Palaeogeography, Palaeoclimatology, Palaeoecology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Evidence of Holocene surface and near-surface palaeofires in karst caves and soils

Stanka Šebela [a,*], Nina Zupančič [b,c], Miloš Miler [d], Helena Grčman [e], Simona Jarc [b]

[a] ZRC SAZU, Titov trg 2, SI-6230 Postojna, Slovenia
[b] Faculty of Natural Sciences and Engineering, Department of Geology, Aškerčeva 12, SI-1000 Ljubljana, Slovenia
[c] Ivan Rakovec Institute of Palaeontology, ZRC SAZU, Novi trg 2, SI-1000 Ljubljana, Slovenia
[d] Geological Survey of Slovenia, Dimičeva ulica 14, SI-1000 Ljubljana, Slovenia
[e] Biotechnical Faculty, Department of Agronomy, Jamnikarjeva 101, SI-1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 29 March 2017
Received in revised form 14 June 2017
Accepted 14 June 2017
Available online xxxx

Keywords:
Black deposits
Radiocarbon dating
SEM/EDS
8200 cal yr B.P.
Slovenia

ABSTRACT

Black deposits covering speleothems, cave walls and floors in Postojna Cave and Predjama Cave (SW Slovenia), and charcoal found in soil outside the Postojna Cave, were studied in order to establish their origin and age. SEM/EDS analysis of these deposits from both caves indicated that they are charred plant remains, very similar to oxidised charcoal in soil. Stable carbon isotope $\delta^{13}C$ values of −29.41‰ (Črna Jama, P1), −26.9‰ (Predjama), and −25.1‰ (charcoal in soil) confirm their origin from biomass burning. Radiocarbon dating from Postojna Cave (Črna Jama (P1) 8394 ± 35 cal yr B.P. and Pisani Rov 8235 ± 25 cal yr B.P.) suggests that the oldest analysed black deposits formed in the Early Holocene (Mesolithic). The age is consistent with soil charcoal found at 1 m depth in the surrounding area. Black deposits from Predjama were dated to 4095 ± 25 cal yr B.P. (Eneolithic) and were caused by burning fires at the cave entrance, as supported by archaeological remains. Prehistoric (2375 ± 20 cal yr B.P.) charcoal from the upper part of the soil profile (0.5 to 0.6 m) and historic (1240 ± 29 cal yr B.P. or 745 cal yr CE) black deposits from Postojna Cave (Črna Jama, P2) are related to forest fires, which are most likely human-induced. We interpret the oldest dated black deposits in Postojna Cave as traces of Early Holocene natural forest fires, since fire activity inside Črna Jama and Pisani Rov is not supported by archaeological remains. Favourable cave entrance morphology and microclimate allowed smoke to enter the cave during the winter period and deposit on speleothems. But an anthropogenic cause of forest fires cannot be excluded, since there are well-documented Mesolithic archaeological cave sites located close to the area. The study shows that black deposits on speleothems in caves are an important palaeoenvironmental record and proxy for Holocene climate.

1. Introduction

Slovenia is famous for its remarkable karst areas and numerous caves. It is the country where the term “karst” was defined and where landforms such as polje, doline and ponor were described for the first time (Gams, 2004). Among the 12,148 known caves in Slovenia (Cave Registry of the Republic of Slovenia, 2017), Postojna Cave is the most visited. In 2016 it attracted 689,650 visitors. Some other show caves, such as Predjama Cave, receive fewer than 10,000 visitors per year. Expert monitoring is required to be carried out in both caves in order to determine the extent of changes to the natural cave environment due to cave tourism. Beside cave microclimatic and biological monitoring, investigations of lampenflora growth, air pollution, flowstone growth, *etc.* are taking place (Mulec and Kosi, 2009; Mulec et al., 2012; Mulec, 2014; Gregorič et al., 2014; Šebela and Turk, 2014a, 2014b; Šebela et al., 2015a, 2015b). The occurrence of dark deposits covering bright speleothems and limestone in several parts of Postojna Cave (Črna Jama and Pisani Rov) and Predjama Cave was considered, in the context of environmental monitoring, an interesting starting point for consideration of the natural and/or anthropogenic causes of their formation.

For many years the black deposits in Črna Jama (Black Cave), part of Postojna Cave, have been described as a consequence of the use of torches by the first visitors (Schmidl, 1854; Habe, 1986; Gams, 2004; Kranjc, 2007; Zupančič et al., 2011). Joseph Anton Nagel visited Črna Jama in 1748 and described many stalactite formations, columns and other shapes, some of them white and others darker (Shaw, 2010). Schmidl (1854) described grey-black rocks at the bottom of a chamber in Črna Jama. Because cave guides illuminated Črna Jama with “bûchettes” (wood chips), the cave passages are black due to the

* Corresponding author.
E-mail addresses: sebela@zrc-sazu.si (S. Šebela), nina.zupancic@ntf.uni-lj.si (N. Zupančič), milos.miler@GEO-ZS.SI (M. Miler), helena.grcman@bf.uni-lj.si (H. Grčman), simona.jarc@ntf.uni-lj.si (S. Jarc).

http://dx.doi.org/10.1016/j.palaeo.2017.06.015
0031-0182/© 2017 Elsevier B.V. All rights reserved.

smoke (Schmidl, 1854). Dark deposits on cave walls in the part of Postojna Cave open to tourists are described as a consequence of 145 years of use of the cave tourist train (Muri et al., 2013).

Schmidl (1854) also mentioned that the use of torches was prohibited in Postojna Cave in order to prevent smoke and the blackening of stalactites; only miner's lamps were allowed. However, in Nagel's (1748) picture of Črna Jama, visitors are depicted with torches in hand (Gams, 2004). Politi (1939/40), on the other hand, stated that microorganisms were responsible for the black coatings in Črna Jama.

Recent studies of poorly crystalline black deposits from Črna Jama have shown the presence of C-rich matter, a form of organic carbon (Zupančič et al., 2011). Besides the use of torches, deposition of organic material of allogenic origin (for example soot from forest fires) was considered one of the possible sources of black deposits due to favourable microclimatic conditions at the Črna Jama entrance (Zupančič et al., 2011). The first radiocarbon dating (Alfonso et al., 2015) suggested that the black deposits were much older than soot from torches used by the first visitors and are instead related to an archaeological period. If the source of soot was not local (torches or fireplaces), but caused by extensive forest fires, such burning record could be preserved in the soil profile in the form of charcoal remains at adequate depth. As charcoal pieces in the soil above Postojna Cave have been reported previously (Šebela, 2010), it was reasonable that for this study we started looking for “forest fires” evidence outside Črna Jama.

Black coatings in Predjama Cave's Črna Dvorana (Black Chamber) have been explained by microorganisms (Politi, 1939/40; Anelli, 1941/1994) and the deposition of dust particles due to cave ventilation (Habe, 1970). The entrance parts of Predjama Cave were closely connected to early human settlement, probably of the Eneolithic period with some Neolithic elements (Korošec, 1975).

Black deposits have been described in many caves worldwide and attributed to natural (Mn-Fe precipitation, microorganism activity) and anthropogenic causes (visitors using torches, forest fires, fires in caves, air pollution) (Hill, 1982; Hill and Forti, 1997, 2004; White et al., 2009; Šebela et al., 2015b).

In certain passages in Mammoth Cave and Salts Cave (Kentucky, USA), brown-black ceiling deposits have been interpreted as organic matter, resulting from the deposition of smoke particles 3075 $\pm$ 140 years ago (Benington and Melton, 1961). A glossy, black deposit covers much of the ceiling and walls of Little Lost River Cave, Idaho. Carbon and nitrogen stable isotope analyses have shown that the deposit seems to have been derived from animal tissue, not plant tissue, which is interpreted as a cooking residue covering 2990 $\pm$ 50 cal yr B.P. old wall paintings (Steelman et al., 2002). Black carbon in speleothems in show caves from South Korea has been reported as a consequence of industrial and urban emissions (Chang et al., 2008).

Studies related to karst caves are becoming more important because speleothems and cave sediments act as a palaeoclimate proxy (Lauritzen and Lundberg, 1999; Baldini et al., 2002; Griffiths et al., 2010; Bar-Matthews and Ayalon, 2011; Fairchild and Baker, 2012; Audra and Palmer, 2015; Wong and Breecker, 2015). If black coatings in caves are related to extensive natural fires, which occurred during the Holocene (Marlon et al., 2013; Feurdean et al., 2013) or to human-induced fires in archaeological and/or historical time, there should be evidence for them in the form of preserved charcoal in different depths of soil profiles. The aims of this research were to establish the time and the cause of deposition of black deposits in two well-known show caves in Slovenia, to compare them with the age of charcoal found in the soil profile from the surrounding area, and to relate them to past climate changes and human impact.

2. Regional setting and site description

Both studied caves are situated in SW Slovenia. Postojna Cave is the second-longest cave in Slovenia with 24,340 m of known passages. It is developed in Upper Cretaceous bedded white-grey limestones (Šebela, 2012). Two locations in Postojna Cave (Črna Jama and Pisani Rov) were chosen for our study (Fig. 1).

Black coatings in Črna Jama can be found on the cave floor, on parts of the cave walls and, in a few cases, on the cave ceiling, covering an area of about 7400 m^2 at an elevation of 500 m to 533 m. The natural entrance to Črna Jama is located at the southern edge of a collapse doline and is open towards the North. Črna Jama is the coldest part of Postojna Cave with at least 4 °C lower air temperature as in other parts of the cave system. In winter when T_{out} is lower than T_{cave} circulation takes place in Črna Jama, but in summer there is almost no circulation (Crestani and Anelli, 1939).

In the period 1763 to 1810 CE the known sections of the Postojna Cave were illuminated by torches carried by guides. Cave guides also used to bring sheaves of straw into the cave, which they set alight by the walls of Veliki Dom (Fig. 1). From the year 1830 onwards the cave was illuminated by oil lamps, while in 1884 arc lamps (electric) were installed in the cave (Habe, 1986).

The second studied cave, Predjama, is developed in Upper Cretaceous thick bedded to massive limestones, in Upper Triassic dolomites, and in Jurassic limestones and dolomites (Čar and Šebela, 2001). The study site, Črna Dvorana (Black Chamber), is located 600 m from the cave entrance (Fig. 1). It was named for the occurrence of black deposits, which can be found just above Vetrovna Luknja, a strong blowhole chimney passage within collapse blocks that connects Črna Dvorana with Stara Jama. Black deposits cover the cave floor, collapse blocks and speleothems in the southern part of the chamber. They cover an area of about 3000 m^2 at an elevation of 490 m to 505 m. The recent speleothems growing over older black deposits are light coloured.

Strong air currents blowing in winter and summer through Vetrovna Luknja, a narrow vertical passage, have been described in historic sources during cave visits (Valvasor, 1689; Nagel, 1748; Schmidl, 1854). In 1912 the passage to Črna Dvorana was opened and new passages of the system were explored (Anelli, 1941/1994). Many inscriptions on cave walls just below Vetrovna Luknja were found, with the oldest from the year 1508, suggesting that visitors used torches for at least 400 years, which could be one of the causes of black deposits in Črna Dvorana above Vetrovna Luknja. Habe (1970) attributed thin black deposits to the deposition of dust particles pulled through Vetrovna Luknja blowhole. Air circulation is strong even far inside the cave and is not limited to the entrance areas. Predjama Cave has dynamic air ventilation because of the numerous cave entrances at different heights. Strong winds (max. wind speed 5.5 m/s, average 2 m/s) blow during winter from Vetrovna Luknja towards Črna Dvorana (Šebela and Turk, 2014a).

In the forested karst area above Črna Jama, 1 km from the cave entrance (western slope of Vodni Dol collapse doline at 530 m above sea level), soil profile, developed on Upper Cretaceous limestone, was excavated to give additional information on occurrence of black deposits in caves.

3. Material and methods

3.1. Sampling locations and sampling methods

In Črna Jama (Postojna Cave), samples of already broken speleothems with 1 mm thick dark deposits were randomly collected at three sublocations from a floor area of 100 m^2, while in Pisani Rov (Postojna Cave), samples were taken at one sublocation from an area of 10 m^2. In Črna Dvorana (Predjama Cave), samples were taken at one sublocation from an area of 70 m^2 (Fig. 1).

The well-developed soil profile was excavated up to a depth of 1 m. Soil description and sampling was done according to FAO guidelines (Guidelines, 2006). At several depths within the soil profile we found pieces of charcoal measuring 0.2 to 0.5 mm and a black substance. We were able to sample them at depths of 0.5 to 0.6 m and 1 m.

All samples of black deposits from the caves and charcoal pieces from the soil were analysed using several methods for organic matter