was
deposited between the years 1845–1955 A.D. Our
sampling site was located in the most impressive
sedimentary section found in the cave, situated at the
east end of the Tunelová Passage (Fig. 2) near the large
flowstone formation “Varhany” (Organ). Here, floodwaters

Fig. 2. Map of the Spirálka Cave showing the location of the sampled sedimentary profile.
have been depositing layers of fine grained sediments reaching a total thickness of 5 m. The studied profile (Fig. 3) consists of sandy silt with layers and lenses of sand with maximum thickness of 10 cm. In the lower part are two 50 cm thick layers of gray green organic rich clayey silt. The top of the bottom layer is coated with a 2–3 mm thick flowstone layer. The base of the profile consists of coarse sands and fine gravels. Isolated wood fragments can be found throughout the profile, the upper part has abundant charcoal fragments. Presently, floodwaters reach this profile only during exceptionally high surface runoff. However, in the past, the conditions might have been different, it is only in the last four decades that the cave has been known, speleologists have observed reactivation of certain passages and sumps. Vit (1998) suggests that in the historical past the Odtokový Sump was clogged and a permanent underground lake connected the Tunelová Passage with parts of the cave lying south of the entrance shaft and continuing further into the Piková Dáma Cave.

2.4. Ecological history of the Bílá Voda catchment

The catchment of the Bílá Voda River was originally densely forested by beach and fir until the arrival of settlers in the 14th century (Nožička, 1957). However, the first human impact was minimal. A 1694 Liechtenstein inventory describes the forest being in very good condition. By the beginning of early 18th century beech wood was intensively harvested for nearby smelters and by the year 1810 hardly any beech trees were left in the vicinity of Blansko (Materna, 1961). The human induced forest calamities of the 18th and 19th centuries were enhanced by forest fires and cyclones occasionally destroying up to 50% of all trees (Knies, 1902). By the end of the 19th century the need for charcoal diminished and wood was used for heating and building instead. The fast growing spruce became the most wanted wood species and was preferentially planted. By the beginning of the 20th century it became the dominant tree in the area of the Moravian Karst and this situation lasts till the present day.

3. Sampling and laboratory methods

3.1. Sampling of the cave sediments

Samples for the mineral magnetic investigation, grain size analysis, trace element geochemistry and organic matter analysis were collected from a profile near the flowstone formation “Varhany”. In the upper part of the section (0–180 cm), large plexi-glass boxes (15 cm × 45 cm × 12 cm) were cut into a smoothed face of the profile. Each box, resampled in the lab, yielded a total of 15 by 3 tightly spaced cube samples (8 cm³). We collected

Fig. 3. Mineral magnetic parameters measured throughout the sedimentary profile in Spirálka Cave — a) magnetic susceptibility, b) ferrimagnetic susceptibility, c) S-ratio (see text), d) ratio of anhysteretic remanent magnetization and saturation isothermal magnetization and e) saturation magnetization. Highlighted are the zones with anomalously low magnetic susceptibility (see text). Also shown is a sketch of the sampled profile showing position of the radiocarbon dated charcoal and wood samples.
5 boxes, placed vertically one above another, providing us with 225 samples from 75 horizons. Samples were taken from the interval 185–410 cm by pushing small sampling boxes (8 cm$^3$) directly into the smoothed face of the profile. In this fashion we collected a total of 180 samples from 90 horizons. Finally, the 28 bottom most samples from the depth interval 410–475 cm were collected from a manually drilled sedimentary core with a diameter of 2.7 cm.

3.2. Mineral magnetic measurements on the cave sediments

Mass specific magnetic susceptibility ($\chi$) on all samples was measured using a Kappabridge KLY-2 instrument. The remaining mineral magnetic measurements were determined on one sample for each horizon. Paramagnetic ($\chi_{\text{para}}$) and ferrimagnetic ($\chi_{\text{ferr}}$) susceptibilities were distinguished from hysteresis loops measured on Variable Field Translation Balance (VFTB). In order to calculate the S-ratio, saturation isothermal remanent magnetization was acquired at 1T (SIRM, IRM$_{1000}$ mT) and at 300 mT (IRM$_{300}$ mT) using a Sapphire Instruments SI-6 pulse magnetizer. Anhysteretic remanent magnetization (ARM), acquired using the Sapphire Instruments SI-4 AF demagnetizer (biasing field 0.05 mT, alternating field 1T) was used to calculate the magnetic grain size dependant ratio ARM/SIRM. All remanence parameters (IRMs and ARM) were measured on a Schonstedt SSM-2 spinner magnetometer. Saturation magnetization ($J_s$) and hysteresis parameters were measured on a EG&G PAR Vibrating Sample Magnetometer (VSM) (maximum field 1T). Frequency dependence of magnetic susceptibility ($\chi_{\text{fdependence}}$) was calculated using measurements taken on a Bartington Instruments MS-2 susceptibility meter at two different frequencies, 470 Hz and 4700 Hz. To complete our investigation of the magnetic phases present in the samples, saturation magnetization versus temperature experiments were performed on 30 representative samples from throughout the profile. A modified VFTB (50 mg specimens) was used to monitor the behavior of saturation magnetization from 20 °C to 700 °C and a Quantum Design Magnetic Properties Measurement System (MPMS) instrument was used on samples (100–200 mg specimens) subjected to low-temperature demagnetization (70 to 200 K). These measurements allowed us to determine the Curie temperature and stoichiometry of magnetic mineral phases present. Collinson (1983), O’Reilly (1984) or Dunlop and Ozdemir (1997) present detail descriptions of measuring procedures and significance of measured parameters discussed above.

3.3. Non-magnetic measurements on the cave sediments

To complement magnetic measurements and tie the mineral magnetic data to other paleoclimatic indicators we determined several other characteristics of the sediments in Spirálka Cave. Grain size distributions (0.7–700 μm) were determined on 150 mg sub-samples using a 20-channel Leeds and Northrup MICROTRAC II laser particle size analyzer. The amount of organic matter present in samples was characterized by loss on ignition (LOI). The concentration of trace elements, namely Zr, Ti and Fe, was measured on an XRF spectrophotometer EX310 from Jordan Valley AR, Inc.. Details of these methods and their significance can be found in Robertson et al. (2004) or Pansu and Gantheyron (2006).

Wood and charcoal fragments ranging in size from several milligrams to tens of grams were collected throughout the sedimentary profile in Spirálka Cave. A total of approximately 30 samples were collected from which we selected 9 specimens from 4 different depth horizons which were sent to Beta Analytic Laboratory, Florida for radiocarbon dating. Four samples had sufficient mass to be dated by the conventional method; the remaining five samples were analyzed using the accelerator mass spectrometry (AMS) technique.

3.4. Sampling and analysis of the surface sediments

Samples from the catchment of Bílá Voda Stream were gathered in order to compare their mineral magnetic properties with those of the cave deposits. A total of 91 hand samples were collected along a 20 km stretch of the stream, from the four sedimentary environments providing a potential source for the cave deposits. We obtained 46 samples of floodplain deposits, 9 samples of field topsoil, 16 samples of forest topsoil, and 20 samples of weathered bedrock. The coordinates of each sample were located using a GPS system; the locations are shown in Fig. 1. The hand samples were re-sampled in the laboratory into 8 cm$^3$ specimens, on which mass specific susceptibility and its frequency dependence were measured.

4. Laboratory results

4.1. Results from mineral magnetic measurements on Spirálka Cave sediments

4.1.1. Magnetic susceptibility results

The values of magnetic susceptibility ($\chi$) of the three samples collected from each horizon of the cave profile...
showed consistent values and on the average did not differ by more than 5 percent. Therefore, the magnetic susceptibility values shown in Fig. 3a represent an average susceptibility determined from three samples from the same horizon. The record of magnetic susceptibility (χ) shows a well-defined oscillatory pattern in the upper 1.5 m of the profile with the most notable oscillations occurring in the upper most 0.5 m. The values vary between 10 and 16 × 10⁻⁸ m³/kg in this depth interval. Lower in the section the χ record shows two prominent zones between 170–190 cm and 200–225 cm where χ values rapidly drop to between 6 and 8 × 10⁻⁸ m³/kg. Below 225 cm χ values decrease more or less linearly to a low value of 5 × 10⁻⁸ m³/kg at 390 cm with the exception of two zones (285–305 cm and 320–390 cm) where again there appears to be a rapid decrease in χ values. At 390 cm depth χ begins to rise steeply with several rapid oscillations that have magnitudes up to 6 × 10⁻⁸ m³/kg. The highest measured values of χ in the entire section are at its base and reach 20 × 10⁻⁸ m³/kg.

In the upper 320 cm of the profile, ferrimagnetic susceptibility (χ_ffe) values (Fig. 3b), in general, mimic the patterns seen in the total magnetic susceptibility record as paramagnetic susceptibility is rather constant (≈6 × 10⁻⁸ m³/kg) in these sediments. However, between 320 and 390 cm, the magnetic susceptibility signal of the sediments is almost entirely paramagnetic and therefore χ_ffe signal in these sediments is minor. Below 390 cm, the sediments again show a χ_ffe signal. In fact, two prominent peaks centered at 400 cm and 450 cm have magnitudes that are similar to the samples measured from upper portion of the section.

4.1.2. Other mineral magnetic results

The S-ratio (Fig. 3c) of the sediments in the upper 320 cm of the profile in Spiráľka Cave is fairly constant with values ranging between 0.8 and 0.85 with exceptions occurring at depth intervals between 170 and 190 cm, 200 and 225 cm, and 285 and 305 cm. Below the 320 cm depth, the S-ratio record drops to values between 0.6–0.65 with little variation downward.

The record of the magnetic grain size parameter ARM/SIRM (Fig. 3d) is fairly constant throughout the upper 350 cm of the profile. However, in the uppermost meter of the profile there are four distinct horizons where the ARM/SIRM values increase indicating a relative decrease in the magnetic grain size in these horizons. These zones of magnetic grain size decrease correlate with lows in the χ and χ_ffe records (Fig. 3a, b). On the other hand, rapid drops in χ and χ_ffe occurring in horizons between 170 and 390 cm, appear to correlate with grain size increase (decrease in ARM/SIRM values). Finally, in the lowermost portion values of ARM/SIRM decrease to the lowest values in the profile.

The saturation magnetization (J_s, Fig. 3e) of these sediments varies between 0 to 7 × 10⁻³ Am²/kg showing variations that are positively correlated to variations seen in both the χ and χ_ffe records.

Frequency dependence of magnetic susceptibility (not shown) is generally fairly low with values between 3–5%. In general, variations in frequency dependence of magnetic susceptibility down profile mimic the variations seen in the χ and χ_ffe records, i.e. where χ and χ_ffe decrease frequency dependence decreases and vice versa and the smallest values of frequency dependence occur at the same horizons where χ and χ_ffe are the smallest.

Lastly, several important observations can be made based on the data described above. Firstly, the data suggest that the susceptibility variations are caused by changes in the content of ferrimagnetic minerals as χ_ffe record correlates well with the record of saturation magnetization (J_s). However, the concentration variations are not the sole factor influencing the magnetic susceptibility changes. The values of S-ratio show several significant drops suggesting that the magnetic mineralogy is not uniform throughout the studied section. Similarly, the ARM/SIRM record shows good correlation with the χ record suggesting that the magnetic grain size also influences the χ record especially in the upper meter of the profile. In the upper meter, χ increase is mimicked by an increase in the average magnetic grain size and vice versa. Similarly, in the lower meter of the profile the overall increasing trend in χ is also followed by an increase in average magnetic grain size. However, in the four intervals between 170 and 390 cm, the rapid decrease in χ values appear correlated to a similar decrease in the ARM/SIRM values suggest the drops in χ are accompanied by an increase in the average magnetic grain size and not a decrease, but then again S-ratio values also suggest a change in mineralogy.

4.1.3. Results from additional mineral magnetic measurements

The mineral magnetic parameters described above yield only a qualitative information about the magnetic
properties of the cave sediments and cannot be independently interpreted since the measured parameters are a non-linear combination of the sediment’s magnetic properties. Further mineral magnetic measurements are necessary to distinguish the degree to which χ is influenced by changes in concentration of magnetic minerals, by grain size changes, and by variations in magnetic mineralogy.

Based on the measurements of the S-ratio the sediments can be divided into two groups. Samples with higher S-ratios between 0.80–0.85 have steep IRM acquisition curves (not shown) and saturate typically by 300 mT. These IRM acquisition curves are characteristic of minerals with low magnetic coercivity and are labeled “magnetite” type minerals. On the other hand, samples from horizons where the S-ratio values of the sediments show significant drops to 0.60–0.65 have IRM acquisition curves (not shown) which are less steep and which do not saturate by the maximum field of 900 mT. Such IRM acquisition curves are characteristic of minerals with higher magnetic coercivity, typically associated with “hematite” type minerals (Dunlop, 1972).

Measurements of saturation magnetization as a function of increasing temperature on the “magnetite” type samples (Fig. 4a) show a gradual decrease towards 580 °C. Above this temperature the saturation magnetization is virtually zero. The shape of the high temperature magnetization curve suggests that mostly multidomain magnetite and/or maghemite are present in the “magnetite” type samples. The presence of multidomain magnetite in these samples is also confirmed by the position of the Verwey transition (Özdemir et al., 1993) which appears as a rapid drop in remanent magnetization observed at low temperatures (Fig. 4b). Magnetite present in the Spirálka sediments is mostly non-stoichiometric, as suggested by the position of the Verwey transition around 115 K (Kletetschka and Banerjee, 1995). Measurement of hysteresis parameters show that most of the grains (Day plot, not shown, Day et al., 1977) fall in the pseudo single domain region which is in a good agreement with the results obtained from measurements of the inter-parametric ratio ARM/SIRM. The samples yield values of ARM/SIRM ratio around $50 \times 10^{-5}$ m/A, which according to experiments of Maher (1988) correspond to grain sizes around 0.1 μm. Finally, low values of the ARM/SIRM ratio as well as low values of the frequency dependence of $\chi_{rd}$ between 3–5% (e.g. Dearing et al., 1996) suggest that the content of superparamagnetic (SP) grains in the Spirálka Cave sediments is minimal.

Samples with a higher content of “hematite” type minerals show different mineral magnetic behavior. Thermomagnetic curves (Fig. 4a) show a gradual decrease towards 580 °C; however magnetization is still present above this temperature. This result suggests that hematite, with a Curie temperature of 680 °C, is also present in the samples.

Finally, the difference in mineralogy throughout the sedimentary section is well demonstrated by a plot of SIRM values against the S-ratio (Fig. 5) (Snowball, 1993). The trend from high SIRM and S-ratio values toward low values of both parameters is characteristic of the trend from magnetite dominated samples towards samples with decreasing magnetite content and increasing hematite content. In the four above discussed intervals (170–190, 200–225, 285–305 and 320–390 cm) the decreasing values of both SIRM and S-ratio are apparent. The above described mineral magnetic results together with the variable character of the $J_s$ record suggest that in these intervals the magnetic grain size decreases and that
this decrease is accompanied by mineralogical changes, in particular a drop in the magnetite content and a relative increase in the hematite content.

4.2. Results from non-magnetic measurements on Spirálka Cave sediments

4.2.1. Sediment grain size

Median grain size (Fig. 6b) characterizing the overall grain size of the samples varied from 20 to 300 μm throughout the sedimentary profile in the Spirálka Cave. In the upper 150 cm of the profile the median grain size shows rapid variations between 60 and 200 μm, a certain degree of negative correlation with the χ record (Fig. 6a) and no correlation with the ARM/SIRM record (Fig. 3d). Deeper in the section between 170 and 390 cm the median grain size varies on a much smaller scale and shows an overall decrease from 70 to 30 μm. The large variations in grain size the dominant the upper 150 cm of the profile are missing in this interval. In the very bottom part of the section the median grain size shows a gradual increase to values reaching 300 μm and a good correlation with the χ record.

4.2.2. Organic matter content

Loss on ignition (LOI, Fig. 6c) measured throughout the sedimentary profile in Spirálka yields generally low values between 3–8%. The only exceptions are two intervals at depths of 170–195 and 200–225 cm, where the LOI values increase to more than 10%. In these intervals the otherwise dark brown sediments turn lighter in color and are characterized by a distinct odor. In the upper part of the profile the LOI values are nearly constant around 5%, at the base of the profile where the content of gravel is increasing the LOI values drop to the minimum values of 3%.

4.2.3. Heavy mineral content

Trace element geochemistry was utilized to detect whether post-depositional dissolution of magnetic minerals
has affected the magnitude of magnetic properties. Ti and Zr occur in heavy minerals and are immobile under most post-depositional conditions (Winchester and Floyd, 1977). Variations in Ti and Zr therefore provide proxies for detrital heavy mineral content at the time of deposition and changes in the Ti/Zr ratio may indicate changes in the source of detritus (Muhs et al., 1990, 1995). In contrast, magnetic Fe oxide minerals, which represent nearly 100% of the total Fe in the samples, are relatively mobile under common post-depositional conditions. For these reasons, comparison between magnetic properties and Fe, Ti and Zr content illustrate both the detrital magnetic signal and post-depositional alteration. The Ti/Zr record (Fig. 6d) shows a gradual rise from values around $1 \times 10^4$ to $4 \times 10^4$ at a depth of about 380 cm, where a sharp drop occurs. The Ti/Fe (Fig. 6e) ratio shows an opposite general trend, i.e. a gradual decrease from the top of the profile ($10 \times 10^{-2}$) to approximately $5 \times 10^{-2}$ at the base.

4.3. Results from the Spirálka Cave catchment area

$\chi$ and $\chi_{fd}$ data were determined from materials cropping out in the catchment of the Bílá Voda River in order to determine the source of the sediments in Spirálka Cave and to investigate how environmental processes affecting the catchment were reflected in the cave sediments. The data presented in Fig. 7a show that the majority of the samples collected from the floodplain (35 out of 46 samples) yield $\chi$ values between 8 and $17 \times 10^{-8}$ m$^3$/kg and $\chi_{fd}$ values between 3 and 6%. When compared with $\chi$ and $\chi_{fd}$ data from the cave sediments, the floodplain samples show a much larger range yet the cave sediments appear to be in the central part of this range. On the other hand the $\chi$ and $\chi_{fd}$ data measured on samples from both field (Fig. 7b) as well as forest topsoil (7c) show significantly higher values of $\chi$ and $\chi_{fd}$ than the cave sediment samples. In the case of the field topsoil the majority of the samples (7 out of 9 samples) fall in the range between 24 and $28 \times 10^{-8}$ m$^3$/kg for $\chi$ and 4 to 8% for $\chi_{fd}$. The majority of the samples collected from the forest topsoil (9 out of 16 samples) yield values of $\chi$ between 17 to $25 \times 10^{-8}$ m$^3$/kg and values of $\chi_{fd}$ between 5 to 8%. $\chi$ and $\chi_{fd}$ measurements of samples collected from the greywacke bedrock of the Bílá Voda River catchment are quite different. Both the $\chi$ values as well as $\chi_{fd}$ values of these samples are quite similar, yet slightly lower than the

Fig. 7. Comparison of two magnetic parameters (magnetic susceptibility and frequency dependence of magnetic susceptibility) measured on samples collected in the Spirálka Cave and in different environments of the catchment of the Bílá Voda River: a) floodplain, b) field, c) forest and d) rock outcrops. The direction of hatching indicates the environment (see legend) and its density the amount of samples which fall in the given area of the plot (dense hatching — 66% of samples, thin hatching — 95% of samples). Finally, N indicates the number of samples analyzed in the given environment.
cave sediment samples (Fig. 7d). The majority of the bedrock samples (17 out of 20 samples) fall into two ranges. One range is between $6-8 \times 10^{-8}$ m$^3$/kg for $\chi$ and between 2–5% for $\chi_{fd}$. The other range yields $\chi$ values between 11 to $13 \times 10^{-8}$ m$^3$/kg and $\chi_{fd}$ between 2 to 3%. Interestingly, the first range yields values of $\chi$ which are lower than those from the cave sediments, yet the values of $\chi_{fd}$ are comparable. On the other hand the second range contains samples which have similar values of $\chi$ to the cave sediments, yet their $\chi_{fd}$ values are somewhat lower. Comparison of $\chi$ and $\chi_{fd}$ data from the cave and its possible sources suggests that cave sediments in Spirálka are most probably re-deposited sediments of the Bílá Voda River floodplain. The transport and deposition processes into the cave provided additional sediment filtering which has resulted in narrowing the range of $\chi$ and $\chi_{fd}$. Sediments of the floodplain yield $\chi$ and $\chi_{fd}$ values which appear to be an average between those of the soil on the one hand and of the bedrock on the other. The perception of the floodplain sediments as a mixture of material provided by these environments is feasible and is supported by our data, as sorting and oxidation of primarily one source is less probable, because coarser grained sediments coming from different sources are observed at other sites in the cave.

5. Age of the Spirálka Cave sediments

Conventional radiocarbon ages based on the ratio of $^{14}C/^{12}C$ from the wood and charcoal samples collected from the Spirálka profile are listed in Table 1 including their one sigma standard deviation. Since the relative concentration of radiocarbon in global reservoirs varies significantly over time, the age determined directly from the $^{14}C/^{12}C$ ratio (the radiocarbon age) has to be corrected by comparing the radiocarbon scale with other scales that use independent dating techniques. In this manner the radiocarbon time scale is calibrated against a chronology of calendar years obtained from tree-rings, varves or uranium series methods (e.g. Vogel et al., 1993). Calendar ages based on the Pretoria Calibration Procedure (Vogel et al., 1993) are also shown in Table 1. In many cases, a single conventional radiocarbon age resulted in several calendar year ages due to the young age of the charcoals.

Comparing the one sigma age intervals from Table 1 to the depths of the dated samples and using the principle of superposition, an age model for our profile was developed. Data from the three samples collected 70 cm below the present day surface allow for only two possible age intervals, namely 1650–1670 A.D. and 1780–1795 A.D. The near present day age (1945–1950 A.D.) is very improbable as the cave was discovered in the year 1958 and the current depositional horizon was marked by the original cave discoverers. Since that time only a few centimeters of sediment have been deposited. The exact depositional rate and regularity of the sedimentary process since the discovery of the cave cannot be exactly estimated as there was not any instrumental monitoring of the sedimentation process installed in the cave. A comparison with age data from

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Sample name</th>
<th>Conventional Radiocarbon Age (B.P.)</th>
<th>Intercept with calibration curve (years A.D.)</th>
<th>Age intervals of one sigma calibrated results (years A.D.)</th>
<th>Age (years A.D.)</th>
<th>Average Sed. Rate (cm/100 yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>97SU2</td>
<td>240±40</td>
<td>1660</td>
<td>1650–1670, 1780–1795, 1945–1950</td>
<td>1660–1690</td>
<td>43</td>
</tr>
<tr>
<td>220</td>
<td>97SD1</td>
<td>130±50</td>
<td>1695, 1725, 1815, 1920</td>
<td>1675–1770, 1800–1940</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>97SU5</td>
<td>410±50</td>
<td>1460</td>
<td>1440–1505, 1595–1620</td>
<td></td>
<td></td>
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<tr>
<td>220</td>
<td>95D2</td>
<td>440±80</td>
<td>1450</td>
<td>1420–1505, 1595–1620</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>95SU2</td>
<td>220±60</td>
<td>1665</td>
<td>1650–1680, 1745–1805, 1935–1950</td>
<td></td>
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</tr>
</tbody>
</table>

Summary of radiocarbon dating on wood and charcoal samples from Spirálka Cave. Indicated is depth of sample below present profile surface, sample name, conventional radiocarbon age with one sigma standard deviation, intercept with Pretoria calibration curve (calendar age), one sigma interval of calendar age, most probable calendar age (see text) and average sedimentation rate for given interval.
the depth of 140 cm suggests that the age interval 1780–1795 A.D. is more probable for the 70 cm depth. If the older age interval (1650–1670 A.D.) of the horizon 70 cm was correct then sediments between the depth of 70 and 140 cm would have to be deposited in less than 15 years which is extremely unlikely. There is no evidence for such rapid sedimentation rate.

Out of the two possible age intervals (1660–1690 A.D. and 1735–1815 A.D.) of the 140 cm horizon only the older is feasible as dendrochronological dating on a P. alba wood sample (R. Réh, personal comm.) confirms an age date prior to 1700 A.D. Two of the samples (97SU5 and 95D2) from the depth horizon 220 cm yield consistent age data yet the remaining third sample 97SD1 has an age which is not compatible with the previous two. We assume that this result is in error as it is not compatible with the other two dated and that the age of the horizon 220 cm is either between the years 1595–1620 A.D. or more probably between the years 1440–1505 A.D.

Finally, the age of sample 95U2 from the bottom most horizon 300 cm below the present day surface is obviously erroneous as even the maximum possible age of this sample (1650 A.D.) is younger than the minimum possible age (1620 A.D.) of the overlying dated horizon.

Other age models than the preferred one discussed above and summarized in Table 1 are possible, but yield fairly unrealistic sedimentation rates.

6. Discussion

The upper most 1.5 m of the profile (Fig. 8) is the only part of the section where sediments did not undergo major post-depositional alteration as the Ti/Fe and Ti/Zr remain fairly constant (Fig. 6d, e). A comparison of the $\chi_{fe}$ and ARM/SIRM records (Fig. 8a, b) indicates that larger magnetic grain size (low ARM/SIRM values) typically corresponds to larger $\chi_{fe}$ values suggesting that the magnetic grains are predominantly multi-domain (Maher, 1988) while small magnetic grain size (high ARM/SIRM values) is associated with low $\chi_{fe}$ values. Therefore, the oscillatory swings in $\chi_{fe}$ are caused by varying concentration of “magnetite type” minerals and changes in their grain size. The fact that $\chi_{fe}$ and $J_s$ (Fig. 8c) show a close positive correlation to the Ti and Zr records (Fig. 8d, e) from this portion of the profile suggests that both the variation in magnetite concentration as well as grain size are directly controlled by the rate of erosion in the catchment of the Bílá Voda River.

Fig. 8. Comparison of parameters providing paleoenvironmental information from the most important upper 150 cm of the sedimentary profile in Spirálka Cave: a) ferrimagnetic susceptibility, b) ratio of anhysteretic remanent magnetization and saturation isothermal magnetization (ferrimagnetic grain size), c) saturation magnetization, d) Ti concentration, e) Zr concentration and f) Fe concentration. Highlighted are environmentally significant zones in the ferrimagnetic susceptibility record and their reflection in the other displayed parameters.
Comparison of the cave sediment properties with the different catchment environments (including the flood-plain, fields and forests) allowed us to place the cave sediment record in historical context of environmental processes occurring in the catchment of the Bílá Voda River. We found that sediments in the cave have very similar properties to sediments of the floodplain and were therefore most probably re-deposited from this environment into the cave during high stands of the Bílá Voda River.

However, water flow conditions in the cave are indeed extremely variable. Just in the last several decades after the cave discovery, significant changes including relocation of the streambed and removal of vast amounts of sediments have been observed. In addition, variable water flow in the Moravian Karst during the last centuries appears quite common. Burkhardt (1952) concludes from historical written records that flooding in the Punkva River cave system was very common in the past and much more severe than in the present years. Knies (1911) also collected historical information on flooding in the Holštějn valley since early 1800’s and suggests that flooding in the last century was more extensive than the present.

Brázdil and Dobrovolný (1992) compiled the most detailed and most reliable record of winter temperatures from the region. Their data consist of a ten year running average of winter temperature anomalies calculated from instrumental measurements conducted in the Prague’s Klementinum Observatory since the year 1771 and reconstructed from historical written records since the year 1500. Their data set is one of the longest instrumental climatic records in Europe. The close proximity of Spirálka Cave in latitude (∼ half a degree) to the observatory allows us the luxury of using this climatic record as a proxy for winter temperatures in the study area. Even though deposition probably occurred only during discrete flood events, our box samples incorporate several flood events resulting in a smoothed signal. Therefore, a reasonable approach is to compare our susceptibility data to the winter temperature data of Brázdil and Dobrovolný (1992). The filtering of the temperature record is in fact comparable to the degree of smoothing of the cave record produced by the 2 cm sample size applied on discrete flood events. The match between the winter temperature anomalies and $\chi_{\text{fe}}$ (Fig. 9) was obtained by using the estimates of the sedimentation rates shown in Table 1 (adjusted for the last several decades) and calculating the position of year 1771, i.e. where the instrumental temperature record begins. This puts the year 1771 at the depth of approximately 75 cm below the surface of the profile.

If our age model is correct then both the $\chi_{\text{fe}}$ and medium grain size (Fig. 6b) records for the uppermost 75 cm show a strong correlation with the averaged winter temperature anomalies for the entire time interval 1771–present. The $\chi_{\text{fe}}$ record shows a positive correlation with the winter temperature anomalies with minor discrepancies attributed to changes in the sedimentation rate resulting from the varying intensity of floods and/or from their altering frequency. The most probable explanation of the correlation of the records is that during years with warmer winters (positive winter temperature anomalies) and less snow cover the floods were less intensive (smaller grain size) but probably had access to larger tracts of cultivated land (discussed below) as agriculture tended to expand during these warmer periods. Cultivation of the land provided flood waters with greater access to coarser grained magnetite-like materials exposed by tilling of the soil. Banerjee et al. (1981) also suggested development of large-scaled cultivation being responsible for the increase in magnetite grain size distribution in post Little Ice Age sediments from Long Lake, Minnesota. Erosion of these cultivated soils resulted in a greater influx of coarser...
magnetic grains into Spirálska Cave leading to increased values of magnetic susceptibility even though the physical grain size of the sediments transported into the cave was smaller. During years with colder winters the situation was the opposite. Cultivated lands were not as plentiful and melting of a larger snow cover resulted in more erosive floods. These floodwaters were more energetic, thus carried larger grain sediments, yet with lesser ferrimagnetic content and therefore lower magnetic susceptibilities.

During the last two hundred years, a broader region including the Bílá Voda catchment underwent considerable environmental changes affecting namely the forest cover caused primarily by technological progress in nearby iron industry centers followed by increased volume of construction work.

We suggest that during warmer periods when forest clearance and cultivation were more prominent, sediments/soils containing abundant ferrimagnetic materials were more easily eroded and transported during snow melting events. This process explains the correlation between increased ferrimagnetic susceptibility of the cave sediments with positive winter temperature anomalies (Fig. 9) and correlation of ferrimagnetic susceptibility to increased concentrations of ferrimagnetic materials with larger grain sizes.

The section of the profile in the depth interval between 160 and 225 cm is affected by post-depositional dissolution of magnetite and is easily detected by a significant decrease in the $\chi_{fe}$ values and in the S-ratio. The color of the sediment in this interval is clearly greener and is rich in organic matter as suggested by two distinct peaks representing two events in the loss of ignition record. Results of the radiocarbon dating imply the age of this organic rich horizon between 1450 and 1600 A.D. According to historical records (Bradley, 1999) the period after the middle of the 15th century was characterized in Europe by a marked climatic deterioration from the conditions of the Medieval Climatic Optimum into the Little Ice Age. In the specific setting of Central Europe this deterioration was accompanied by an increased rate of precipitation (Brázdil, 1998) leading to devastating floods and following increased erosional parameters from this portion of the profile.

According to the record from Spirálska Cave the increased flooding led to redeposition of the surficial weathering products into the cave. The green-organic rich layers are most likely sediments from the floodplain covered by rich vegetation, which were being rapidly re-deposited into the interior of the Spirálska Cave during floods. Therefore sediments characterizing seemingly milder and more humid conditions were in fact deposited in the cave during periods of apparent climatic deterioration. The susceptibility lows, however, are not in this case indicative of temperature changes but are a result of reducing conditions in the organic rich layers leading to magnetite dissolution.

The magnetic and non magnetic parameters deeper in the section below the depth of 225 cm are fairly monotonous and indicate warmer and more humid conditions corresponding to the Medieval Climatic Optimum. The values of LOI are fairly high; the median grain size and other erosion indicators are low thus suggesting more humidity and less snow cover. The data paint a picture of a gradual climatic improvement toward the depth of 380 cm i.e. toward ages of approximately 1050–1100 A.D. This climatic improvement is apparent in the LOI record (gradual increase) and perhaps also in the $\chi_{fe}$ record (minimal gradual decrease).

Finally, in the bottom most 1 m of the section we witness once again a definite climatic deterioration. All the parameters show abrupt changes indicative of increased erosion (grain size, Ti/Fe, Ti/Zr, $\chi_{fe}$) and less vegetation cover (LOI).

7. Conclusion

(1) Results from Spirálska Cave suggest that deposits in the interior of this cavern yield a detailed record of changing environmental conditions during the last millennium. However, transport, sedimentary, and post-depositional processes in the cave environment are complicated and may obscure the primary paleoenvironmental signal. Prior to attempting a climatic reconstruction, a thorough understanding of the above mentioned processes had to be reached.

(2) We have shown that ferrimagnetic susceptibility variations in the upper 1 m of the Spirálska Cave profile are caused by changes in concentration and grain size of “magnetite type“ minerals. Since ferrimagnetic susceptibility and concentration variations also show a positive correlation to the erosional parameters from this portion of the profile and to changes in the 10-year running average of winter temperature anomalies for the last 200 years calculated from instrumental measurements at Prague’s Klementinum Observatory (Brázdil and Dobrovolný, 1992), these variations are depositionaly controlled by factors affecting the catchment area of the Bílá Voda River, i.e. namely spring floods induced by melting of the snow cover, forest clearance and cultivation episodes, and forest fires.
Therefore, ferrimagnetic susceptibility in the upper 1 m of our profile is a sensitive indicator of environmental events (interplay of man and changing climate) occurring in the catchment area.

(3) The investigation of the conditions in the catchment of the Bila Voda River also suggest that this area was affected by climatic changes observed in other parts of Europe. The actual events such as the Little Ice Age, Medieval Climatic Optimum, etc. are identified in the data at well defined time/depth intervals. Due to the exclusive conditions operating in the cave which are described above in great detail, the sediments responded with a unique feedback mirrored in the specific response of the mineral magnetic parameters.

(4) Radiocarbon age dating for this time interval remains problematic due to the rapid variation of the carbon isotopic content in the atmosphere. Yet, when ages are assigned to the record based on the best age estimate obtained from the radiocarbon dating the correlation between the record and the winter temperature anomalies is remarkable.

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