Geoarchaeological research into Palaeolithic cave sites as a source of palaeoenvironmental data

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Jamski sedimenti zaradi svoje starosti in dobre ohranjenosti hranijo edinstven zapis o klimatskih dogajanjih v pleistocenu. Sedimenti so v jamah odlično ohranjeni v primerjavi s tistimi na površju, ki so izpostavljeni ne le močnejšemu preperevanju, temveč tudi eroziji in drugim eksogenim procesom. Prav arheološka najdišča iz obdobja paleolitika so zaradi sistematičnih izkopavanj in odkopanih arheoloških profilov verjetno najbolj primerna za interdisciplinarne raziskave različnih sedimentov, vključno peloda, oglja in kostnih ostankov. Te raziskave so zelo pomembne tudi za arheologe, saj nudijo vpogled v klimatske razmere v obdobju, ko so jame obiskovali ljudje in v njih pustili razne sledi. Tako imenovane geoarheološke raziskave zahtevajo tesno sodelovanje arheološke in geološke stroke.

Ključne besede: paleolitik, pleistocen, geoarheologija, jamski sedimenti, paleoklima, okoljske spremembe, kronologija, datacije

Abstract

Cave sediments are more protected from weathering, erosion and other exogenic processes in comparison with sediments that accumulate at the Earth's surface. For this reason, cave sediments keep a unique record of climate variations in the Pleistocene. Archaeological (Palaeolithic) sites, where sediments (including pollen, charcoal and bone fragments) can be systematically studied in one or several profiles, are the most useful for multidisciplinary surveys. Such surveys are very important for archaeologists because they offer insight into climate conditions that prevailed in the period when humans visited the cave and left various traces there. So-called geoarchaeological surveys demand extensive cooperation between archaeologists and geologists.

Keywords: Palaeolithic, Pleistocene, geoarchaeology, cave sediments, palaeoclimate, environmental changes, chronology, radiometric dates

1. INTRODUCTION

Archaeological investigations of Palaeolithic sites demand a multidisciplinary approach, not only due to palaeontological finds, which are usually much more abundant than artifacts, but also to gain a better understanding of evolution of sedimentary and postsedimentary processes in the cave. These processes have a direct influence on stratigraphy, on sediment characteristics and on preservation of archaeological finds. Archaeological finds do not have great significance if their chronological position is not known. Proper methodological implementation of archaeological excavations is crucial to define the chronological position of Pleistocene finds. Finds need to be linked with environmental changes, which were very significant in the Pleistocene and directly impacted the life-style of humans. Humans preferred to find shelter inside the caves during cool and especially wet climate periods. Because caves are always wet, and therefore less suitable for residence during periods when the climate was relatively warmer, it was more convenient to build primitive dwelling places in the open air in such climate conditions.

The age of finds and traces of human presence in the cave can be determined by radiometric dating of sediments. Dating is usually carried out on bones and teeth, but also can be performed on charcoal and burnt artifacts. In the past the age of sediments was determined based on the typology of stone artifacts found within these sediments.

However, this method is considered less reliable these days, when more accurate chronology can be obtained by radiometric dating. Besides the chronological position of the sediments, scientists would also like to know the palaeoclimate and environmental conditions that prevailed during the sedimentation. Some common data on palaeoclimate conditions for the Pleistocene exist. Based on these data we can already place the archaeological finds to different climate periods by radiometric dating. However, climate was changeable not only regionally, but also locally, similar to today. More reliable environmental data may be obtained by surveys which are performed directly in caves. There are various approaches to obtain environmental reconstructions; however all are based on the study of sediments, where the finds are situated. Archaeological excavations need to be carefully planned. Accessibility of the sedimentary samples, on which palaeoclimate studies are based, can be limited, especially if the methodology of the excavations was not carefully planned and well considered. Environmental reconstructions carried out at various sites (caves) can be compared and correlated. It is very important to obtain as many radiometric dates as possible, in order to facilitate the correlations. With the help of radiometric data it can be determined whether the reconstructions are really similar, and whether they can therefore be considered reliable.

2. CAVE SEDIMENTS AND SEDIMENTARY PROCESSES

This paper is focused on Palaeolithic sites in caves which are filled with clastic sediments. Clastic cave sediments include autochthonous (derived from host rock of the cave) and allochthonous (derived from outside) stone fragments in all size ranges (clay to cave gravel and large boulders). Allochthonous sediments also include bones, artifacts, charcoal, etc.

Cave sediments can be roughly divided into three groups, based on their origin (Lau et al. 1997; Farrand 2001; White 2007; Ghinassi et al. 2008):

– *Geogenic sediments* (rubble which spalled from the cave ceiling and walls; clay which was washed into the cave through the cave mouth or through fissures in the cave ceiling; flowstone which deposited chemically from dripping water; loess and other aeolian – fine – sediments; alluvial sediments if the cave is hydrologically active or used to be active in the past; colluvium – gravel from external slopes above the cave mouth and other material from scree above the cave).

– *Biogenic sediments* (fossil remains of animals that inhabited the cave – mainly bones and teeth; coprolites; remains of plants such as charcoal and pollen).

– *Anthropogenic sediments* (artifacts; hearths; other material which humans brought to the cave such as pebble, dust, wood, etc.).

Biogenic and anthropogenic sediments are mixed with geogenic sediments, but the abundance of biogenic and anthropogenic sediments is usually minor in comparison with the dominating geogenic sediments.

Processes that lead to deposition and accumulation of sediments are called sinsedimentary. Postsedimentary processes lead to modifications of the sediments, after their deposition on the cave floor. Postsedimentary processes have the most effect on the topsoil layer of the sedimentary sequence.

2.1 Sinsedimentary processes

Accumulation of cryoclastic sediments in the caves takes place because of mechanical weathering of cave ceiling and walls. Weathering is most effective directly at the cave mouth. The influence of external climate (i.e. frost action) diminishes toward the interior part of the cave; for this reason mechanical weathering is less significant or even does not have any role there. Mechanical weathering is more intensive under climate conditions where the frequency of freeze and thaw cycles is higher. Also high humidity is an important factor. Cryoclastic gravel is most abundant just at the cave mouth; for this reason talus forms there. Also colluvium can contribute to the formation of talus. Colluvium can roll down through the cave entrance toward the interior part of the cave. Therefore, depending on the morphology of the cave bottom, colluvium can also be found deeper inside the cave. Great collapse blocks, which can be found in some caves, had presumably spalled from the ceiling during extremely strong earthquakes. If the cave mouth is large enough, then aeolian deposits may be transported and deposited in the cave. Loess is a typical aeolian deposit. Wind may also bring to the cave volcanic ash and other fine deposits from near or far surroundings. Deposition of alluvium takes place in hydrologically active caves. Soil and clay can be washed from the surface into the cave.

Washing takes place through fissures, which connect the surface and the cave. As mentioned, all these sediments are of geogenic origin.

2.2 Postsedimentary processes

The main postsedimentary processes that take place in caves are (Lau et al. 1997; Angelucci, Zilhão 2009):

– *Bioturbation* by faunal and animal activity (root action, compaction, displacement, burrowing).

– *Mass movement* due to periglacial conditions (cryoturbation, solifluction).

– *Carbonate dissolution.*

– *Secondary mechanical* and *chemical weathering.* Mechanical weathering is due to frost action and chemical weathering is due to dissolution (corrosion) of sediments that are water soluble (carbonates and partly bones).

– *Various diagenetic processes* such as dissolution, cementation, recrystallization.

Bioturbation and processes that are linked with a periglacial climate (cryoturbation, solifluction) can lead to mixing of sediments and displacement of archaeological finds between various layers. For this reason, caution is necessary while interpreting the chronological position of finds that occur in sediments where such postsedimentary processes took place.

3. DATING

Age of finds and chronological position of determined environmental changes are obtained by dating methods. The most reliable absolute dating methods for cave deposits are: thermoluminiscence on burnt flints (which occur in the vicinity of hearths); U/Th dating on animal bones and speleothems; radiocarbon dating (AMS ^{14}C) on wood, charcoal, bone, pollen or other organic material preserved in the sedimentary sequence; electron spin resonance (ESR) of cave bear teeth (of teeth enamel) (Lau et al. 1997; Angelucci, Zilhão 2009; Blackwell et al. 2009).

The upper age limit of ^{14}C dating methods is 50,000 BP; it is not possible to date the older organic sediments. This method is applicable only for the final phase of the Middle Palaeolithic and for the Late Palaeolithic. Reliability of this method is already questionable at age 45,000 years. The upper age range of U/Th dating is around 350,000 or at most 600,000 years (Low, Walker 1997; White 2007), and the upper age range of the ESR method is five or ten million years (Blackwell 2006). The lower age range of the thermoluminiscence method depends on the sensitivity of the sample (artifact made from flint, ceramic…); the upper limit is usually around 100,000 years (Low, Walker 1997).

4. PALAEOCLIMATE RECONSTRUCTIONS

Cave sediments are better preserved in comparison with sediments that occur at the Earth's surface because cave sediments are more protected from erosion and weathering. This is especially true for preservation of bones, charcoal and organic artifacts, which are of main interest for archaeologists and palaeontologists. The study of one or more types of sediments (for example charcoal, pollen or bones) may reveal some information about environmental conditions that governed during the deposition of the studied sediments at a certain level. However, high resolution environmental reconstructions can be obtained only by systematic study of prevailing sediments. For this reason, the main focus in this paper is given to the study of fine grained sediments (sand, silt, clay) and gravel. These sediments usually greatly dominate in archaeological caves. Sedimentary and postsedimentary processes are important indicators of climate conditions. Based on the study of dominating sediments (clay, silt, sand, gravel), we may presume which sedimentary and postsedimentary processes took place in the cave at a certain sedimentary level and then we may try to also interpret the climate conditions. Postsedimentary processes are the most effective at the topsoil of the sedimentary sequence. When topsoil sediments become buried by a new sedimentary sequence of sufficient thickness, all weathering processes stop. Postsedimentary characteristics of buried sediments are preserved, as no further modification takes place in buried sediments. During and after the excavations, archaeologists or geologists can study these modifications, which reflect certain past conditions (i.e. conditions of a limited time period when these sediments occurred at the topsoil). Archaeological (Palaeolithic) caves are probably the most suitable places, where sediments can be collected from profiles and then studied. Based on the study of sedimentary samples from various levels, environmental or even temperature conditions can be interpreted for the time period when studied sediments were exposed to weathering and other modifications of the topsoil. All modifications are direct reflections of climate and environmental conditions on the surface, above the cave. Sediments need to be dated; otherwise it is not possible to place the determined environmental changes into the Pleistocene chronology. The changeable rate of sedimentation and sedimentary gaps, which can last for more than 10,000 years, present the main problems for environmental reconstructions that are performed in caves.

4.1 Classical approaches to study fossil bones and pollen found in the sedimentary sequence

Classical environmental reconstructions from Palaeolithic sites (caves, rock shelters) are based on bones of Pleistocene fauna and pollen. Pollen may be carried to the cave by wind or by biotic transport (cave bear, small mammals, owl etc.). Pollen passes through the digestive tract, hence faecal material may contain reliable pollen spectra. Also percolating water that infiltrates through bedrock can be a source of pollen. Cave morphology, especially size of the cave mouth, is an important factor affecting the transport of airborne pollen to the cave. The highest concentrations of pollen are usually at the cave entrance (Navarro et al. 2001).

Such environmental reconstructions are problematic, due to the fact that pollen concentrations are low and only rare species of cave fauna are significant environmental indicators. The majority of taxa are (were) adapted to all kinds of climate conditions, and for this reason it is not possible to make conclusions about environmental or climate conditions for layers where many bone remains of *Ursus spelaeus* occur. Reliable indicators of severe climate conditions are arctic and tundra species, such as arctic fox, mammoth, woolly rhinoceros, reindeer, but remains of these species are usually very rare in karst infillings. Bones of small mammals are more frequent. Moles for example cannot live in cold climates, where the ground is frozen for most of the year. Marmot is adapted to more severe climate conditions; today it populates mountainous regions such as the Alps. Many environmental reconstructions are based on bones of rodents. Rodents are probably the most reliable environmental indicator, because their remains are quite frequent in cave sediments, especially in comparison with other (bigger) mammals (Madeyska, Cyrek 2002; Bona et al. 2006; Toškan 2009).

Pollen concentrations are usually very low in caves. Moreover, pollen is subjected to displacement, differential destruction or selective preservation of palynomorphs and reworking of sediments. For these reasons its representativeness and its primary stratigraphic position may be questionable (Woodward, Goldberg 2001; Groner 2004). Preservation of pollen is higher in caves with low humidity, but such conditions are rare in caves. Occurrence of bacteria is high under humid conditions, and bacteria are responsible for the degradation of pollen (Navarro et al. 2001). A more reliable indicator of environmental conditions than pollen is charcoal. It may be concentrated at hearths or scattered through the sediments (Culiberg, Šercelj 1997). Analysis of charcoal reveals the identity of the vegetation at a certain time period and consequently the environmental conditions.

4.2 Study of cave sediments

Rock fragments usually dominate cave sediments. They are of all sizes, from clay to rubble and large boulders. Of all sediments (including organic), the dominating ones keep the most continuous palaeoclimate record.

There are several approaches to studying cave sediments; some of them are more appropriate for environmental (or palaeoclimate) reconstructions and some less. The most used methods are granulometry, micromorphological analysis, magnetic susceptibility, geochemical analysis and study of autogenic minerals, which were formed after the deposition of sediments on the cave floor.

4.2.1 A granulometric histogram

A granulometric histogram shows the particle-size distribution of the total sediment. Cave sediments can originate from two or more simultaneous inputs (primary weathering of cave ceiling, wind action, colluvium etc.), and the source of the sediment can be presumed by analysis of the histogram. Multiple peaks or modes occurring on histograms are attributed to different sources of the material. For example, a peak at fine fraction can originate by aeolian transport or transport with water trickles, and a peak at coarse fraction can originate by grain to grain disintegration of the rock fragments composing the walls and ceiling (Mandel, Simmons 1997; Farrand 2001).

Sedimentary samples need to be acid treated, if we want to determine the original size of the grains, before secondary cementation of grains and formation of aggregates. Clay and silt may cement together and form aggregates. In such a case, granulometrical analysis will reveal dominance of the sand fraction, but the sand fraction is composed mostly of sand-size aggregates. Organic material may also cause disturbance. Organic matter can be removed with $H_2O_{2.}$ To remove carbonate and phosphate cements, the samples can be reacted with 10 % HCl, and embedded mineral grains are added to the silt and clay bars of the histogram (Farrand, McMahon 1997).

4.2.2 Micromorphological analysis

For micromorphological analysis, undisturbed sedimentary samples need to be collected from profiles. Only fine grained sediments are suitable for this analysis (clay, silt and partly sand). Samples are impregnated by low-viscosity polyester resin. Then thin sections are made, which are studied under a petrographic microscope. Fine sediments are mainly of allochthonous origin in caves, i.e. they were transported to the cave from the external environment. Based on mineralogical composition of the samples, the ratio between different mineral grains, their microstructure (b-fabric), roundness of rock fragments and other characteristics, we may make some conclusions about their origin and also about the environmental conditions that prevailed at the time when these sediments were deposited in the cave. Aeolian sediments (fine grained, having sharp angles and corners, mineral composition is various: quartz, feldspar, mica) indicate cool and arid climate conditions, while washed clay (having the same mineral composition as surface clay) indicates mainly humid climate conditions. We are also interested in postsedimentary modifications of the sediments and (climate) conditions that are responsible for such modifications. Micromorphological analysis is especially applicable in those caves where allochthonous sediments are relatively frequent throughout the sedimentary sequence and where sediments are strongly anthropogenically reworked (Ioconis, Boschian 2007; Boschian, De Santis 2010).

Angeluci and Zilhão (2009) used micromorphological analysis to study the sediments in Gruta da Oliviera cave (Portugal). Samples for thin layer preparation were taken from all layers and the constituents, microstructure and pedofeatures were studied. Based on microscopy, they determined the porosity, color of the cement, b-fabric (crystallic, granostriated, undifferentiated), aggregation, pedofeatures (coatings on voids or around grains), sedimentary features etc. They determined four main groups of sediments (>1 mm) based on microscopy. Grains of quartz dominate in the first group; also feldspars and mica occur there, but carbonate grains are not present. Carbonate fragments of various size and shape dominate in the second group. In the third group, other carbonate components occur (calcite crystals, fragments of speleothem, carbonate crusts). Anthropogenic and biogenic components (lithic artifacts, bones, phosphates) are found mainly in the fourth group. Based on the results, they interpreted the processes that led to the deposition of sediments at a certain level, and interpreted the origin of the sediments. Alluvial sediments were recognized in some layers. The build-up of the sequence between layers 14 to 9 resulted from slope-wash (probably through fissures communicating with the surface). Secondary carbonates (flowstone) were detected in all samples, indicating continuous flow of carbonate-saturated water into the cave or continuous percolation. The same may be said for the accumulation of phosphates. Both flowstone and phosphates indicate continually humid conditions, during the time interval corresponding to the accumulation of the strata. Results of micromorphological analysis offer an insight into the occurrence and magnitude of various sedimentary and postsedimentary processes in the cave. Climate conditions may be interpreted only indirectly, due to the fact that the discussed processes are linked with external climate conditions. Temporal resolution of determined climate changes depends on the magnitude of climate variations and on sensitivity of the site (cave environment) to such variations (important roles are played by the morphology of the cave mouth, thickness of the cave ceiling, topography of the surface area above or near the cave etc.). However, in the literature this method is often interpreted as the most appropriate approach for palaeoclimate reconstructions.

4.2.3 Magnetic susceptibility

This survey is performed mainly in those caves where allochthonous sediments dominate or at least represent a significant portion of the

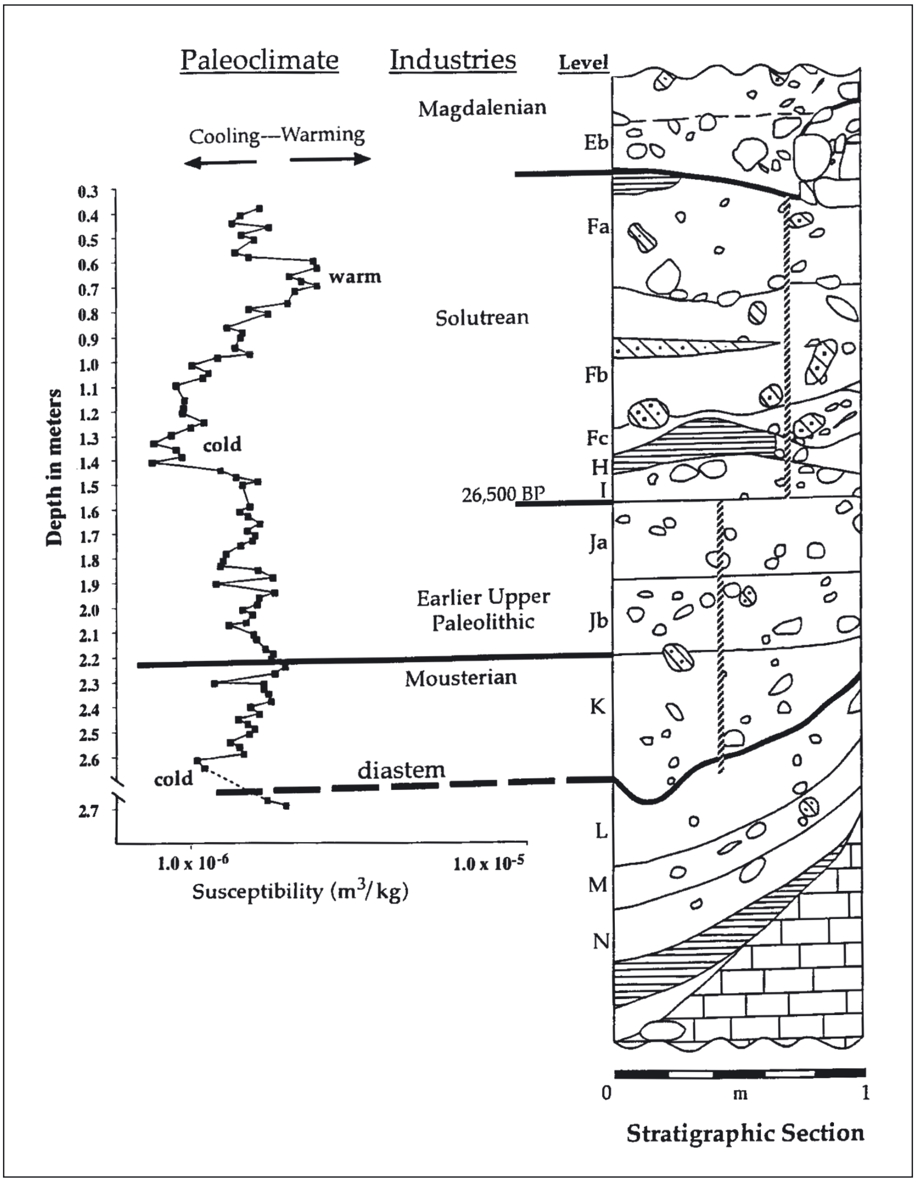

Fig. 1: The stratigraphic section for the excavation within Caldeirao cave (right). Plotted are the samples for which magnetic susceptibility was measured (left, in log scale, m^3/kg). Magnetic susceptibility decreases to the left; the lower the value, the cooler the climate. Gradual increase in magnetic susceptibility indicates warming. A specific cool phase was determined to have occurred after 26,500 BP (^{14}C dating). This phase may be correlated with the Last Glacial maximum (24,000–22,000 BP) (adapted from Ellwood et al. 1998).

Sl. 1: Izkopano sedimentno zaporedje v jami Caldeirao (desno). Črtkano so prikazani sedimentni vzorci, na katerih je bila merjena magnetna susceptibilnost – MS (levo, v logaritemski skali, m^3/kg). MS ki pada proti levi nakazuje ohlajanje podnebja, naraščanje MS proti desni pa ogrevanje. Izrazito ohladitev so ugotovili v obdobju po 26.500 pred sedanjostjo (datacija s ^{14}C), ki jo korelirajo z zadnjim glacialnim vrhuncem 24.000–22.000 let pred sedanjostjo (prirejeno po Ellwood et al. 1998).

sedimentary sequence. Such is, for example, terrigenous material eroded into the cave from the surface above the cave; another example is alluvial material. Changing climate alters the magnetic properties of materials, mainly as the result of pedogenesis. Pedogenesis outside the cave during times of cool climate produces sediments with low magnetic susceptibility magnitudes, while warmer climate yields higher magnetic susceptibility magnitudes. During warm climate conditions, strong chemical modifications take place on the Earth's surface, such as oxidation due to intense microbial catalysis. On the contrary, reduction takes place during cool climate conditions. A result of oxidation is accumulation of maghemite (Fe_2O_3) in the sediments, and consequently the magnetic susceptibility of these sediments is higher. After the removal of these surface sediments to the cave, magnetic susceptibility no longer changes, due to minimal pedogenesis and biological disturbance in caves. These disturbances may be significant only during long depositional breaks (hiatuses), when postsedimentary modifications at the topsoil take place for a relatively long time. Continuously sampled profiles of cave sediments allow palaeoclimatic estimates for all archaeological levels. The concentration of iron minerals is measured in samples: the higher the concentration, the higher the magnetic susceptibility (Ellwood et al. 1998).

Continuously sampled sediments collected from two profiles were studied by this method in Caldeirao Cave (Portugal). The chronology of climate changes was corroborated by ^{14}C dates. Sediments with the lowest magnetic susceptibility (indicating cool climate) were dated to 24,000–22,000 BP, which coincides with the last glacial maximum. Additionally, three glacial cycles were identified, each of them lasting around 2500 years (*fig. 1*) (Ellwood et al. 1998).

The method yielded good correlation with other independent surveys of climate in the Pleistocene. However, it is limited to those archaeological sites in caves where allochthonous sediments (derived from the surface) occur continuously between autochtonous sediments. Another limitation of the method is the expensive analytical procedure to measure the magnitude of magnetic susceptibility in sedimentary samples.

4.2.4 Geochemical analysis and study of diagenetic modifications

The mineral composition of cements (in breccias and aggregates) can be studied by geochemistry. Moreover, interest is given also to the mineral composition of coatings on the clasts and to the origin of allochthonous sediments. Based on geochemical analysis of sediments, diagenetic modifications and especially chemical conditions under which modifications take place can be interpreted. Indirectly, palaeoclimate and environmental conditions may be inferred. Underground (percolating) water, which is directly linked with the amount of precipitation, is the main driver of diagenetic modifications. In dry caves, modifications usually do not occur (Woodward, Goldberg 2001). Dissolution and corrosion of carbonate grains (clasts) and also bones are two of the most characteristic modifications. Etching of clasts and bones by corrosion is an indicator of humid climate (Turk et al. 2005). Water dissolves the carbonate and bones, calcium, and phosphorous migrate and precipitate as a cement. Rock and bone fragments of various sizes are cemented together, and for this reason autogenic aggregates (smaller fragments are cemented together) and breccias (larger fragments are cemented together) occur in sediments. Phosphate occurs in those caves which are rich in organic material (bones, guano) (Turk et al. 2007). Coatings that occur on sediments are usually manganese and iron dioxide, or clay coatings. Coatings are formed during humid and oxidizable conditions. Coatings are usually thin (<1 mm) (White 2007).

4.2.5 Study of autogenic minerals

Autogenic minerals are formed in situ within the cave sediments, (i.e. postsedimentary), under specific chemical conditions (pH, Eh) and in the presence of high calcium, phosphate or aluminum concentrations. There are several autogenic minerals; each is stable under certain chemical conditions only. Any change in water chemistry leads to recrystallization into more stable mineral forms. All changes in chemical properties of the water are linked with biological activity outside the cave; the latter depends on climate and the dynamics of the external environment (Woodward, Goldberg 2001; Madeyska, Cyrek 2002).

Various assemblages of autogenic minerals occur through the sedimentary sequence in Theopetra cave (Greece). Each assemblage reflects specific conditions that prevailed at the time of mineral formation. Formation takes place in topsoil exclusively (Karkanas et al. 2000). When water passes through sediment rich in organic material, it reacts with calcite (or dolomite), which is altered to dahllite (carbonate apatite). Dahllite is the main component of fossil bones. Dahllite is stable under alkaline conditions only ($pH > 7$). Alkaline conditions prevail in caves that are filled with carbonate sediments (limestone, dolomite). The reaction between acid water and carbonate uses acid, and the remaining solution becomes more alkaline. As long as calcite is present in the sediments, the calcite acts as a buffer, which in turn prevents the associated dahllite from being dissolved. However, if the pH decreases between 6 and 7 (acid), then dahllite is dissolved and reprecipitates in the form of more stable crandallite or montgomeryite. If the acidity increases, both minerals finally reprecipitate to taranakite (a potassium aluminum phosphate mineral). Properties of the autogenic minerals can be used to reconstruct ancient palaeonvironmental chemical conditions of water and its corrosion capability. Bones, charcoal and pollen may be totally dissolved by percolating water under acid conditions (pH < 7), and for this reason organic remains do not occur in the cave. Identification of autogenic minerals is done by X-ray diffraction or infra-red spectroscopy (Karkanas et al. 2000; Shahack-Gross et al. 2004).

4.2.6 Sedimentary analysis of coarse fraction (rubble)

There has been some belief in geoarchaeological science that it is not possible to obtain high resolution palaeoclimate records from data derived from the analysis of bulk coarse-grained samples. It has been presumed that sensitivity of the coarse sedimentary fraction to climate changes is relatively low. By contrast, fine-grained sediments have been presumed to be much more sensitive to climate changes and to have a much higher stratigraphic resolution. Environmental reconstructions based on micromorphology have been presumed to be the most accurate and to have the highest temporal resolution (Woodward, Goldberg 2001). Such a presumption may be correct, if we have in mind the classical analysis of coarse-grained sediments. Cryoclastic rubble accumulates due to weathering (frost action) of cave walls and ceiling. Frost action is the most intensive at the cave mouth; its role diminishes toward the cave interior. That is, the greater the distance from the cave mouth, the lower the temperature variations (or the role of freezing) in the cave. Accumulation of cryoclastic material (angular, corners are sharp) indicates cool climate. However, some caution should be taken into consideration. Angular and sharp edged material can also be produced by other geomorphological processes, such as degree of (tectonically) fracturing of the host rock, hydration shattering, seismic activity etc. (Woodward, Goldberg 2001). Also colluvial sediments are an indicator of cool climate (Cremaschi 1990).

The presence of flowstone within sediments is an indicator of relatively warm climate. Flowstone precipitates only in relatively warm and especially humid conditions (*fig. 2*). When rain water percolates through organic rich soils, the CO_2 concentration rises. Such water is corrosive, and when it percolates through fissures that link the surface and the cave, it dissolves carbonate and becomes supersaturated. The CO_2 concentration in the cave atmosphere is typically ten times that of the surface atmosphere. CO_2 is degassed into the cave atmosphere and $CaCO_3$ is precipitated in the form of flowstone (White 2007). Breccias, where clasts are cemented by calcite or phosphate, are also an indicator of warm and humid climate. Dissolution and reprecipitation of calcite or phosphate takes place in humid conditions (Campy et al. 1994; Quinif 2006). Chemical weathering is the most intense in warm periods. A consequence of such weathering is the formation of iron, manganese or clay coatings or crusts around clasts. Residual clay and cave loam (the products of limestone dissolution) also occur, but production is very low (Madeyska 2002).

Research by Cremaschi (1990) is represented as an example of classical analysis of clastic sediments. Such classical research offers only a rough palaeoclimate interpretation. Cremaschi studied both coarse and fine-grained sediments from seven Italian caves (Palaeolithic sites). He divided the sediments into three pedo-sedimentary cycles, which reflect climate changes in the Pleistocene. Colluvium was deposited during the first cycle, interpreted as wet and moderately cold. Colluvium was still deposited during the second cycle, but also deposition of thermoclastic breccias and loess took place. Soil horizons were identified within the sedimentary sequence that belongs to the second cycle. These sediments indicate successive climate conditions. Colluvium was deposited in a wet and cold climate; deposition of thermoclastic breccias should take place in even more severe conditions. Loess indicates a dry, but still cold, climate. After that, climate conditions seem to have mitigated (as indicated by the soil horizon). This cycle should belong to the glacial period. Sedimentation during the third cycle was similar to during the second cycle. The third cycle was also interpreted as a glacial one. On the basis of the stratigraphic relationships of the lithic assemblages and of some radiocarbon datings, the determined climate cycles were placed in Pleistocene chronology. The first cycle was correlated to OIS (oxygen isotopic stage) 5a to 5d (115,000–74,000 BP). It is a stage after the last interglacial (Eemian); climate conditions

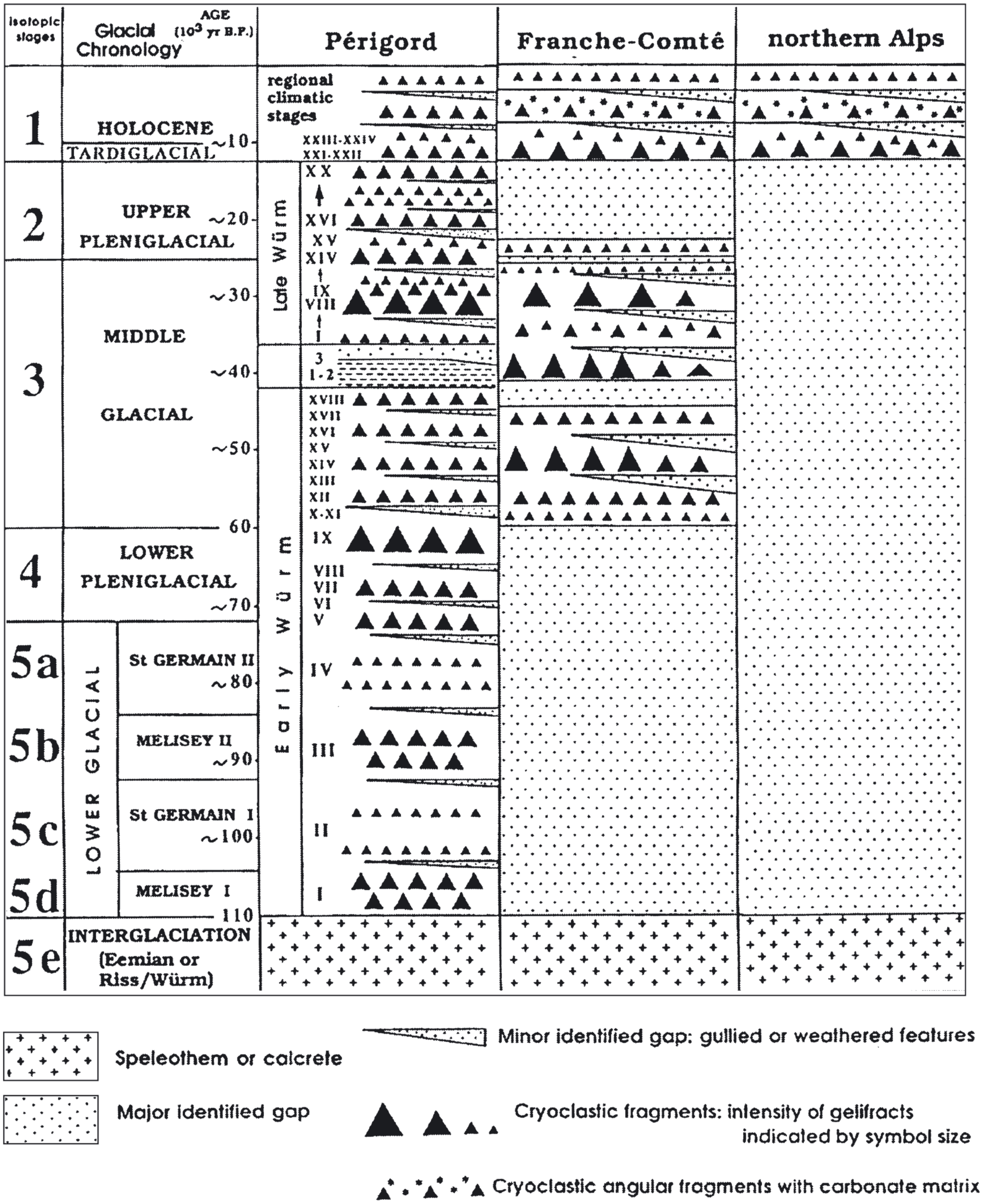

Fig. 2: Comparative sedimentary record from Palaeolithic cave sites in Perigord, Franche-Comte and the northern Alps. Sedimentation was the most continuous in Perigord. The longest sedimentary gap occurred at sites from the northern Alps, where sediments from the whole Würm are missing (OIS 5–OIS 2). Cryoclastic fragments are an indicator of cool climate. Sedimentary levels where the abundance of cryoclastic fragments is lower and where carbonate cements or traces of chemical weathering occur indicate moderate climate (interstadial). Flowstone and secondary calcite are indicators of warm climate (last interglacial) (adapted from Campy et al. 1994).

Sl. 2: Značilnosti sedimentov v izkopanih profilih v arheoloških najdiščih Perigord, Franche-Comte in v severnih Alpah. Sedimenti so se najbolj zvezno odlagali v Perigordu, največja sedimentacijska vrzel je v najdiščih v severnih Alpah, kjer manjkajo sedimenti celotnega Würma (OIS 5 do OIS 2). Krioklastični grušči nakazujejo mrzlo klimo, nivoji z manj izrazitim krioklastičnim gruščem, kjer se pojavljajo tudi kalcitni cementi in sledovi kemičnega preperevanja, kažejo bolj zmerno klimo (interstadiali). Siga in sekundarno izločeni kalcit kažeta toplo klimo (zadnji interglacial) (prirejeno po Campy et al. 1994).

were becoming gradually more and more severe during OIS 5. The second pedo-sedimentary cycle was correlated to OIS 4 (74,000–59,000 BP – interstadial) and to OIS 3 (59,000–29,000 BP – stadial). The third pedo-sedimentary cycle was correlated to OIS 2 (29,000–11,000 BP – stadial). Such classical palaeoclimate reconstructions were very rough, and direct correlations with high resolution climate records (such as GRIP – see chapter 6. *Correlations*) were not possible. Lack of dates is a big problem. Correspondence with reliable dates is a preliminary condition for determination of the chronology of climate changes.

Ivan Turk (2006; 2007) developed some innovative methods to reconstruct palaeoclimate from cave sediments. The methods are based on the study of coarse grains and were performed in Divje babe I cave. He studied autochtonous congelifracts to reconstruct palaeotemperature conditions. Palaeohumidity was assumed, based on the occurrence of autogenic aggregates and corrosionally etched clasts or bones throughout the sedimentary sequence.

High resolution palaeotemperature records may be obtained by studying the morphological characteristics of coarse-grained sediments, which are a direct result of (postsedimentary) frost action taking place in the cave topsoil. The abundance of congelifracts was studied in samples, corresponding to 10 cm thick sedimentary levels. These samples were collected from two profiles (J. Turk, M. Turk 2010). The main characteristic of congelifracts is that they are diagenetically linked with mechanical weathering and frost action, respectively. However, the methodology of I. Turk (2006) takes into consideration only those congelifracts which were frost-shattered post-depositionally (in the topsoil layer of cave sediments). Sediments only freeze to a certain depth; when topsoil sediments become buried with a new sedimentary sequence, all weathering processes stop and the buried clasts remain preserved from further modifications. The higher the percentage of congelifracts in a certain sedimentary level, the cooler the climate was (mechanical weathering was more intense) during the time period when sediments from this level were exposed to weathering at the topsoil (Turk et al. 2006; Turk et al. 2007; J. Turk, M. Turk 2010). Continuous sampling and analysis of sedimentary samples revealed that two significantly cool phases occurred between 80,000 and 40,000 BP in Divje babe I. These two dates are approximately the ages of the uppermost and lowermost sedimentary levels in the sequence studied (*fig. 3*). More accurate placement of the two cool phases is possible by performing additional radiometric dates or by correlations, as was done in Divje babe I (see chapter 6. *Correlations*). Temporal resolution of climate phases determined in Divje babe I depends on the rate of sedimentation, which varied between 0.01 to 0.04 cm per year (Blackwell et al. 2009). Hence, temporal resolution of climate changes was estimated to 1000±500 years, which is probably the highest resolution obtained by study of clastic cave sediments.

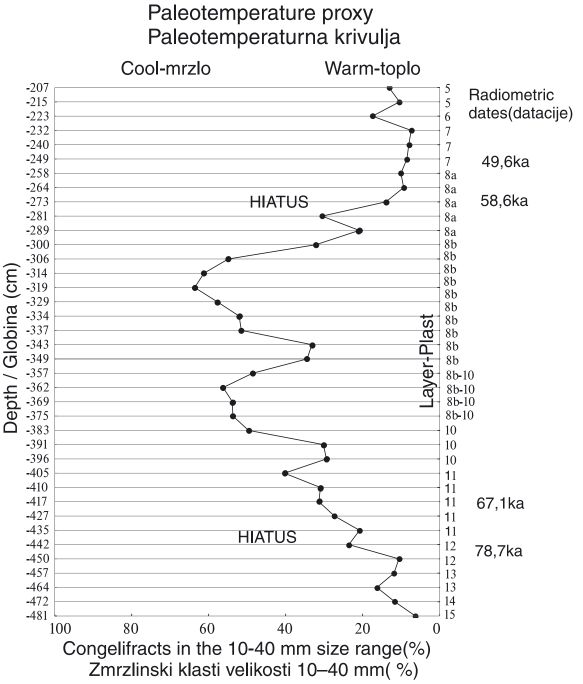

Fig. 3: Curve of the relative abundance of the congelifracts, which were continuously sampled from two profiles in Divje babe I cave. A higher percentage of the congelifracts indicates cool climate, while a lower percentage indicates warm climate. Based on radiometric dates, the Divje babe I palaeotemperature proxy can be correlated with proxies obtained at other sites or with GRIP palaeotemperature proxy (cf. *fig. 5*).

Sl. 3: Delež zmrzlinskih klastov v zvezno vzorčenih profilih v jami Divje babe I. Večji delež zmrzlinskih klastov nakazuje mrzlo, manjši delež pa toplejšo klimo. Prikazane so tudi radiometrične datacije, na podlagi katerih lahko poskušamo dve izraziti hladni dobi korelirati z drugimi najdišči oziroma z GRIP-krivuljo (prim. *sl. 5*).

I. Turk et al. (2006) studied the occurrence of autogenic aggregates throughout the sedimentary sequence, to reconstruct palaeohumidity. Samples were taken from 64 profiles in the cave. The main components of aggregates are mainly phosphoric; their genesis is linked with the accumulation of

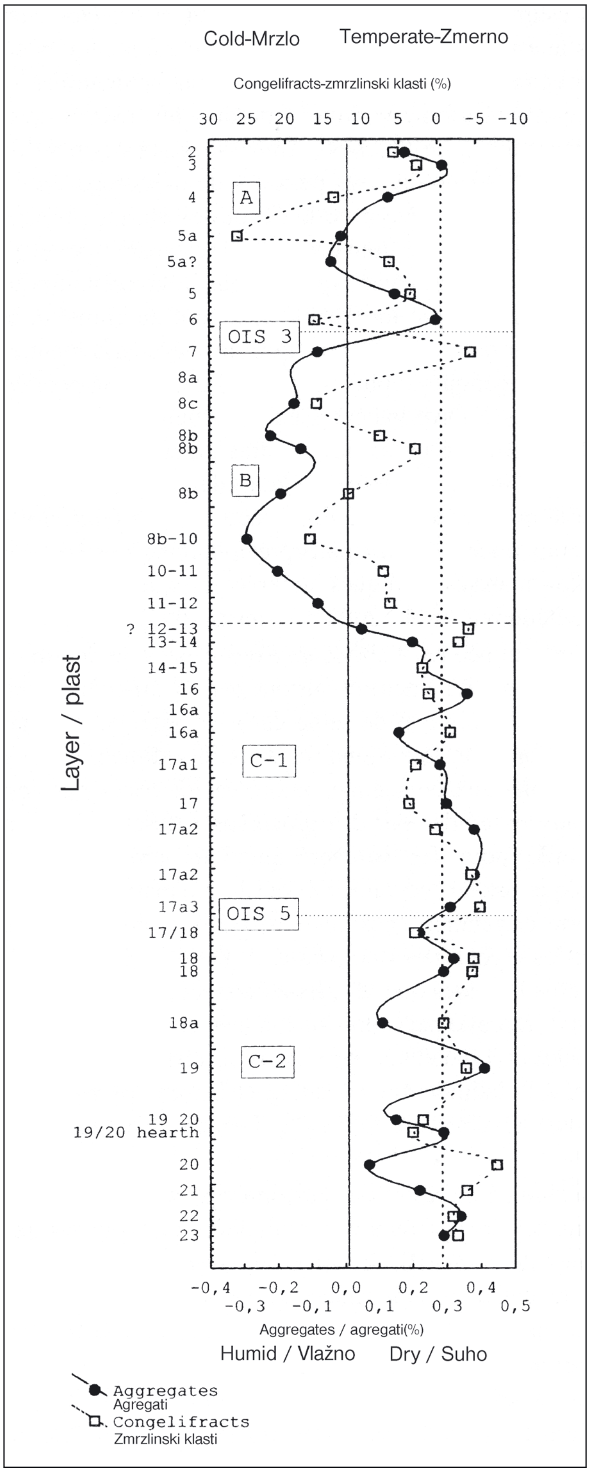

Fig. 4: The percentage of aggregates and congelifracts through the layers in Divje babe I cave. One sample was collected from each layer; sampling was not continuous. A higher percentage of aggregates indicates humid conditions, while a low percentage of aggregates indicates arid conditions. The percentage of aggregates for the Holocene is also presented (vertical line). Based on deviation from the Holocene value, it may be presumed when the climate was more humid than in the Holocene and when more arid. The dotted line is the curve of the congelifracts and the vertical dotted line is the Holocene value of congelifracts. A high percentage of aggregates significantly coincides with a high percentage of congelifracts. Therefore, it may be concluded that the climate conditions in OIS 3 were humid and cool (from Turk et al. 2006, fig. 10).

Sl. 4: Delež agregatov in zmrzlinskih klastov (kongelifrakti) po plasteh v jami Divje babe I. Iz vsake plasti je bil pobran le en vzorec, vzorčenje ni bilo zvezno po nivojih. Večji delež agregatov kaže na vlažne razmere, manjši pa na bolj sušne. S primerjavo vrednosti holocenskega povprečja deleža agregatov (navpična črta) lahko sklepamo na pretekla odstopanja od sedanjosti. Prekinjena krivulja predstavlja delež zmrzlinskih klastov. Navpična prekinjena črta prikazuje delež zmrzlinskih klastov, značilen za holocen. Značilno je ujemanje velikega deleža agregatov (neprekinjena krivulja) z velikim deležem zmrzlinskih klastov, kar nakazuje, da so bile klimatske razmere v OIS 3 vlažne in mrzle (po Turk et al. 2006, sl. 10).

organic remains, which derive mainly from cave bear (Turk et al., 1988). Distribution of aggregates is irregular, not only throughout the depth of the sedimentary sequence, but also within a certain sedimentary level. It may be explained by recharge of ground (percolating) water. Results show that autogenic aggregates are the most abundant in those layers that were dated to the upper part of OIS 3, or to OIS 4 (at least part of the sediments from OIS 4 is missing due to sedimentary hiatus) (Turk et al. 2006) (*fig. 4*). The reliability of results can be corroborated with the abundance of cavernously corroded clast and etched bones (also by corrosion). The high occurrence of corroded clasts and bones also indicates a humid climate (Turk et al. 2005).

5. HIATUSES

Sedimentation does not occur continuously in caves, and this is the main problem for determining the chronology of past environmental changes. Sedimentary gaps or hiatuses are the biggest problem in caves. If the sedimentation ceases for a thousand or even several tens of thousands of years, then it is not possible to make climate or environmental records for these periods.

It may be a problem even to identify the hiatus; its duration can be reliably determined by radiometric dating exclusively. Some characteristics of the sediments may indicate the occurrence of a hiatus. When sediment input is strongly reduced or ceases entirely, strong weathering, bioturbation, chemical and diagenetic modifications take place at the exposed sedimentary surface. Such periods with no sedimentation can be inferred from the color of the sediments, increased roundness of rock fragments, higher clay content, decreased $CaCO_3$ content, and in some cases, changes in heavy mineral suites (Zn, Cu, Ni, Co, V, Cr etc.) (Farrand 2001). At a level where intense chemical weathering and leaching occurred, the $CaCO_3$ content of the stratum is reduced below the usual value found throughout a section of similar deposits. However, some caution should be taken into consideration, because the $CaCO_3$ content may also be reduced by other reasons, such as high temperature combustion in hearths (Mandel, Simmons 1997). The degree of alteration and soil formation is a function of both the duration of surface stability and the intensity of the weathering climate. They are favored in localities close to the cave entrance or drip line (Farrand 2001). The accumulation of secondary carbonates (flowstone) on a cave floor can take place only during a period of depositional hiatus. Hence, occurrence of flowstone at certain levels of the sedimentary sequence is an indicator of a break in deposition (Angelucci, Zilhão 2009). Flowstone is also an indicator of humid and relatively warm climate conditions, as already mentioned.

A new approach to identifying breaks in sedimentation was developed at the Divje babe I Palaeolithic site. I. Turk (2006) found that the sedimentation rate can be defined by study of cavernously corroded clasts, which broke from the cave ceiling and walls. Condensation corrosion to a large extent affects the cave ceiling and walls, when the ceiling and walls remain stable for a significantly long period. When the cave bedrock begins to collapse after the hiatus, then a layer which corresponds to resumption of the sedimentation process after a hiatus contains a significantly higher percentage of (pre-depositionally) cavernously corroded clasts in comparison with the adjacent lower layer, which corresponds to a slow sedimentation rate (J. Turk, M. Turk 2010).

6. CORRELATIONS

Climate reconstructions determined by various methods do not have any significant importance if they are not correlated with dates and if we do not know when in the Pleistocene the determined climatic phases occurred. It is very expensive to perform detailed dating of the sedimentary sequence, and for this reason chronology is usually based on only a few datings. Even based on rare dates, we can correlate determined climate phases with phases of other, independent studies, performed elsewhere in the region or in the world. However, the results of these studies must be reliable.

Global chronology of climate changes is based on sediments from deep-sea cores and ice cores from Greenland (Lowe, Walker 1997). Oxygen-isotope ($\delta^{18}O$) composition of sediments and ice from such cores directly depends on climate conditions. The age of ice with a characteristic isotopic composition (corresponding to a certain climate phase) is determined by counting of annual layers throughout the core. However, annual layers are compressed at higher depths, and counting is uncertain. Some simplifications are used to estimate the age of ice in such a case, but the estimated ages are not completely certain. It is presumed that annual layers are around 1 cm thick, at around 100 ka and more (Svensson et al. 2008). Determination of age for climatic phases that occurred far in the Pleistocene can therefore experience greater error.

Regional chronologies of climate changes are based mainly on palynological research on lacustrine sediments (Watts et al. 2000; Andrič et al. 2009). Pollen remains found in sediments reveal which tree species grew at that period; they also indirectly indicate climate conditions. Pollen can be dated and any significant change in tree species can be placed in time.

The main disadvantage of climate reconstructions performed in caves was the relatively low temporal resolution. For this reason, only rough correlations with other high resolution records such as GRIP ($\delta^{18}O$ in Greenland ice, *fig. 5*) or pollen records from lacustrine environments were possible. One of the rare exceptions is the record from Divje babe I cave (*fig. 3*). Different Palaeolithic sites from one region or sites from a similar geographical latitude have usually been correlated. However, such correlation can be problematic, due to the variable thickness of sediments in caves, different rates of sedimentation, non-contemporaneous sedimentation in different caves, and variation in frequency and chronological position of the hiatuses from one region to another (Campy et al. 1994; Woodward, Goldberg 2001) (*fig. 2*).

Different cave sites can be correlated if some markers occurred within the sedimentary sequence. Loess and volcanic ash are significant markers. If the horizon of loess occurs in several caves situated in the same region, then it can be concluded that

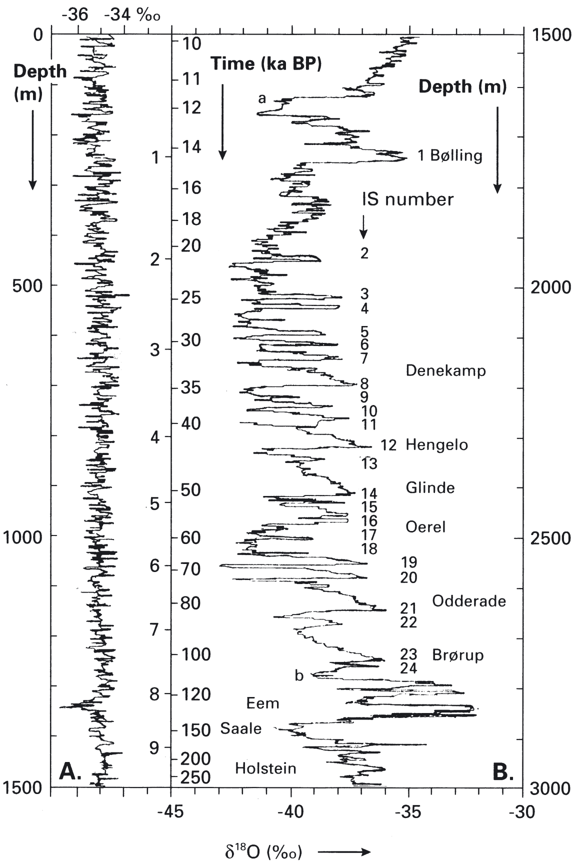

Fig. 5: The continuous GRIP Summit $\delta^{18}O$ record from Greenland ice cores. The left section is from the surface to 1500 m deep and the right section from depth 1500 m to 3000 m. The lower the per mil of $\delta^{18}O$ on the graph, the cooler the climate. The record extends over the past 250,000 years (adapted from Dansgaard et al. 1993). Two climate phases, which were identified in the Divje babe I record (cf. *fig. 3*), can be correlated with cool phases on the Grip record. Correlations supported by radiometric datings indicate that cool phases in Divje babe I occurred during the periods 67,000–62,000 and 61,000–58,000 BP.
Sl. 5: Zapis GRIP-vrh, ki prikazuje variacije $\delta^{18}O$ v grenlandskem ledu. Levo je zapis do globine 1500 m, desno pa od globine 1500 do 3000 m. Manjši promil $\delta^{18}O$ pomeni hladnejšo klimo. Zapis sega 250.000 let v preteklost (po Dansgaard et al. 1993). Hladni dobi iz paleotemperaturnega zapisa v Divjih babah I (prim. *sl. 3*) lahko glede na radiometrične datacije koreliramo s hladnima dobama izpred 67.000–62.000 in 61.000–58.000 let pred sedanjostjo iz GRIP-zapisa.

this horizon is of the same age, and it therefore represents a chronological marker. It is the same with volcanic ash. Ash can travel several hundreds of kilometres after the volcanic eruption, and wind eventually brings it to the cave, where it then deposits. Volcanic ash that belongs to a certain eruption has characteristic mineral composition. Ash horizons from different caves can be correlated based on mineral composition, and they can also be dated (Pirson et al. 2006).

7. CONCLUSION

There are several methods to study palaeoclimate changes, but none of them is totally certain. For this reason, it is better to apply several independent methods. Once obtained, various reconstructions can be compared. If they correlate well, then it is very probable that such reconstructions are reliable. Which method is going to be applied depends on the type of sediments in the cave (cryoclastic rubble dominates, or allochthonous sediments such as colluvium and clay dominate). In the next phase, determined climate cycles can be correlated with climate proxy records obtained at other Palaeolithic sites which are situated at a similar geographical latitude. Correlations with proxy records obtained in other environments, such as lacustrine or deep sea sediments and GRIP, are desirable. Development of new methods, such as the study of congelifracts or magnetic susceptibility through sedimentary profiles in archaeological sites, is very important for Pleistocene climate reconstructions. These surveys are not only important for archaeologists and geologists, they can also reveal some basic knowledge about climate changes in the Pleistocene. With these data, we can also understand better the contemporary climate changes.

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Geoarheološke raziskave v paleolitskih jamskih najdiščih kot vir paleookoljskih podatkov

1. UVOD

Arheološke raziskave paleolitskih najdišč zahtevajo interdisciplinarni pristop. Ta je potreben ne le zaradi paleontoloških najdb, ki so precej pogostejše od artefaktov, pač pa tudi zaradi razumevanja razvoja sedimentacijskih in postsedimentacijskih procesov v jami, ki so neposredno vplivali na stratigrafijo, značilnosti sedimentov in ohranjenost arheoloških najdb. Arheološke najdbe same po sebi nimajo velikega pomena, če niso umeščene v čas. Zato je pravilen metodološki pristop k arheološkim izkopavanjem ključnega pomena za umeščanje najdb v pleistocensko dogajanje. Najdbe je potrebno povezati z okoljskimi spremembami, ki so bile v pleistocenu zelo izrazite in so neposredno vplivale na življenjske navade ljudi. V mrzlih in predvsem vlažnih obdobjih so se ljudje raje zatekali v jame, ki so sicer že same po sebi vlažne in kot take manj primerne za bivanje v toplejših klimatskih fazah, ko je bilo ljudem udobneje zgraditi preprosto bivališče na prostem.

Starost najdb in sledov človekovega bivanja v jamskem okolju lahko določamo z različnimi neposrednimi datacijami sedimentov, v katerih se najdbe nahajajo. Običajno se datirajo kostni ostanki in zobje ter tudi ožgana orodja in oglje. Predvsem v preteklosti se je starost v grobem določala na podlagi tipologije kamnitih orodij, kar pa je danes ob razvoju številnih metod datiranja manj smiselno.

Poleg časovnega obdobja so posebno pomembni še paleoklimatski podatki oziroma rekonstrukcija okoljskih razmer, v katerih se nahajajo določene najdbe. Obstajajo splošni globalni podatki za paleoklimatske razmere v pleistocenu, s čimer lahko najdbe že s samimi datacijami uvrstimo v določena klimatska obdobja. Vendar se je klima podobno kot danes lahko regionalno in tudi lokalno zelo spreminjala. Zato dobimo veliko natančnejše podatke z raziskavami nekdanjih okoljskih razmer neposredno v jamskih najdiščih. Te raziskave temeljijo na različnih metodah, vse pa se opirajo na preučevanje sedimentov, v katerih so najdbe. Zato je potrebno izkopavanje že pred pričetkom skrbno načrtovati, saj je dostopnost vzorcev za ugotavljanje paleoklimatskih razmer po končanih izkopavanjih lahko zelo omejena, če metodologija izkopavanj ni bila dodelana. Interpretacije z bližnjih najdišč lahko med seboj koreliramo. Zaželeno je, da so korelacije podprte s čim večjim številom datacij, saj le tako lahko ugotavljamo, ali so si rekonstrukcije resnično podobne, in jih potemtakem lahko štejemo za zanesljive.

2. JAMSKI SEDIMENTI IN SEDIMENTACIJSKI PROCESI

V članku se osredotočam na paleolitska najdišča v kraških jamah, ki so zapolnjena s klastičnimi sedimenti. Mednje prištevamo avtohtone (izvirajo iz jamskega okolja) in alohtone (v jamo so prineseni iz zunanjega okolja) kamninske drobce vseh velikosti, od gline do jamskega grušča in velikih blokov, ter tudi vse drugo gradivo, kot so kosti, artefakti, oglje itd.

Jamske sedimente lahko glede na njihov izvor v grobem delimo na tri skupine (Lau et al. 1997; Farrand 2001; White 2007; Ghinassi et al. 2008):

– *sedimenti geogenega izvora* (jamski grušč, ki se je krušil z jamskega oboda in kopičil v jami; jamska ilovica, ki je bila sprana s površja v jamo skozi razpoke v jamskem obodu; jamska siga, ki se kemično izloča iz prenikle vode; puhlica in drugi drobni eolski – vetrni – nanosi; aluvialni nanosi, če v jamo teče oziroma je tekel vodni tok; koluvialni nanosi – predvsem pobočni grušč in material z melišč nad jamo);

– *sedimenti biološkega izvora* (ostanki živali, ki so bivale v jami – predvsem fosilne kosti in zobje; živalski koproliti; razni rastlinski ostanki, kot so pelod in oglje);

– *sedimenti antropogenega izvora* (razni artefakti; ognjišča; tudi drug material, ki so ga v jamo prinesli ljudje, npr. prod, prah, les itd.).

Biogeni in antropogeni sedimenti so pomešani med geogenimi sedimenti, njihov delež pa je praviloma razmeroma majhen v celotni sedimentni skladovnici.

Procesi, s katerimi se sedimenti odlagajo in kopičijo v jamskem okolju, so sinsedimentacijski. S postsedimentacijskimi procesi pa prihaja do sprememb v sedimentih, potem ko so se ti že odložili v jami. Postsedimentacijski procesi najbolj intenzivno potekajo v vrhnji plasti jamskih tal.

2.1 Sinsedimentacijski procesi

Krioklastični jamski sedimenti se v jamah kopičijo zaradi mehanskega preperevanja jamskega oboda. To je najbolj intenzivno ob samem jamskem vhodu, manj pa v notranjosti jame, kjer vpliv zunanjih klimatskih sprememb pojenjuje (s tem pa tudi vpliv zmrzali). Preperevanje je še posebej intenzivno, če se temperature gibljejo okoli nič stopinj Celzija in ob veliki količini vlage. Največ krioklastičnega grušča se odloži ob vhodu v jamo, kjer se tvori sedimentni stožec (talus). K njegovemu nastanku lahko prispeva tudi koluvialni material. Koluvialne sedimente lahko najdemo tudi globlje v jami, če to dopušča morfologija jamskih tal in se koluvialni material tja prikotali. Večji podorni bloki, ki jih najdemo v jamah, naj bi se odkrušili ob rušilnih potresih. Če je jamski vhod dovolj velik, lahko vanj zaidejo eolski nanosi. Značilen eolski nanos je puhlica. Veter lahko prinese v jamo tudi vulkanski pepel in drobni material iz bližnje in daljne okolice. V hidrološko aktivnih jamah se odlagajo aluvialni nanosi. Skozi razpoke v jamskem stropu pa lahko voda spira prst in ilovico s površja nad jamo. Kot je bilo že omenjeno, gre v vseh primerih za material geogenega izvora.

2.2 Postsedimentacijski procesi

Med postsedimentacijske procese štejemo (Lau et al. 1997; Angelucci, Zilhão 2009):

– *bioturbacija* zaradi aktivnosti živali in rastlin v jamskem okolju (teptanje in kompakcija sedimentov, prekopavanje oziroma ritje, razno premeščanje);

– *premeščanje sedimentov* zaradi periglacialnih pojavov (krioturbacija, soliflukcija);

– *raztapljanje karbonatov;*

– *sekundarno fizikalno in kemično preperevanje.* Fizikalno preperevanje se nanaša na delovanje zmrzali, kemično pa predvsem na raztapljanje (korozijo) v vodi topnih sedimentnih kamnin in sedimentnih drobcev (karbonati, deloma kosti);

– *različni diagenetski procesi,* kot so raztapljanje, cementacija in rekristalizacija.

Zaradi biturbacije in procesov, vezanih na periglacialno klimo (krioturbacija, soliflukcija), lahko pride do mešanja sedimentov in premeščanja arheoloških najdb med različnimi plastmi, zaradi česar je potrebna posebna previdnost pri kronoloških interpretacijah najdb v plasteh, kjer sklepamo, da so potekali ti procesi.

3. DATACIJE

Starost najdb in kronologijo ugotovljenih klimatskih sprememb določamo z datacijami. Najbolj razširjene in zanesljive metode datiranja jamskih sedimentov so: termoluminiscenčna metoda datiranja ožganih kremenovih artefaktov (npr. v bližini ognjišč); datacije z uranovim nizom (U/Th) za določevanje starosti kosti in sige; radiokarbonsko datiranje (^{14}C) lesa, oglja, kosti, peloda ali drugih organskih ostankov, ki jih najdemo v sedimentu; elektronska spinska resonanca (ESR) za datiranje sklenine na zobeh jamskega medveda (Lau et al. 1997; Angelucci, Zilhão 2009; Blackwell et al. 2009).

^{14}C-datacije so omejene s starostjo 50.000 let, starejših sedimentov ni možno datirati, zato je ta metoda uporabna samo za končno fazo srednjega paleolitika in mlajši paleolitik. Zanesljivost metode je vprašljiva že pri starosti 45.000 let. U/Th-datacije sežejo okoli 350.000 do največ 600.000 let v preteklost (Low, Walker 1997; White 2007), ESR pa do pet oziroma deset milijonov let v preteklost (Blackwell 2006). Časovni doseg termoluminiscenčne metode je okoli 100.000 let, odvisen je tudi od materiala, ki ga datiramo (kremenov artefakt, keramika …) (Low, Walker 1997).

4. PALEOKLIMATSKE REKONSTRUKCIJE

Posebnost jamskih sedimentov je, da so v primerjavi s površinskimi veliko bolje ohranjeni, saj so v veliki meri zaščiteni pred erozijo in preperevanjem. Še posebej to velja za ohranitev kosti, oglja in organskih artefaktov, ki so glavni predmet zanimanja arheologov in paleontologov. S preučevanjem ene ali več vrst sedimentnih drobcev (npr. oglja, peloda ali kosti) pridobimo informacije o okoljskih razmerah, ki so prevladovale v času odlaganja sedimentov na določenem nivoju. Vendar lahko visoko ločljive okoljske rekonstrukcije pridobimo le s sistematičnim preučevanjem večinskih sedimentov. Zato v tem prispevku namenjam posebno pozornost predvsem preučevanju drobnozrnatih sedimentov (pesek, melj, glina) in grušča, ki običajno predstavljajo večinski delež sedimentne zapolnitve v mnogih paleolitskih jamskih najdiščih. Sedimentacijski in postsedimentacijski procesi so pomemben kazalec klimatskih razmer. S preučevanjem večinskih sedimentov (glina, melj, pesek, grušč) lahko ugotavljamo sedimentacijske in postsedimentacijske procese v jamskem okolju in sklepamo na klimatske procese na površju.

Postsedimentacijski procesi najbolj intenzivno potekajo v vrhnji plasti jamskih tal. Ko se na nekdanja jamska tla odloži nova skladovnica sedimentov, se zapis vseh teh sprememb v zakopanih sedimentih ohrani, saj so ti zaščiteni pred nadaljnjim preperevanjem in nadaljnjimi spremembami, ki bi prejšnje lahko zabrisale. S preučevanjem jamskih sedimentov v profilih, kar je možno predvsem v nekaterih arheoloških (paleolitskih) najdiščih, lahko sklepamo na okoljske in celo temperaturne razmere v času, ko so bili ti sedimenti izpostavljeni spremembam na nekdanjih tleh. Slednje so namreč neposreden odraz klimatskih in okoljskih razmer na površju nad jamo. Da ugotovljene okoljske spremembe uvrstimo v pleistocensko kronologijo, je potrebno sedimente datirati. Neenakomerna hitrost sedimentacije in številne sedimentacijske vrzeli, ki lahko trajajo tudi več 10.000 let, so glavni problem takšnih rekonstrukcij v jamskih okoljih.

4.1 Klasične metode preučevanja fosilnih kosti in peloda v sedimentnem zaporedju

Klasične okoljske rekonstrukcije paleolitskih najdišč v jamah in spodmolih temeljijo na kostnih najdbah pleistocenske favne in pelodov. Pelod je prišel v jamo z vetrom ali preko prehranjevalne verige občasnih jamskih obiskovalcev (predvsem jamski medved, mali sesalci, sove …). Pelod lahko prinese v jamo tudi prenikla voda. Na koncentracijo peloda torej vpliva tudi velikost jamskega vhoda – veter odloži največ peloda v bližini vhoda, precej manj pa v notranjosti jame (Navarro et al. 2001).

Problem takšnih rekonstrukcij je, da je teh najdb razmeroma malo ali pa so za okoljske rekonstrukcije neznačilne, kar velja predvsem za jamsko favno. Na podlagi kostnih ostankov velikih sesalcev ne moremo zanesljivo sklepati na klimo, saj so ti običajno prilagojeni na življenje v različnih klimatskih pasovih. Zanesljiv kazalec ostrih klimatskih razmer so nekatere arktične vrste velikih sesalcev, kot so na primer polarna lisica, mamut, dlakavi nosorog, severni jelen, vendar so kostni ostanki teh živali zelo redki. Pogostejše so kosti malih sesalcev (na primer krt – kjer so tla večino leta zmrznjena, jih ni, ali pa svizec – prilagojen na življenje v ostrejših klimatskih pogojih), še posebej pomembne so kosti glodavcev, na katerih navadno tudi slonijo mnoge okoljske rekonstrukcije, interpretirane na podlagi ostankov favne (Madeyska, Cyrek 2002; Bona et al. 2006; Toškan 2009).

Problem peloda je njegova redkost v jamskih okoljih in vprašljiva reprezentativnost. Pelod je podvržen premeščanju in različnim postsedimetacijskim procesom, zato je običajno slabo ohranjen ali pa je primarnost njegove stratigrafske lege lahko vprašljiva (Woodward, Goldberg 2001; Groner 2004). Pelod se v jamskem okolju dobro ohrani, le če je vlažnost nizka, kar pa je v jamah redko. V vlažnih razmerah je aktivnost mikroorganizmov povečana, ti pa razgrajujejo pelod (Navarro et al. 2001). Bolj zanesljiv kazalec okoljskih razmer je oglje, ki je lahko skoncentrirano v ognjiščih ali pa je razpršeno med sedimenti (Culiberg, Šercelj 1997). Z analizo oglja lahko ugotavljamo vegetacijske združbe in posredno torej tudi okoljske razmere.

4.2 Metode preučevanja jamskih sedimentov

Prevladujoč jamski sediment so kamniti drobci vseh velikosti od gline do grušča in velikih podornih blokov. Zato ti, kot je bilo rečeno, hranijo najbolj zvezen paleoklimatski zapis od vseh jamskih sedimentov.

Metode preučevanja jamskih sedimentov so številne, nekatere so se izkazale kot bolj primerne za rekonstrukcijo paleoklime ali nekdanjega okolja, druge pa manj primerne. Najbolj razširjene metode so granulometrija, mikromorfološka analiza sedimentnih vzorcev, magnetna susceptibilnost (sposobnost namagnetenja), geokemične analize, preučevanje avtogenih mineralov, ki so nastali po odložitvi sedimentov na jamskih tleh.

4.2.1 Granulometrični histogrami

Granulometrični histogrami prikazujejo razporeditev zrn po velikosti v celotnem sedimentnem vzorcu. Če sedimenti pripadajo dvema sedimentacijskima viroma (avtohtonemu – primarno preperevanje jamskega oboda in alohtonemu – na primer eolski nanosi ali koluvij), lahko to ugotovimo že na podlagi analize granulometričnega histograma. Histogram z dvema ali več vrhovi nakazuje dva ali več virov sedimentov. Vrh v območju gline ali melja lahko pripada eolskemu nanosu ali transportu materiala s preniklo vodo skozi jamski obod. Vrh v območju debelozrnatega peska pa lahko pripišemo posledici mehanskega preperevanja jamskega oboda (Mandel, Simmons 1997; Farrand 2001).

Če želimo z granulometrično metodo ugotoviti primarno velikost zrn v sedimentih še pred sekundarno cementacijo zrn v agregate, je potrebno vzorce posebej pripraviti. V vzorcih, kjer se glina ali melj cementirata v agregate, bo granulometrična analiza pokazala največji delež peščene frakcije, ki v resnici ustreza agregatom. Podobno lahko povzročajo določeno motnjo tudi organski delci. V ta namen lahko organsko snov iz vzorcev odstranimo z vodikovim peroksidom (H_2O_2), kalcitni in fosfatni cement, ki vežeta zrna v agregate, pa z razredčeno (10 %) kislino HCl. S to metodo dobimo originalno velikost zrn, odloženih v jamskem okolju, torej še pred postsedimentacijskimi spremembami (Farrand, McMahon 1997).

4.2.2 Mikromorfološka analiza

Mikromorfološka analiza temelji na vzorcih, pobranih iz profila na takšen način, da se vsi sedimenti ohranijo v prvotni legi. Preučujejo se drobnozrnati sedimenti (glina, melj, pesek). Vzorci se zalijejo s smolo, naredijo se zbruski oziroma preparati, ki se pregledajo pod optičnim mikroskopom. Drobnozrnati sedimenti so v kraških jamah večinoma alogenega izvora, torej so bili v to okolje prineseni od zunaj. Na osnovi ugotovljene sestave vzorcev, razmerja med različnimi (mineralnimi) zrni, njihove mikrostrukture, zaobljenosti in drugih lastnosti lahko sklepamo na njihov izvor in posredno na okoljske razmere v času njihovega odlaganja v jami. Eolski sedimenti (manjši od peska, ostrorobi, različne mineralne sestave – kremen, glinenci, sljuda) kažejo na hladno in aridno klimo, sprana ilovica (sestava ustreza sestavi ilovice na površju) pa kaže predvsem na vlažno klimo. Ugotavljamo tudi postsedimentacijske spremembe na sedimentih in (klimatske) pogoje ki so do teh sprememb pripeljali. Mikromorfološka analiza je uporabna predvsem v tistih jamah, kjer se v sedimentnem zaporedju pojavlja pomemben delež sedimentov iz zunanjega okolja, in v jamah kjer so sedimenti močno antropogeno predelani (Ioconis, Boschian 2007; Boschian, De Santis 2010).

Angeluci in Zilhão (2009) sta mikromorfološko analizirala sedimente v jami Gruta da Oliviera na Portugalskem. Z mikroskopijo mikromorfoloških vzorcev sta določila štiri glavne skupine sedimentov, večjih od 1 mm. V prvi skupini sta melj in pesek, kjer prevladujejo kremenova zrna, med zrni se pojavljajo še glineni minerali in sljuda, karbonatnih zrn pa ni. V drugo skupino sta uvrstila sedimente, kjer prevladujejo karbonatni drobci (karbonatna zrna različne velikosti in oblike). Naslednjo skupino tvori sekundarno izločeni karbonat (kalcitni kristali in siga). Četrta skupina so antropogene in biogene komponente, kot so mikroliti (artefakti), kostni drobci in fosfati. V vsaki plasti sta preučevala sestavo oziroma prisotnost štirih glavnih skupin sedimentov velikosti nad 1 mm. Z mikroskopijo sta določila poroznost (prisotnost in velikost por), barvo in tip veziva, mikrostrukturo sedimentnih vzorcev (nedoločljiva, kristalinska, zrnata), prisotnost agregatov, pedomorfološke značilnosti vzorcev (kot so glinene ali fosfatne prevleke na klastih) … Na podlagi analize sta interpretirala procese, ki so vodili do odlaganja sedimentov v določenih plasteh v jami, in ugotavljala izvor teh sedimentov. Ugotovila sta vodne nanose v jami, spiranja ilovice v jamo skozi razpoke v jamskem stropu. Siga se pojavlja v vseh plasteh, kar kaže na stalen dotok prenikle vode v jamo v vseh časovnih obdobjih. Podobno velja za kopičenje fosfata v jami. Tako siga kot fosfat kažeta na trajno vlažne razmere v času odlaganja sedimentov v jami. Rezultati nudijo predvsem vpogled v pojav in jakost različnih sedimentacijskih in postsedimentacijskih procesov v jami, ki jih lahko razlagamo z zunanjimi klimatskimi procesi. Sklepanje na klimo je torej le posredno, časovna resolucija ugotovljenih klimatskih sprememb pa je odvisna od jakosti procesov na površju in izpostavljenosti jamskega okolja tem vplivom (torej od morfologije jamskega vhoda, debeline jamskega stropa, topografije reliefa v okolici jame itd.). Kljub vsemu se ta metoda v literaturi velikokrat navaja kot najbolj perspektivna za preučevanje paleoklime.

4.2.3 Magnetna susceptibilnost

Raziskave te vrste (sposobnost namagnetenja) so možne tam, kjer so bili površinski sedimenti preneseni ali erodirani v jamsko okolje. S spreminjanjem klime se spreminja tudi magnetni zapis v sedimentih na Zemljinem površju. V mrzlih klimatskih obdobjih se pedogeni procesi na površju odražajo v manjši jakosti magnetne susceptibilnosti (MS) kot v toplih klimatskih obdobjih. V toplih klimatskih razmerah potekajo močne kemijske spremembe v sedimentih na Zemljinem površju, predvsem oksidacija kot posledica mikrobiološke aktivnosti. Nasprotno v mrzli klimi poteka redukcija. Oksidacija vodi v kopičenje hematita (Fe_2O_3) v sedimentih in torej v povečanje jakosti MS. Zapis se po transportu v jamsko okolje ohrani, saj so nadaljnji pedogeni procesi v jamah minimalni v primerjavi s tistimi na površju, seveda če niso izpostavljeni močnim postsedimentacijskim spremembam zaradi daljše sedimentacijske vrzeli. Paleoklimatske rekonstrukcije so možne na podlagi zveznega vzorčenja takšnih sedimentov iz arheoloških profilov. V sedimentnih vzorcih se meri koncentracija železovih mineralov, večja, kot je koncentracija, večja je MS (Ellwood et al. 1998).

V jami Caldeirao na Portugalskem so z omenjeno metodo preučili zvezne sedimentne vzorce, vzete iz dveh profilov. Kronologija klimatskih sprememb na MS-krivulji je bila podkrepljena s ^{14}C-datacijami. Najbolj mrzla klima sovpada z zadnjim glacialnim vrhuncem (24.000–22.000 let pred sedanjostjo). Ugotovili so še tri klimatske cikle, vsak naj bi obsegal časovno obdobje okoli 2500 let (*sl. 1*) (Ellwood et al. 1998).

Metoda je pokazala dobro korelacijo z neodvisnimi raziskavami klime v pleistocenu. Vendar je omejena na jamska najdišča, kjer so v sedimentni skladovnici zvezni nanosi alohtonega materiala, ki izvira s površja ali pa ti vsaj predstavljajo znaten delež v vsakem sedimentnem nivoju. Omejitev metode je tudi drag analitični postopek ugotavljanja MS v sedimentnih vzorcih.

4.2.4 Geokemične analize in preučevanje diagenetskih sprememb

Z geokemičnimi analizami ugotavljamo predvsem sestavo cementov (v brečah, agregatih), sestavo oblog na klastih in izvor alohtonih sedimentov. Geokemične analize vključujejo tudi preučevanje diagenetskih sprememb. S preučevanjem diagenetskih sprememb na sedimentih lahko sklepamo, pod kakšnimi pogoji so te spremembe potekale, in torej ugotavljamo paleoklimatske in okoljske kazalce. Podzemna (prenikla) voda, ki je v jami neposredno povezana s količino padavin, povzroča večino diagenetskih sprememb, zato te niso značilne za suhe jame (Woodward, Goldberg 2001). Najbolj značilni sta raztapljanje in korozija karbonatnih zrn (klastov) ter tudi kosti. Korozijske razjede na klastih in kosteh so torej kazalec vlažne klime (Turk et al. 2005). Voda hkrati z raztapljanjem povzroča migracijo kalcitnih in fosfatnih komponent, ki se nato odložijo v obliki cementa. Kalcitni ali fosfatni cement lahko zlepi skupaj različno velike klaste grušča in kosti, s čimer v jamskih tleh nastanejo strukturni (avtogeni) agregati (zlepljeni so manjši drobci) ali pa breče. Fosfat je v jamah, kjer je veliko organskih ostankov (kosti, gvano) (Turk et al. 2007).

Pojav raznih oblog na klastih, kakršne so glinene, železove in manganove, je tudi kazalec vlažnih in oksidacijskih razmer. Obloge so različnih debelin, običajno pa so zelo tanke, tudi manj kot 1 mm (White 2007).

4.2.5 Preučevanje avtogenih mineralov

Avtogeni minerali nastajajo sekundarno v že odloženem sedimentu pod določenimi kemičnimi pogoji (pH, Eh) ob prisotnosti raztopin, bogatih s kalcijem, fosforjem ali aluminijem. Avtogeni minerali so stabilni le v določenih kemijskih pogojih, s spremembo kemizma prenikle (ali podzemne) vode pa pride do rekristalizacije v bolj stabilno mineralno obliko. Vsaka sprememba v dotoku in v kemičnih lastnostih vode v jami je povezana z biološko aktivnostjo (zunaj in v jami) in torej tudi s spremembami v zunanji klimi (Woodward, Goldberg 2001; Madeyska, Cyrek 2002).

V jami Theopetra (Grčija) se v različnih plasteh pojavljajo nekoliko drugačne združbe avtogenih mineralov, vsaka odseva točno določene kemične pogoje, ki so vladali v tistem času, ko so ti minerali nastajali. Njihov nastanek je vezan le na skrajno vrhnjo plast jamskih sedimentov oziroma na jamska tla (Karkanas et al. 2000). Voda, ki je tekla skozi sediment, bogat z organskimi ostanki, je reagirala s kalcitom (ali dolomitom) in izločil se je avtogeni mineral dahllit (karbonatni apatit), ki je tudi glavna sestavina fosilnih kosti. Dahllit je obstojen le v bazičnih pogojih (pH nad 7). Takšni pogoji prevladujejo v jamah, zapolnjenih predvsem s karbonatnimi sedimenti (apnenec, dolomit), saj karbonat nevtralizira kisle raztopine, ki se sproščajo ob raztapljanju organskih snovi (npr. kosti). Če pH-vrednost pade med 6 in 7 (kislo), potem dahllit rekristalizirala v bolj stabilna crandallit ali montgomerit, slednja pa ob še bolj kislih pogojih končno rekristalizirata v taranakit (kalijev, aluminijev fosfat). S preučevanjem združb avtogenih mineralov torej sklepamo predvsem na kemične lastnosti prenikle vode in na njeno korozijsko sposobnost, ki lahko v izjemnih pogojih (pH nižji od 7) povzroči, da se kostni ostanki, ter tudi oglje in pelod, ne ohranijo v jamskem okolju. Identifikacija avtogenih mineralov poteka z difrakcijo X-žarkov ali pa z metodo infrardeče spektroskopije (Karkanas et al. 2000; Shahack-Gross et al. 2004).

4.2.6 Sedimentološka analiza debelozrnate frakcije (grušča)

V geoarheološki znanosti je nekako veljalo prepričanje, da s preučevanjem debelozrnatih sedimentov ni možno pridobiti visoko ločljivih paleoklimatskih zapisov. Občutljivost debelozrnatih sedimentov naj bi bila tudi manj dovzetna na klimatske spremembe. Podatke o klimatskih spremembah naj bi bolj zanesljivo pridobili z analizo drobnozrnatih sedimentov, predvsem z mikromorfološko analizo. Drobnozrnati sedimenti naj bi bili bolj občutljivi na klimatske spremembe, okoljske in klimatske rekonstrukcije naj bi imele zato tudi boljšo časovno ločljivost (Woodward, Goldberg 2001).

Pri klasičnih analizah debelozrnatih klastičnih sedimentov takšna hipoteza sicer velja. Osnovna analiza sedimentov loči debelozrnat grušč, ki se je odlagal predvsem zaradi krušenja jamskega oboda ob delovanju zmrzali. Takšen grušč je torej krioklastičnega nastanka. Delovanje zmrzali in krušenje je najbolj intenzivno ob jamskem vhodu oziroma v njegovi bližini ter pojenja v smeri proti jamski notranjosti. Globlje v jamo gremo, manjši je vpliv zunanje klime. Odlaganje grušča (oglat, ostrorob) torej nakazuje mrzlo klimo. Pri interpretaciji je vseeno potrebna pazljivost, saj na odlaganje grušča vplivajo tudi pretrtost kamnine (na primer tektonska), rast sekundarnih mineralov in seizmična aktivnost (Woodward, Goldberg 2001). Tudi nanosi koluvialnih sedimentov so kazalec hladne klime (Cremaschi 1990).

Prisotnost jamske sige kaže na toplejša klimatska obdobja, saj se siga izloča le v razmeroma topli in predvsem vlažni klimi (*sl. 2*). V takšnih pogojih je voda, ki pronica s površja skozi jamski strop, zaradi bujnega rastja in biološke aktivnosti bogata z ogljikovim dioksidom. Takšna voda je korozivna in raztaplja kalcijev karbonat v kamninski gmoti, s čimer postane prenasičena. Koncentracija CO_2 v jamski atmosferi je okoli desetkrat manjša kot na površju, zato CO_2 iz prenikle vode uide v jamsko atmosfero, hkrati pa se izloča kalcijev karbonat v obliki sige (White 2007). Tudi breče, kjer kot vezivo ponovno nastopa kalcit ali pa tudi fosfat, so kazalec tople in vlažne klime. Izluževanje in ponovno izločanje kalcita in fosfata zahteva vlažno klimo (Campy et al. 1994; Quinif 2006). Kemično preperevanje nasploh je intenzivnejše v toplih obdobjih. Posledica takšnega preperevanja so železove, manganove in fosfatne obloge na klastih. V zelo majhnih količinah nastaja tudi netopni ostanek v velikosti gline (Madeyska 2002).

Kot primer klasične analize klastičnih sedimentov, ki nudi le grobo paleoklimatsko interpretacijo, navajam raziskavo Cremaschija (1990). Preučil je debelo- in drobnozrnate sedimente v sedmih italijanskih jamah (paleolitskih najdiščih). Sedimente je razdelili v tri sedimentacijske cikle, ki odražajo klimatske spremembe v pleistocenu. V prvem ciklu se je odlagal koluvij, ki nakazuje vlažno in hladno klimo. V drugem ciklu je sledilo ponovno odlaganje koluvija ter krioklastičnega grušča, puhlice, vmes se pojavlja še pedogeni horizont (nekdanja tla). Vse to nakazuje spremenljive klimatske razmere. Koluvij se je odlagal v vlažni in mrzli klimi, krioklastični grušč v podobnih a še bolj ostrih (mrzlih) klimatskih razmerah, puhlica pa v suhi in še vedno mrzli klimi. Sledila naj bi postopna omilitev klimatskih razmer, saj pedogeni horizont nakazuje zmerno klimo. Omenjeni klimatski cikel kaže na glacialne razmere. V tretjem ciklu so se odlagali podobni sedimenti kot v drugem. Tudi zadnji sedimentacijski cikel je Cremaschi (1990) interpretiral kot glacialni. Na podlagi tipologije kamnitih orodij, najdenih v omenjenih sedimentih, in na podlagi redkih radiokarbonskih datacij so ugotovljene klimatske cikle uvrstili v pleistocensko kronologijo. Prvi cikel naj bi odgovarjal kisikovi izotopski stopnji (OIS) 5a do 5d (115.000–74.000 let pred sedanjostjo). Ta stopnja je sledila zadnjemu interglacialu (Eemian), zanjo je značilno hitro zaostrovanje klimatskih razmer. Drugi sedimentacijski cikel so uvrstili v OIS 4 (74.000–59.000 let pred sedanjostjo, stadial) in OIS 3 (59.000–29.000 let pred sedanjostjo, interstadial), zadnji sedimentacijski cikel pa v OIS 2 (29.000–11.000 let pred sedanjostjo, stadial). Takšne klasične paleoklimatske rekonstrukcije so bile zelo grobe in primerjave z visoko ločljivimi klimatskimi zapisi niso bile možne (na primer primerjava s krivuljo GRIP – glej poglavje *6. Korelacije*). Velik problem so bile redke zanesljive datacije, ki so nasploh predpogoj za določanje kronologije klimatskih sprememb.

Ivan Turk (2006; 2007) je v jami Divje babe I (Slovenija) uvedel nekatere inovativne metode ugotavljanja paleoklime, ki temeljijo prav na analizi debelozrnate sedimentne frakcije. Rekonstrukcijo temperaturnih razmer je izvedel s preučevanjem avtohtonih zmrzlinskih klastov, na vlažnost v pleistocenu pa je sklepal na podlagi pojavljanja avtogenih agregatov in izjedkanih klastov ter kosti v sedimentih.

Visoko ločljive paleotemperaturne zapise lahko dobimo s preučevanjem morfoloških značilnosti debele frakcije in ugotavljanjem delovanja zmrzali na že odložene klaste. Delež zmrzlinskih klastov je bil zvezno preučen v okoli 10 cm debelih sedimetacijskih nivojih, ki so bili vzeti iz dveh profilov (J. Turk, M. Turk 2010). Značilnost zmrzlinkih klastov je, kot že ime pove, da so nastali zaradi mehanskega preperevanja ob delovanju zmrzali. Pomembno pa je, da metodologija I. Turka (2006) temelji izključno na tistih zmrzlinskih klastih, ki so razpadli postsedimentno oziroma v vrhnji plasti jamskih tal. Ker zmrzal deluje v tleh le do določene globine, so vsi klasti po zasutju z novimi sedimenti zaščiteni pred nadaljnjim preperevanjem in drugimi spremembami. Večji kot je delež zmrzlinskih klastov v določenem nivoju, bolj intenzivno je potekalo preperevanje v času, ko so bili sedimenti tega nivoja izpostavljeni klimatskim pogojem (na površju sedimentov v jamskih tleh) (Turk et al. 2006; Turk et al. 2007; J. Turk, M. Turk 2010). Zvezno vzorčenje in analiza sedimentov iz teh vzorcev je pokazala dve izraziti ohladitvi, ki sta se pojavili nekje med 80.000 in 40.000 pred sedanjostjo, kolikor je ocenjena skupna starost sedimentov iz preučevanih profilov glede na razpoložljive datacije (*sl. 3*). Natančnejša umestitev ugotovljenih hladnih dob je možna z dodatnimi radiometričnimi datacijami ali pa s korelacijami (glej poglavje *6 Korelacije*). Slednje smo uporabili v jami Divje babe I. Časovna ločljivost ugotovljenih klimatskih sprememb pri omenjeni metodi je odvisna od povprečne hitrosti sedimentacije. V Divjih babah I je ta zanašala od okoli 0,01 do 0,04 centimetrov na leto (Blackwell et al. 2009), časovna ločljivost klimatskih sprememb pa 1000±500 let, kar je verjetno najvišja časovna ločljivost, pridobljena z analizo klastičnih sedimentov.

I. Turk s sodelavci (2006) je na nekdanjo vlago sklepal na podlagi količine avtogenih agregatov, ki so jih vzorčili v 64 profilih. Agregati so predvsem fosfatni in so jih povezovali z organskimi snovmi, ki jih je prispeval predvsem jamski medved (Turk et al. 1988). Ugotovil je, da so avtogeni agregati neenakomerno porazdeljeni ne samo po globini sedimentacijskih nivojev, pač pa tudi vzdolž posameznega nivoja. Slednje se dobro ujema z dotokom podzemne vode. Glede na zastopanost avtogenih agregatov v sedimentacijskem zaporedju na dveh lokacijah v jami so ugotovili, da je njihov delež na obeh lokacijah povečan v plasteh, ki datirajo v starejši del OIS 3 oziroma morda v OIS 4 (vsaj del OIS 4 manjka zaradi sedimentacijske vrzeli) (Turk et al. 2006) (*sl. 4*). Ugotovljene rezultate so korelirali in podkrepili z deležem reliefno korodiranih klastov in izjedkanih kosti. Stopnjo korozije in količino izjedkanih kosti so povezali s količino vlage v tleh in s kemičnimi reakcijami (Turk et al. 2005).

5. HIATUSI

Problem pri določevanju kronologije preteklih okoljskih sprememb v jamah je, da se sedimenti ne odlagajo zvezno. Še poseben problem predstavljajo sedimentacijske vrzeli oziroma hiatusi. Če se sedimenti več tisoč ali več deset tisoč let niso odlagali, potem za ta obdobja ni možno dobiti klimatskih in okoljskih zapisov.

Problem je že določiti hiatus, njegovo trajanje pa lahko zanesljivo ugotovimo le z datacijami sedimentov tik nad in tik pod njim. Na hiatus lahko sklepamo že na podlagi značilnosti sedimentov. V obdobju daljše sedimentacijske vrzeli so talninski sedimenti dolgo časa izpostavljeni mehanskemu in kemičnemu preperevanju, bioturbaciji, kemičnim in drugim diagenetskim spremembam. Na te procese kažejo že sprememba v barvi sedimentov zaradi oksidacije, povečana zaobljenost klastov (grušča), povečan delež glinene frakcije, manjša vsebnost karbonata v klastih, ter tudi nenadne spremembe v združbi težkih mineralov (Zn, Cu, Ni, Co, V, Cr itd.) (Farrand 2001). V nivoju, kjer je delež kalcijevega karbonata izrazito manjši kot v sosednjih nivojih, lahko sklepamo na močno kemično preperevanje kot posledico sedimentacijske vrzeli. Kemično preperevanje vodi v izluževanje karbonata, kar se pozna na deležu kalcijevega karbonata v nivoju, ki se je odložil tik pred nastopom sedimentacijske vrzeli. Seveda je pri takšnih interpretacijah potrebna določena previdnost, razlogi za zmanjšanje vsebnosti kalcijevega karbonata so lahko tudi drugi, kot je na primer izpostavljenost visokim temperaturam v neposredni bližini ognjišč (Mandel, Simmons 1997). Opisane spremembe niso odvisne le od trajanja sedimentacijske vrzeli, pač pa tudi od klimatskih pogojev. Ker imajo ti večji vpliv v vhodnem delu jam, so spremembe tu večje kot v notranjih predelih jam (Farrand 2001). Za obdobje sedimentacijske vrzeli je značilno tudi odlaganje sige na jamskih tleh. Če se med plastmi klastičnih sedimentov pojavlja siga, je to že znak, da je bila sedimentacija tedaj prekinjena za daljše časovno obdobje (Angelucci, Zilhão 2009). Hkrati pa siga, kot rečeno, kaže na vlažno in razmeroma toplo klimo.

Inovativen pristop za ugotavljanje sedimentacijskih vrzeli je bil izveden v paleolitskem najdišču Divje babe I. Ivan Turk (2006) je ugotovil, da je možno oceniti relativno hitrost sedimentiranja s preučevanjem reliefno korodiranih klastov, ki so se odluščili z jamskega svoda (J. Turk, M. Turk 2010). V času daljše stabilnosti jamskega stropa (oziroma sedimentacijske vrzeli) je kondenzna vlaga strop močno korodirala. Ponovno krušenje stropa je povzročilo, da dobimo v sedimentnem nivoju, ki se je odložil tik nad sedimentacijsko vrzeljo, veliko povečanje klastov z značilnimi oblikami, nastalimi na stropu zaradi reliefne korozije (ki jo je povzročila kondenzna vlaga).

6. KORELACIJE

Ugotovljene klimatske spremembe same po sebi nimajo velike vrednosti, če jih ne moremo umestiti v pleistocensko kronologijo. Detajlno datiranje celotnega sedimentnega zaporedja je draga metoda, zato se pri kronologiji običajno zanašamo na nekaj opornih datacij, ki služijo za pomoč pri korelaciji ugotovljenih klimatskih sprememb z neodvisnimi raziskavami, opravljenimi drugod v regiji ali po svetu, in za katere velja, da so kronološko zanesljive (vsaj za obstoječ znanstveni pristop).

Kronologija globalnih klimatskih sprememb naj bi se najbolje odražala na globokomorskih sedimentih in v arktičnem (ter antarktičnem) ledu (Lowe, Walker 1997). Z vrtanjem v globokomorske sedimente in v "večni" led (neprekinjeno se je kopičil v obdobjih pleistocena in holocena) so pridobili zapis o izotopski sestavi kisika ($\delta^{18}O$), ki je odvisen od klimatskih razmer. Starost sedimentov oziroma prirastnic v ledu z določenim izotopskim zapisom pa ugotavljajo s štetjem letnih prirastkov. Ker je letne prirastke na večjih globinah med seboj težko ločiti, uporabljajo nekatere poenostavitve, ki lahko povečajo napako v dataciji določene klimatske faze (Svensson et al. 2008).

Regionalne kronologije klimatskih razmer temeljijo predvsem na palinoloških raziskavah jezerskih sedimentov (Watts et al. 2000; Andrič et al. 2009). Pelodni ostanki v sedimentih nam govorijo o drevesnih združbah, po čemer lahko sklepamo na klimo. Ker je pelod možno datirati, so te rekonstrukcije dobro umeščene v čas.

Problem jamskih okolij je, da so imeli klimatski zapisi nizko časovno ločljivost, zato so bile možne le grobe korelacije z visoko ločljivimi klimatskimi zapisi, kakršen je GRIP ($\delta^{18}O$ v grenlandskem ledu, *sl. 5*), ali zapisi iz jezerskih sedimentov. Ena od redkih izjem je paleotemperaturni zapis iz Divjih bab I (*sl. 3*). Korelacije so potekale predvsem med različnimi najdišči v isti regiji oziroma na podobni geografski širini. Pri takšnih korelacijah se pojavljajo problemi, saj se debelina sedimentov od najdišča do najdišča razlikuje, razlikujejo se hitrosti sedimentacije, sedimentacija ni potekala v različnih najdiščih istočasno, torej se hiatusi pojavljajo v različnih časovnih obdobjih (Campy et al. 1994; Woodward, Goldberg 2001) (*sl. 2*).

Korelacije različnih jamskih najdišč lahko temeljijo na markerjih, to so značilni sedimentni horizonti, kakršna sta na primer puhlica in vulkanski pepel. Če se puhlični horizont nahaja v več jamah v isti regiji, lahko sklepamo, da gre za sedimentacijski horizont iste starosti, torej za kronološki marker. Podobno velja za vulkanski pepel. Ob večjih vulkanskih izbruhih ta potuje več sto kilometrov daleč in lahko z vetrom zaide v jame. Na podlagi značilne mineralne sestave pepela lahko te horizonte v različnih jamah med seboj koreliramo in tudi določimo njihovo starost (Pirson et al. 2006).

7. SKLEP

Metode preučevanja paleoklimatskih sprememb so številne, vendar nobena sama po sebi ni popolnoma zanesljiva. Zato je treba uporabljati več med seboj neodvisnih metod, dobljene rekonstrukcije pa med seboj primerjamo in ugotavljamo njihovo ujemanje, s čimer lahko potrdimo njihovo pravilnost. Katere metode bomo uporabili, je zelo odvisno od vrste sedimentov, ki so v jami, to se pravi, ali prevladuje krioklastični grušč, ali pa sedimenti prineseni v jamo iz zunanjega okolja (alohtoni sedimenti, kot sta koluvij, ilovica).

V naslednji fazi poskušamo ugotovljene klimatske cikle korelirati z drugimi klimatskimi zapisi, pridobljenimi v drugih paleolitskih najdiščih, ki se nahajajo na podobni geografski širini. Korelacije lahko izvajamo tudi z zapisi, pridobljenimi iz palinoloških raziskav, opravljenih v jezerskih sedimentih, in pa z globokomorskimi zapisi ter GRIP-zapisom. Razvoj novih metod, kakršna je metoda preučevanja deleža zmrzlinskih klastov ali pa magnetna susceptibilnost v sedimentih, vzorčenih iz arheoloških profilov, predstavlja izredno pomemben vir za paleoklimatske interpretacije iz obdobja pleistocena. Torej ne gre za raziskave, ki bi bile pomembne le za arheologe in geologe, temveč tudi za splošno pomembne raziskave ugotavljanja klimatskih nihanj v preteklosti.

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