On the Significance of Divje babe I Cave for the Stratigraphy, Sedimentology, and Chronology of Palaeolithic Cave Sites in Slovenia

O pomenu jame Divje babe I za stratigrafijo, sedimentologijo in kronologijo jamskih paleolitskih najdišč v Sloveniji

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Izvleček

V članku sta podana pregled razvoja in razlaga postopkov, uporabljenih pri proučevanju profila paleolitskega jamskega najdišča Divje babe I. Podatke smo pridobili iz objav, arhivskega gradiva in osebnih informacij Ivana Turka, ki je vodil izkopavanja in ciljno usmerjal laboratorijske raziskave. Profil Divjih bab I je trenutno najbolje raziskan in kronološko opredeljen mlajšepleistocenski jamski profil v Sloveniji. Različni sedimentološki in drugi podatki iz standardnega profila so bili prvič nadgrajeni z istimi podatki, pridobljenimi na standardnih tlorisnih površinah in globinah. Ugotovljena je bila velika prostorska (lateralna) variabilnost, povezana s sicer sočasnimi, vendar različnimi jamskimi mikrookolji, na katera je odločilno vplivala različna prisotnost vode v vseh agregatnih stanjih. Brez upoštevanja časovne in prostorske dimenzije ne bi bilo mogoče povezati vseh statističnih množic zbranih podatkov o sedimentih, njihovi vsebini in klimatskih parametrih v enovit sistem.

Ključne besede: jama Divje babe I; mlajši pleistocen; variabilnost sedimentov; jamska mikrookolja; kongelifrakcija; korozija; klima

Abstract

The article reviews the development and interpretation of procedures used in the study of the sedimentary sequence of the Divje babe I Palaeolithic cave site. The data were obtained from publications, archives, and personal information provided by Ivan Turk, who directed the excavations and directed the laboratory investigations. The profile of Divje babe I is currently the best researched and chronologically defined Late Pleistocene cave profile in Slovenia. For the first time, various sedimentological and other data from the standard profile were upgraded with the same data obtained on standardized ground plan surfaces and depths. A large spatial (lateral) variability was discovered, associated with generally contemporaneous but different cave microenvironments, which were crucially influenced by different amounts of water in all aggregate states. Without taking into account temporal and spatial dimensions, it would not be possible to combine all statistical sets of collected data on sediments, their contents, and climatic parameters into a unified system.

Keywords: Divje babe I cave; Late Pleistocene; sedimentary variability; cave microenvironments; congelifraction; corrosion; climate

Fig. 1: The view of the north slope of the Šebreljska planota (Šebrelje plateau) with the entrance to the Divje babe I cave (marked by a circle) and a location map.
Sl. 1: Pogled na severno pobočje Šebreljske planote z označenim položajem jame Divje babe I (označeno s krogom).

The palaeontological and archaeological cave site Divje babe I is located in western Slovenia, in the pre-Alpine hills, under the edge of the Šebreljska planota (Šebrelje plateau) (*Fig. 1*). The cave, formed in dolomite, opens on the steep, north-facing slope above the valley of the Idrijca River at an altitude of 450 m a.s.l. The site is widely known for the discovery of the unusually perforated femur of a young cave bear, which is interpreted as a Neanderthal musical instrument (M. Turk *et al.* 2018). However, the site is also interesting because of other important finds and innovative research approaches (Turk 2007a; 2014a).

In the years 1978–1986, Mitja Brodar carried out systematic excavations in Divje babe I. The excavations were continued in 1989–1999 by Ivan Turk and Janez Dirjec. The second excavation campaign brought some completely new approaches to the interpretation of the cave clastic and chemical sediments. I. Turk was their conceptual creator. Because of the potential of the findings from these approaches for the study of cave sites, this paper presents a summary with additional explanations of his ideas and findings published in numerous articles. Some previously unpublished data and findings are reproduced according to the extensive documentation from the archives of the Institute of Archaeology ZRC SAZU.[1]

Pleistocene cave sediments are important, both for their archaeological and/or palaeontological content and for the possibilities they offer for various other interdisciplinary studies. The study of sediments determines their formation, origin, and diagenesis. All this can be observed more or less continuously (depending on interruptions in sedimentation) in a given sedimentary profile. In contrast, such observation is usually not possible for archaeological and palaeontological finds, due to the presence of sediments without finds. Since cave sediments vary according to their micro-location due to the specific sedimentary environment, the interpretation of sedimentological research must necessarily take into account their spatial variability, to which too little attention has been paid thus far (see Farrand 2001).

The study of Pleistocene sediments in Palaeolithic cave sites has a long tradition in Slovenia (S. Brodar 1939; 1958; 1966; M. Brodar 1959; Osole

[1] Turk, I. 2002, Elaborat Divje babe I. Izkopavanja 1989–1999, Archives of the ZRC SAZU, Institute of Archaeology.

1961; 1968; 1986). It was mainly limited to karst caves formed in limestone. In contrast, the Divje babe I cave is formed in dolomite, and at the beginning of M. Brodar's excavations, this site was an exception without a corresponding comparative practice due to the different sediments (M. Brodar 1999, 39). Thus, Divje babe I became a seemingly unsolvable, or at least difficult to solve, problem in the field of Pleistocene cave sedimentology in Slovenia. The question even arose as to what sense the routine sedimentological analysis valid at that time would have in this case. In 1997, when the opportunity arose for systematic radiometric dating of the Divje babe I profile with electron spin resonance (ESR),[2] I. Turk decided to carry out a parallel pilot analysis of sediments from all layers, dated by this method. After the end of the systematic excavation in 1999, he started a thorough analysis of all excavated sediments based on his own idea and started an informal cooperation with the geologist Dragomir Skaberne from the Geological Survey of Slovenia.[3]

THE RESEARCH METHODS AND THEIR USE IN SLOVENIAN PALAEOLITHIC CAVE SITES WITH EMPHASIS ON THE NEW METHOD APPLIED IN DIVJE BABE I

Let us first present the main characteristics of the primary working method in sedimentology of Palaeolithic sites in Slovenia until 1999. The results of investigations of cave sediments in Palaeolithic sites in Slovenia were usually a component part of the chronology of sites and Palaeolithic finds. In research, the qualitative and deductive method was used almost exclusively, which presupposed certain regularities in sedimentation (e.g., alternation of gravel and clay layers) based on hypotheses. For example, it was assumed that the cave gravel was typical of colder climates and the cave clay of warmer climates (S. Brodar 1958; M. Brodar 1959, 438; Osole 1961), which is a fundamental fallacy (White 2007). The main assumption that climate was a key factor influencing cave sediments during the Pleistocene has never been tested from site to site. Therefore, the deviation of the values of the analysed attributes (parameters), mainly grain (clasts) size, in Pleistocene sediments from those of Holocene sediments, formed in a more or less known climate, was never determined. Not a single example of such a test is known from anywhere else. Exceptionally, the repeatability of the results of the technical part of the method has been verified within a single site by the samples from different profiles (M. Brodar 1959; Farrand 1975, and others). From the multitude of sedimentological attributes that may or may not be related to climate, the most influential attribute or attributes were never selected by the consistent application of the abstraction method. Therefore, once a particular attribute was analysed, which was usually the distribution of fine grain size fraction in profiles analysed by the quantitative method, no attempt was made to link it to other sedimentological attributes using the synthesis method. Indeed, this was not possible as other attributes were not adequately quantified but were at best descriptively stated.

After almost 70 years of extensive, including multidisciplinary research (see Stritar *et al.* 1967) in numerous Palaeolithic cave sites in Slovenia, the excavations at Divje babe I and the innovative sedimentological research of I. Turk mark a turning point (Skaberne *et al.* 2015a; 2015b). We expect his findings to be useful at other sites with similar sedimentary environments and similar phenomena, such as congelifracts, cavernously corroded clasts, and phosphate aggregates. In Slovenia, such sites are caves Jama pod Herkovimi pečmi, Matjaževe kamre, Mokriška jama, Njivice and Potočka zijalka. For the analysis of sediments from Divje babe I, Turk used the empirical method, supported by statistics, not neglecting the qualitative signs of attributes, which he combined with the quantitative ones. Each hypothesis, either his own or adopted, he tested within the given possibilities, also experimentally if possible. In order to test the old chronological scheme for the classification of Middle Palaeolithic sites in Slovenia, he laid the foundations for an independent radiometric chronology in informal cooperation with foreign colleagues (Nelson 1997; Ku 1997; Lau *et al.* 1997; Blackwell *et al.* 2007; 2009). To the extent possible, he applied the method of abstraction and removed all sedimentological attributes irrelevant to the

[2] The site was first dated in 1990 using the then-new AMS ^{14}C method. The method was developed by D. E. Nelson and his team (Nelson 1991; 1997). Divje babe I is one of the first Palaeolithic sites in Europe to be dated using this method.

[3] The sediment analysis project was not approved. Nevertheless, sediment analysis was carried out in the 1999–2014 period within the limited financial and technical possibilities.

climate model, including the distribution of fine grain size fraction. During the fieldwork, I. Turk developed a new model of the sedimentation process in the cave environment based on the interrelated sedimentological attributes reflecting both climatic conditions and sedimentation rate. The latter was insufficiently or not at all considered in the old model. The only attributes that are important are those that are undoubtedly related to climate and that occur continuously in time (vertical dimension) and space (lateral dimension) at the site. Previously, too little attention had been paid to the collection and statistics of continuous data on sediment properties and their spatial variability. Despite the opportunities offered by each major excavation and computer support to process the data sets, in most cases, this opportunity was not taken. The main reason for this was the technique of frontal excavation by layers from profile to profile and collecting finds without sieving the sediments. The new sedimentation model could only be developed on the basis of excavation by spits and quadrats and the wet sieving of all sediments, including the archaeologically sterile ones.

The vertical dimension

In Divje babe I, the vertical dimension was mainly represented by spits used to remove sediments. After 1989, the spit thickness was always 12 cm, which is the optimal thickness considering the texture of the sediments, which contain many clasts larger than 10 cm. Spits can be equated with sedimentation levels, a stratigraphic category used and defined in Divje babe I by I. Turk. Sedimentation levels follow the dip of layers when the boundaries between layers are not horizontal in the transverse and/or longitudinal directions. If necessary, several successive sedimentation levels

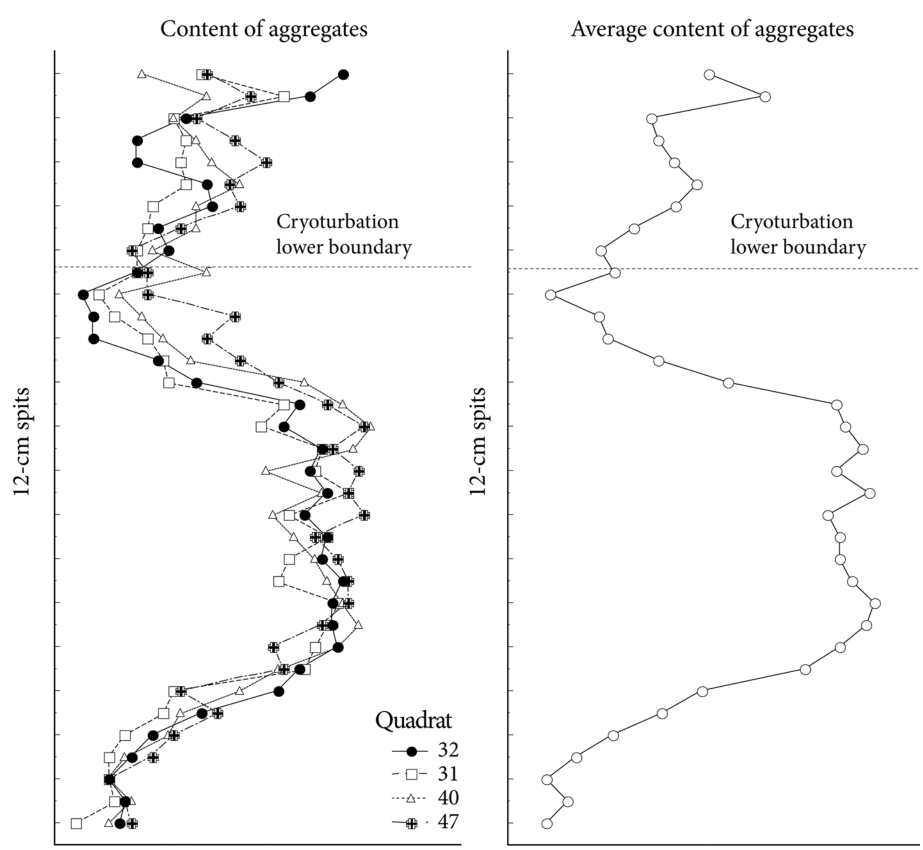

Fig. 2: A simplified presentation of variability of aggregate content in the lateral direction according to spits and quadrats (left) and their mean value (right) in a constant volume of sediments of constant ground plan surface, which represents 0.73% of the entire cave surface.
Sl. 2: Poenostavljen prikaz variabilnosti vsebnosti agregatov v bočni smeri po režnjih in kvadratih (levo) ter njihova srednja vrednost (desno) v stalnem volumnu sedimentov stalne tlorisne površine, ki predstavlja 0,73 % celotne površine jame.

can be joined into a larger unit, such as a layer, and several layers in their sequence (see Skaberne *et al.* 2015a).

A geological layer, by its definition, is a homogenous unit formed (theoretically) under the same physicochemical conditions and in uniform processes and their uniform sequence. Each layer is separated from the lower and upper layers on the basis of one (or more) basic sedimentary characteristics. The characteristics of the layers are influenced by physical, chemical, biological (including anthropological), geological and diagenetic conditions. As a rule, stratification occurs in the sediment when changes arise in the material that is being deposed. In the cave environment where clastic sediments prevail, this is not a frequent occurrence. Invisible sedimentary hiatuses (gaps) between layers, which affect the completeness of the chronological record, result from interruption of sedimentation, erosion, or changes in sedimentation conditions. If we manage to determine hiatuses using dating and sedimentological research, we can distinguish multiple sedimentation cycles separated by interruptions in sediment deposition (see Blackwell *et al.* 2020; J. Turk 2011). When excavating new layers, this obviously cannot all be determined simultaneously in the field. Therefore, so-called geological layers determined in the field are only a temporary working aid for stratigraphic and chronologic sorting of finds, carrying no significantly greater weight than artificial spits until the true nature of each individual layer or sequence of specific layers is determined by routine analytical techniques. A layer may contain archaeological and other finds either distributed throughout the entire thickness of the layer or concentrated in one or more levels (I. Turk 2003).

Both layers and sedimentation levels belong to time intervals of different lengths, since the

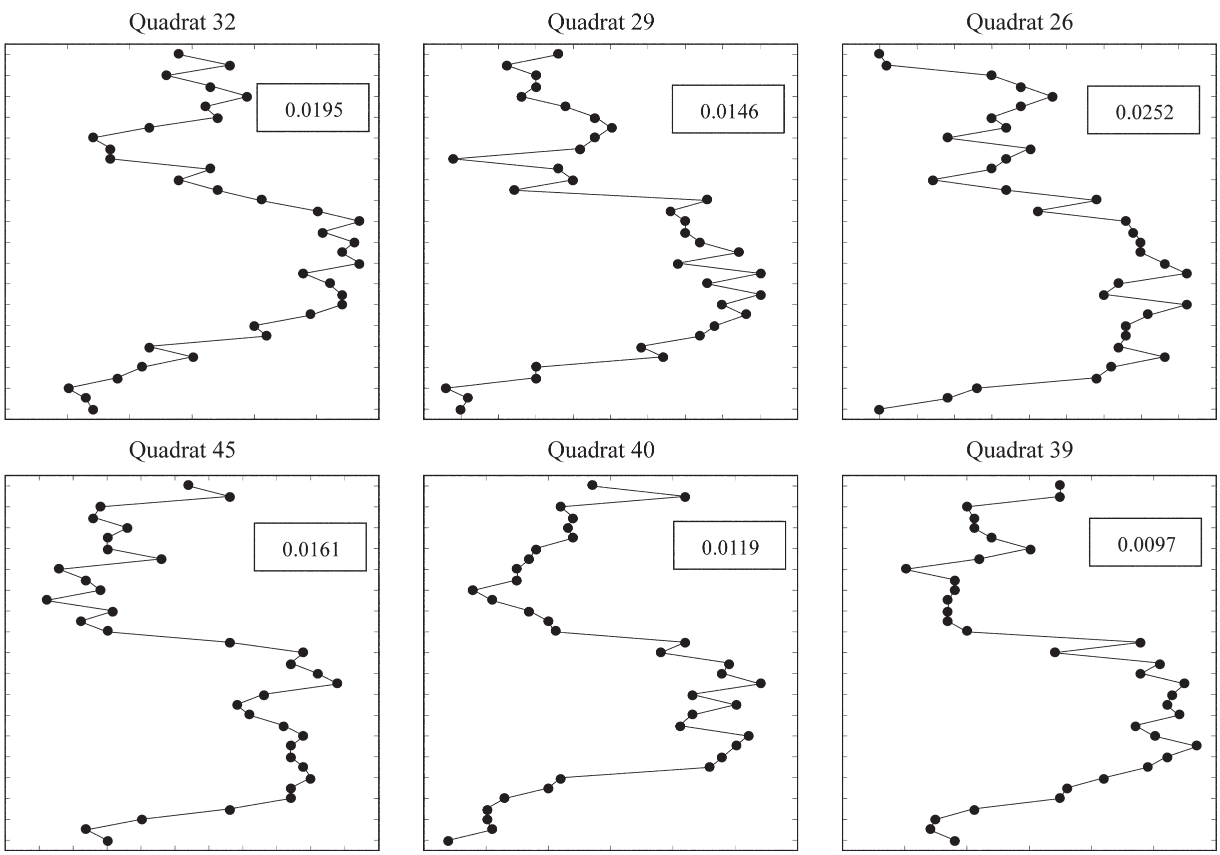

Fig. 3: A simplified example of selecting the most (quadrat 26) and least divergent profile (quadrat 39) of aggregates from six profiles using a calculation procedure (numbers in the right corner of the graphs). The profile includes data from spits 2–36, layers 2–17a1 in six quadrats.

Sl. 3: Poenostavljen primer izbora najbolj (kvadrat 26) in najmanj odstopajočega profila (kvadrat 39) agregatov izmed šestih profilov s pomočjo računskega postopka (številke v desnem vogalu grafov). Profil zajema podatke iz režnjev 2–36, plasti 2–17a1 v šestih kvadratih.

sedimentation rate is not constant. In the cave environment, sedimentation takes place (or not) depending on various internal and external conditions of local and/or global nature. Thus, the sedimentation rate is a very important variable on which the rate of sediment modification, sediment distribution, and temporal unity or disunity of archaeological and other finds depend (I. Turk 2003). Temporal unity is not necessarily guaranteed with the occurrence of finds in a particular layer. Namely, the interruption or deceleration in sedimentation may cause the mixing of finds from different time periods.

In addition to determining layers and sedimentary hiatuses, chronology is crucial in any research. Therefore, stratigraphy (i.e., the vertical dimension of the phenomenon under study) is of paramount importance. In Divje babe I, Turk defined the vertical dimension (i.e., the profile) quantitatively and qualitatively in two different ways (*Figs. 2* and *3*):

1 – Using the mean values of the data set of a particular sedimentological attribute in a sufficiently large volume of stratified cave fill with ground plan area that comprised 15% (83 m²) of the total present-day cave area (550 m²) (I. Turk 2003, Fig. 6a). The data were arranged by sedimentation levels, represented by 12 cm thick spits. Once excavation was complete, sedimentation levels were arranged to roughly follow the dip of the layers in the direction of the longitudinal axis of the cave. *Fig. 2*, like the already published Figs. 6a and 7a (I. Turk 2003), show that the mean values of the sedimentological attributes change in the proportion of the sampled area to the total ground plan area, and that the larger the proportion of the sampled area, the more reliable they are.

2 – Using two profiles from the available set of profiles of a particular sedimentological attribute that were maximally different and represented the two extremes of a stratigraphic sequence: a) the profile that deviated the least from all available profiles, and b) the profile that deviated the most (*Fig. 3*). Both were more reliable the larger the set of profiles from which they were selected both visually and computationally. The profile that deviated the least from all available profiles represents the so- called type profile (I. Turk 2003). *Fig. 3* shows considerable variability of the studied attribute in space (quadrats), which is to be expected for the cave environment. Thus, a very accurate and sophisticated analysis at a particular micro-location does not mean that the results obtained in this way are representative of the whole, which has not been subjected to such an analysis. It is a shortcut that can also be used when revising a specific site and can lead to a significantly different result than the original. However, we still do not know which result is more and which is less correct.

The lateral dimension

In Divje babe I, the lateral dimension was represented by 1×1 m quadrats. The sedimentary environment of the cave consists of microenvironments. These change with the size of the cave entrance and the distance from it, so the phenomenon of gradient or gradual decrease of external influences proportional to the distance from the entrance and its size occurs. At the same time, the changes in microenvironments may be influenced by other factors that do not depend directly on the size of the entrance and distance from it. In particular, these other factors influence fossil remains and underground water (i.e., the percolating water and the moisture in the sediments). The variability of cave sediments is the result of the action of various factors. A great variability is the main characteristic of cave sediments. For all these reasons, documenting and analysing the lateral characteristics of sedimentological attributes can be as important as documenting and analysing their vertical characteristics.

The new methodological approaches could be applied without adapting the archaeological field method to the new requirements resulting from the application of the different post-excavation analytical methods and procedures than were used in Slovenia until the end of the first phase of excavation at Divje babe I in 1986. The sedimentological research at Divje babe I was carried out in such a way that, in addition to the above written, the accuracy and reliability of the data, on which the credibility or accuracy of the interpretation depends, were checked at the same time.

– The accuracy of the data collected depends primarily on the method, the time invested, and the precision of those performing the method. Accuracy controls that provide an estimate of the error are essential.

– Data reliability does not always depend on the precision with which the data are collected. The number of data is also important. A large number of less accurate data may provide a more reliable result than a small number of very accurate data. Reliability can only be evaluated based on a set of data related to each of the attributes analysed.

– The credibility or accuracy of the interpretation of the data collected depends on how reliable the data are. However, the reliability of the data in itself does not guarantee the credibility of the interpretation. Therefore, any interpretation is only hypothetical until it is confirmed or disproved by verification with other independent data and methods. A verified assertion remains valid until it is replaced by another substantiated assertion or proven false. The credibility of the interpretation does not mean that the interpretation is correct. Any interpretation should be based on an analysis of the accuracy and significance of the original data (facts). In Slovenia, only M. Brodar (1959) attempted to adhere to this principle in his granulometric analysis of the sediment in the Mokriška jama cave.

In studying problems related to past events and phenomena, we usually infer the causes and processes that lead to a particular current state from the consequences (i.e., facts). The problem with this is that different causes and processes can have similar consequences. This means that every interpretation and every conclusion carries a certain risk of being wrong. The risk can be reduced if we treat the facts not individually, but together with other available facts, by analysing their relationships and identifying meaningful links that lead to systematic solutions.

To summarise, we may say that I. Turk has upgraded the old methods, which were based on logical thinking, intuition, and experience, with research methods that derive their quality from quantity. He limited himself to autochthonous cave sediments and the site of Divje babe I, where he had the most personally collected data and the possibility of maximum verification of analytical results. It is understandable that his new findings did not always coincide with those obtained by other methods, including those he had used before following the example of his predecessors, and with the results of analyses of allochthonous admixtures in cave sediments. The latter are often treated preferentially, although they constitute an insignificant proportion of the cave sediments and may be episodic in nature.

THE GOAL AND INNOVATIVE APPROACH OF SEDIMENTOLOGICAL RESEARCH IN DIVJE BABE I

In the case of Palaeolithic sites, the study of Pleistocene sediments has a specific goal: to determine the origin and, more importantly, the age of the sediments. In the case of the sediments from Divje babe I, both have been more or less clarified. Due to the sedimentary environment and the structure of the sediments, there is no doubt about the almost exclusively autochthonous origin of most of the sediments. Numerous radiometric dates also explained the basic chronological questions raised by M. Brodar (1999). What remained was the question of additional (alternative) aims of the sedimentological analysis (for routine procedures, see Farrand 2001; Woodward, Goldberg 2001). These were:

– to determine the factors responsible for sediment deposition (including the finest fraction), weathering and further diagenesis of sediments;

– and possibly to determine indicators of basic climatic parameters.

Together with palynological, anthracotomical, macro- and microfaunal data, these factors would contribute to the reconstruction of the palaeoclimate. The palaeoclimate, together with radiometric data, is currently the only basis for a more or less reliable climatochronological placement of the site in the scheme of the contemporary global (climato)chronology of the Late Pleistocene, since the so-called complete division of Würm has long ceased to be relevant (see I. Turk, Verbič 1993).

In pursuing the goals set, I. Turk analysed samples of sediments taken from the profiles, as well as samples of sediments taken after spits and quadrats in the excavated area.[4] A precise analysis of sediments from the profile is usually primarily or exclusively representative of a particular section of the profile, but it also has a broader significance, as each individual analysed value of a specific sediment characteristic in a profile certainly belongs to a population with a particular range of values. Thus, using data from individual profiles *sensu stricto*, we can compare the results of the analysis of sets of sedimentological data collected at spits and later combined into sedimentation levels, with so-called geological layers, as were determined

[4] Samples of sediments are kept together with other finds in the National Museum of Slovenia.

visually in profiles. The data collected according to spits pertained to the following categories:

– mass of dolomite blocks and fractions from fine-grained gravel to silt;

– volumetric mass of sandy fraction;

– fossil and archaeological remains.

Although sedimentological data were in no way as precise as the corresponding data from the profiles, their number (ranging from a few hundred to about 2,500 unpublished data points for a single category from layer 2 to including layer 16a, or an average of 150 data point for each excavated layer)[5] made them statistically significant and thus allowed the recognition of the variability of the collected data according to the above categories. Since they were stratigraphically objectively defined with an accuracy of 12 cm, they could be compared quite well with the stratigraphically presumably comparable data from profiles, the comparative analysis could be carried out and the correlation between the sedimentation levels and the geological layers could be verified. In order to understand better the whole process of sedimentation and sediment diagenesis, I. Turk and his colleagues systematically studied:

a – the grain size distribution (of clasts and aggregates) of the various fractions;

b – the average grain size in each clast fraction;

c – the post-sedimentary fragmentation of clasts (the so-called congelifracts);

d – the corrosion of clasts (the so-called cavernously corroded clasts);

e – the volumetric (specific) mass of the fine sediment fractions;

f – the chemical composition of the individual sediment fractions with emphasis on the fine fraction.[6]

I. Turk focused on certain universal characteristics of clastic sediments (weathering, congelifraction, corrosion, cementation), which he assumed to be directly related to climatic parameters (temperature, humidity). Using radiometric dates, he managed to directly parallel them with global climatic temperature fluctuations (Blackwell *et al.* 2007; Turk 2007b), whereas modern palaeoclimate and palaeoenvironmental research does so on the basis of other parameters that can only be indirectly paralleled with dated climate curves (Ellwood *et al.* 2004; Spötl *et al.* 2006; Aubry *et al.* 2010). Congelifracts are thought to be highly correlated with temperature, whereas cavernously corroded clasts and various structural aggregates with cement binding are correlated with humidity or precipitation. He was able to reliably correlate cavernously corroded clasts with stagnations in the predominant mechanical weathering of the cave ceiling. These are also reflected in a discontinuity in the ESR dates in the Divje babe I profile. To date, no one has paid much attention to the relationship between hiatuses and cavernously corroded clasts, not even authors who have dealt specifically with stratigraphic hiatuses in cave sites (Campy, Chaline 1993). Structural aggregates have also never been analysed quantitatively, as was done in Divje babe I.

In the analysis of the sediments of Divje babe I, Turk proceeded from general knowledge of the weathering and cementation of sedimentary rocks (which is also dolomite), as well as from his own field observations during 19 years of excavations at Divje babe I. His basic ideas regarding the correlation between weathering and cementation with climate came from wet sieving and examination of all excavated sediments in 1990–1999. Unfortunately, these ideas only emerged towards the end of the excavations, so it was not possible to verify congelifracts and cavernously corroded clasts in their lateral dimension, as was the case with structural aggregates.

Weathering

Weathering is a combination of inextricably linked mechanical and chemical processes that lead to the decomposition of rock (I. Turk 2006, 21). Weathering of the dolomite parent rock could have been primary, *synsedimentary, syngenetic* (on the ceiling, walls, and shelves of the cave) and/or secondary, *post-sedimentary, post-genetic* (on/in the cave ground). The mass of post-sedimentary weathering products is the same as the mass of synsedimentary if there is no transport out of the cave or a major influx of allochthonous regolith. Both weathering categories are similar processes occurring under different sedimentary conditions (humidity, temperature, transport). Therefore, the final products may also be different. However, the products of one or the other type of weathering can only be distinguished in exceptional cases.

[5] Unpublished data from the Archives of the ZRC SAZU, Institute of Archaeology: Turk, I. 2002, Elaborat Divje babe I. Izkopavanja 1989–1999.

[6] The latter in cooperation with the geologist D. Skaberne.

Both synsedimentary and post-sedimentary weathering take place continuously, except in cases in which the protective layer of weathering products (on the shelves or ground) or chemical sediments such as sinter (on the ceiling, walls, shelves, and ground) begins to form. Weathering may be uniform or non-uniform. To what extent the weathering is non-uniform depends primarily on the degree of anisotropy of the rock (fracturing, etc.). If there is a prolonged interruption of primary weathering, corrosion lesions occur on the ceiling and walls. When the cave ceiling thus affected begins to fracture again, cavernously corroded clasts accumulate in the sediments. Under similar conditions, they can also occur in the ground.

Erosion, which plays an important part in the weathering of deposits in the open, was the exception rather than the rule in Divje babe I. It was only possible for the finest sediments washed into the pores and vacuoles between clasts by percolating water, and possibly from the cave if surface runoff occurred. Evidence of erosive solifluction is found only on the slope in front of and below the cave, where an unknown portion of the Pleistocene sediments is apparently missing. Also, the sediments of layer 2 at the present cave entrance were partly (anthropogenically?) removed (I. Turk 2007c, Fig. 4.1b).

Synsedimentary weathering, which takes place on a small area represented by the cave ceiling and shelves, is accompanied by the constant erosion of the weathering products due to gravity, which is greatest on the ceiling and the least on the shelves. In terms of quantity, the results of synsedimentary weathering are mainly coarse fractions conditioned by primary macrocracks in the dolomite parent rock. Despite the potentially greater number of microcracks, the proportion of fine fractions conditioned by primary microcracks and the crystalline structure of the dolomite is relatively small due to the relatively small surface exposed to weathering.

Postsedimentary weathering, which occurs over a large area represented by the surfaces of all clasts and includes the occurrence of secondary cracks, is inversely proportional to synsedimentary weathering. This is because the rapid deposition of continually new sediments from the cave vault slows weathering of previously deposited sediments, while slow deposition allows greater weathering of previously deposited sediments. Post-sedimentary weathering depends not only on the climate and sedimentation rate of the gravitational gravel/debris that retains the moisture necessary for weathering but also on the amount of biomass. The result of post-sedimentary weathering is primarily fine fractions, which are usually the subject of analysis of grain size distribution and micromorphology. The experiments of I. Turk have shown that gelifraction is most efficient when the sediment is flooded with water. This, of course, is possible mainly in/on the ground, if the necessary conditions are met (the presence of a less permeable ground in the form of a trampled surface). Under such conditions, silt and sand-sized clasts detached first, followed by coarse-grained clasts and so on, until large fragments break off that can reach half the size of a primary clast. Large fragments formed by frost action are called congelifracts.

Based on the basic law of syn- and post-sedimentary weathering, the grain size distribution in the profile of Divje babe I has been explained, especially the coarsest and finest fractions (Skaberne *et al.*, Fig. 17.2.1). These are not as clearly related to climate, as assumed by M. Brodar and some other authors. Both fractions are inversely proportional and predominantly of different origin. The coarse fraction, as already mentioned, was created predominantly synsedimentary in connection with the unstable cave vault. The finest fraction was created primarily post-sedimentary in connection with breaks in the sedimentation of the coarse fraction during periods of stable cave vault. Gravitationally, it is the most mobile fraction, which over time can fill all the pores between clasts.

The sedimentation rate of all gravitational cave sediments depends on the climate (temperature, humidity, seasonal distribution of precipitation), the nature of the rock (degree of fraction and structure), the inter-granular porosity of the clastic sediments, and seismic activity. Early chemical diagenesis (the formation of chemical deposits) depends on the physical and physicochemical properties of the sediment and the solutions flowing through it. These properties depend on the composition of parent rock and sediments, as well as on exogenous conditions (climate, plant and animal compounds, living environment). Therefore, it was essential to consider all these factors in explaining the results of sediment analysis. Some of them are interrelated. For example, the sinter could not have formed without a plant cover on the slope above the cave. The size of the populations of herbivorous cave bears that contributed to the organic component of the sediments was directly dependent on food or vegetation. The latter, in turn, was associated with higher temperatures, higher humidity, and longer summers.

MODEL USED TO INTERPRET SELECTED CHARACTERISTICS OF CLASTIC SEDIMENTS AND DIVJE BABE I

The model is based on the following general facts

Because underground caves do not receive direct sunlight, they have a special microclimate that can also be influenced by the microclimate in the immediate vicinity of the cave. The microclimate in caves is influenced by the size of the cave entrance, the temperature of the soil (including and especially of the cave sediments), the presence of people (fire), and the vegetation above and in front of the cave (trees, bushes, barren land). All of these factors may change in relation to climate change, and some of them may change in the context of natural disasters (forest fires, ice-break in the forest, etc.). While microclimate affects cave sediments in the short term and are specific to a single site, the atmospheric climate has a long-term and global influence that allows comparisons on a global scale.

The humidity in the caves appears as condensed water vapour and as underground (ground) water. Underground waters are all waters below the surface, including the water in the porous part of the cave sediments. Both condensed water vapour and ground water depend on the outside air temperature and precipitation. Humidity in the cave environment is closely related to differences between cave and outdoor temperatures, which are negatively correlated with the size of the entrance (see *Fig. 4*).

The inflow of underground water, such as percolating water in the horizontal underground caves, depends on precipitation. *Fig. 5* shows the results of occasional measurements of underground inflow (percolating water) from the ceiling area of 91 m² in Divje babe I from January 2000 to February 2001. The average value is 22.7 litres in one hour or 0.25 litres per 1 m² in one hour if the underground inflow of water was evenly distributed over the entire area of 91 m². The highest value for the 91 m² area was 112 litres per hour and the lowest was 2 litres. Therefore, 2,190 litres of water could drip onto 1 m² of cave floor each year, which is just above the local average precipitation for the period 1961–1990, which is 2,098 litres (Nadbah 2012). Unlike precipitation, the underground outflow is constant. It increases rapidly after rainfall and then decreases in the form of an exponential curve. The latter decreases rapidly at first and then decreases very slowly after a certain point of runoff and probably never reaches the value of 0. The underground outflow depends on the separation of precipitation into the surface and subsurface outflow and on evapotranspiration (evaporation of water from the earth's surface).

For the interpretation of humidity in the cave environment of Divje babe I, I. Turk used the following microclimatic model:

– *At lower temperatures*, the air contains less and the ground more humidity due to reduced evapotranspiration. For a 30-year average annual temperature of 10°C and 1,800 mm of precipitation, both measured in the vicinity of the cave, the evapotranspiration amounts to 572 mm per year

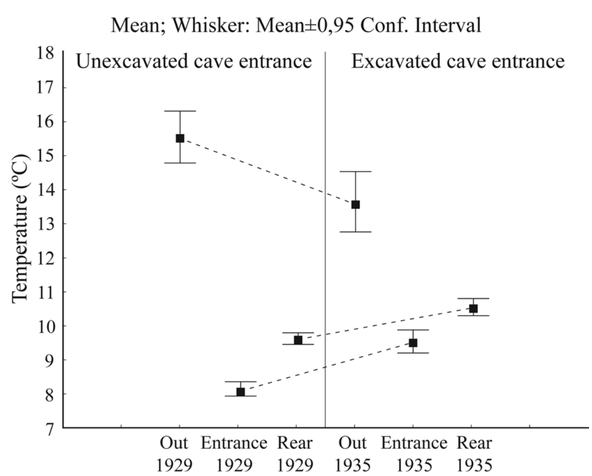

Fig. 4: The change of summer temperature in Potočka zijalka, connected with the changed size of the entrance as a result of the excavations that took place in 1928–1935. In 1929, S. Brodar collected 87 measurements for each part of the cave and outside the cave and 107 analogous measurements in 1935 (data: S. Brodar, Archives of the ZRC SAZU, Institute of Archaeology).

Sl. 4: Sprememba poletne temperature v Potočki zijalki, povezana s spremenjeno velikostjo vhoda kot posledico izkopavanj v letih 1928–1935. V letu 1929 je S. Brodar zbral 87 meritev za vsak predel in 107 meritev za vsak predel v letu 1935 (podatki: S. Brodar, Arhiv ZRC SAZU Inštitut za arheologijo).

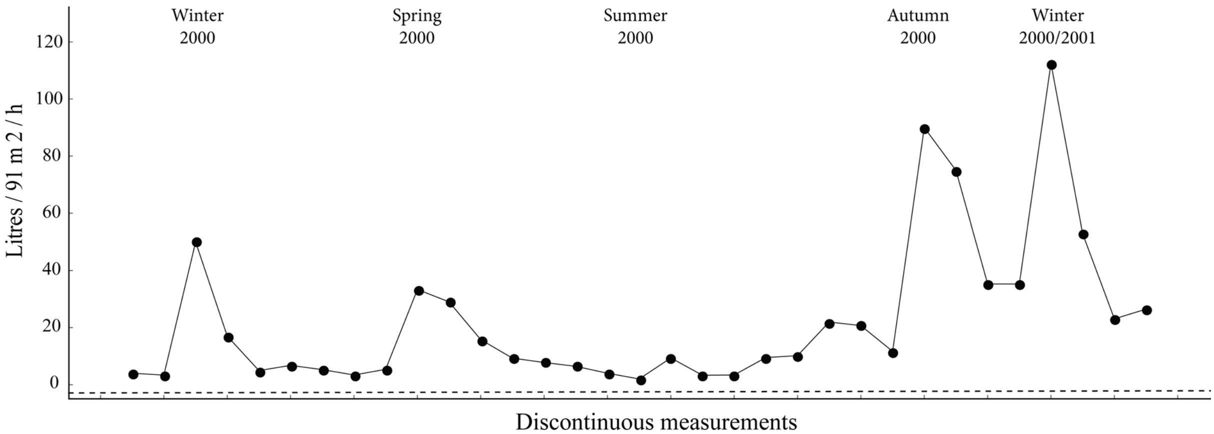

Fig. 5: The inflow of underground water into Divje babe I in the 2000–2001 period.
Sl. 5: Dotok podzemne vode v Divje babe I v obdobju 2000–2001.

(cf. Verheye *et al.* 1991, Table 1). If the average annual temperature falls by 5°C and precipitation remains the same, evapotranspiration falls by 35%, equivalent to 372 mm per year. In the long term, this means less condensed water vapour (i.e., condensation humidity) in the cave environment and more groundwater. The latter is more aggressive due to the lower temperature and may produce more cavernously corroded clasts in the ground, which may be joined by clasts detached from the cavernously corroded cave vault of the previous warmer period with more condensation humidity and corrosion (see I. Turk *et al.* 2005, Fig. 7). Precipitation primarily increases groundwater inflow because it does not have a major influence on evapotranspiration. With an average annual precipitation of 2,500 mm, which is probably close to the possible maximum for this area, and an average annual temperature of 5°C, annual evapotranspiration would be 425 mm, which is only 12% more than with a precipitation of 1,800 mm. Grass vegetation, typical of a colder climate, increases the vertical permeability of the ground, which has a positive effect on the underground water flow, which can increase by up to 50% as a result (Ćirić 1986, 123s). In contrast, the day--night temperature amplitude is smaller at lower temperatures than at higher temperatures. A smaller amplitude also means less condensation humidity. The temperature amplitudes are smaller in the caves with the smaller entrance. This was demonstrated during the excavation in the Potočka zijalka, which took place in the summer of 1929–1935 and was accompanied by daily temperature measurements inside and outside the cave (S. Brodar 1934) (*Fig. 4*). In 1929, before the entrance was enlarged, only 13% of the air temperature fluctuations behind the entrance ($n = 87$, $p = 0.001$) and 24% of the air temperature fluctuations at the end of the cave ($n = 87$, $p < 0.001$) were explained by fluctuations in the outside air temperature. After the entrance was enlarged by excavation, variations in outside air temperature in 1935 explained 64% of the variation in air temperature behind the entrance ($n = 107$, $p < 0.001$) and 72% of the variation in air temperature at the end of the cave ($n = 107$, $p < 0.001$). With a statistical significance of 95%, the average air temperature behind the enlarged entrance increased by 1.3–1.5°C in 1935 and by 0.8–1.0°C at the end of the cave, even though the average outside air temperature decreased by 1.8–2.0°C in the same year compared to 1929, when the entrance had not been enlarged. Looking at the difference in average outside air temperature, the largest average increase was 3.5°C behind the entrance and 3°C at the end of the cave. Analogous to the increase in summer temperatures would be the decrease in winter temperatures in the cave due to the enlarged entrance.

– *At higher temperatures*, the air contains more humidity and the ground less due to higher evapotranspiration. In the long run, this means more condensation in the cave environment and somewhat less underground water. Precipitation increases the inflow of underground water, but much less than at lower temperatures. With an average annual precipitation of 2,500 mm and a temperature of 10°C, annual evapotranspiration would be only 2% higher than at the same temperature and 1,800 mm precipitation. The runoff deficit (the difference between the amount of water that has fallen on a given area and the amount of water that has run off from that area; it is roughly equivalent to evapotranspiration) is also increased by forest vegetation, which can be expected to be more developed in a warmer climate than in a colder climate. Therefore, precipitation at higher temperatures increases condensation humidity more than at lower temperatures. The amount of condensation humidity also increases due to the greater temperature amplitude, which is a consequence of higher temperatures. The larger temperature amplitude may also be caused by the smaller cave entrance *(Fig. 4)*.

– Since condensation humidity accelerates the corrosion of the cave vault, we can theoretically expect more cavernously corroded clasts to appear in the sediments after warmer periods than after colder periods. The extent of corrosion depends primarily on the stability of the cave vault and partly on the amount of precipitation. The cave vault is destabilised by earthquakes and frost. Since frost depends on temperature and underground (percolating) water, it is minor at higher average annual temperatures. This has a positive effect on the development of corrosion on the cave walls and ceiling.

– Since underground water accelerates the formation of aggregates, breccias, and sinter, these formations are to be expected in both cold and warm periods. The freezing of ground with a silty-sandy matrix, as found in the Divje babe I sediments, further contributed to the formation and consolidation of structural aggregates (Williams, Smith 1989, 42, 46). The range and development of these formations depend on the amount of precipitation, which more or less directly affects the amount of (percolating) underground water. Lower temperatures and more water accelerate the action of frost, which destabilises the cave vault and increases the post-sedimentary fragmentation of clasts (gelifraction) and the formation of cavernously corroded clasts and aggregates in the cave ground. The instability of the cave vault only further reduces the already limited efficiency of corrosion. The likelihood of slope erosion also increases. If erosion destroys the vegetation above the cave, which could have happened in the past at Divje babe I due to the very steep, ridge-like terrain above the cave, there are no longer conditions for sinter to form. The eroded slopes also increase surface water outflow, possibly causing the percolating underground water inflow to decrease. On the present erosion-instable slope above Divje babe I, we cannot expect thicker deposits of clay, which water would substantially wash into the cave. Since there is practically no clay in the Pleistocene sediments of Divje babe I, we can assume that in the Pleistocene slope above the cave was as steep and unstable as the present one.

The proposed microclimatic model is comparable to climate models based on temperature change. The long-term change in average annual temperature does not mean that summer and winter temperatures would have changed equally. On the contrary, it is more likely that winter temperatures would change much more than summer temperatures. The consequence of the temperature changes would be the changed amount of precipitation, which would be distributed differently in winter than in summer. This would affect the thickness of the snow cover, which is one of the main regulators of ground temperature in cold climates (cf. Williams, Smith 1989, 81).

Since, according to the proposed model, humidity and temperature are interdependent climatic parameters in the cave environment, it was possible to verify the extent to which findings based on presumed sedimentological attributes for temperature and humidity, represented by congelifracts, cavernously corroded clasts, and aggregates, are consistent. These currently presumed climatic attributes were represented by completely independently obtained continuous sedimentological data related to syngenetic and various post-genetic processes. Since the results of the analyses of selected sedimentological data agree well, we can trust the explanation of climate based on the proposed model. Since the influence of temperature and humidity on carbonate rocks is universal, the method of I. Turk can be applied in all similar sedimental environments with similar results of post-sedimentary processes.

SYNTHESIS

The synthesis of the pioneering sedimentological research in Divje babe I was only possible on the basis of numerous dates of layers using the electron spin resonance (ESR).[7] By dating the layers and comparing analytical findings with the oxygen

[7] After 1999, when the informal project of sedimentological analyses was carried out, dating was kindly provided by Bonnie A. B. Blackwell (MA lab: Dept. Of Chemistry, Williams College, RFK Research Institute, Williamstown, MA, USA) (Blackwell *et al.* 2007; 2009).

isotope stage (OIS) temperature curve and similar curves for the period of the Late Pleistocene (see I. Turk, Verbič 1993), it was possible to identify the boundary between the warm Early Glacial (OIS 5) and the cold Full Glacial (OIS 4) in the curves of congelifracts, cavernously corroded clasts and structural aggregates.[8] This boundary, set by agreement at 74,000 years before present (I. Turk 2007b), divides the Divje babe I profile into two parts with statistically different characteristics of clastic and chemical sediments (Skaberne *et al.* 2014; 2015a; 2015b). The lower part of the profile represents the warm and dry Early Glacial, while the upper part represents the cold and humid Full Glacial (Pleniglacial). Within both parts, sediments reflect major or minor millennial climate changes defined by temperature and humidity (I. Turk *et al.* 2001; 2005; J. Turk, M. Turk 2010; Skaberne *et al.* 2014; 2015a; 2015b; Blackwell *et al.* 2009). I. Turk's findings on humidity in the Early and Full Glacial contradict the commonly accepted belief that there were humid-warm periods in the Early Glacial and dry-cold periods in the Full Glacial. This belief is based primarily on the loess sediments that are typical of the Glacial climate. However, the formation and growth of glaciers are conditioned by abundant snowfall combined with a more humid climate and lower summer temperatures.

The cornerstones of I. Turk's synthesis

1 – In both chronostratigraphically delineated parts of the profile, the proportion of cavernously corroded clasts (*Fig. 6a*) that he associated with condensation and ground humidity is significantly different ($p < 0.05$) (Skaberne *et al.* 2014, Fig. 17.2.2). Thus, the differences in amplitude and proportion of cavernously corroded clasts between the upper (OIS 3) and lower part of the profile (OIS 5) could reasonably have been explained by the stable and dry climate in the lower part of the profile and the unstable, humid climate in the upper part. The ceiling corrosion features could be explained by smaller or larger temperature differences between the air outside and inside the cave, while increased precipitation accounts for the ground corrosion feature (I. Turk *et al.* 2001; 2005). There were more ceiling corrosion features in the warm climate. However, due to the larger entrance, the temperature differences between the air outside and inside the cave were smaller. In contrast, there was more corrosion in the ground in the cool climate with the same amount of precipitation. By reducing the size of the entrance during the period of the cold climate, the temperature differences between the air outside and inside the cave increased, which consequently led to more corrosion on the ceiling. Since condensation and groundwater depend on temperature, it is significant that the distribution of the proportions of cavernously corroded clasts, in general, matched the distribution of the proportions of post-sedimentary fragments (Skaberne *et al.* 2014, Fig. 17.2.2).

2 – The proportion of congelifracts with sharp edges (*Fig. 6a*) and fresh (not-weathered) fracture surfaces differs significantly ($p < 0.05$) in both chronostratigraphically delineated parts of the profile (Skaberne *et al.* 2015a, Fig. 7). The proportion of congelifracts has been related to the number of days in a year when it freezes, or to the average winter temperature in a relatively short period before new sediments are deposited (I. Turk *et al.* 2001). Thus, the differences in amplitude and percentage of congelifracts between the upper and lower parts of the profile could be explained by a stable, globally warmer climate in the lower part of the profile (OIS 5) and the unstable, globally colder one in the upper part (OIS 3) or by higher and lower temperatures. The size of the entrance influenced the congelifraction in an inverse way compared to the corrosion of the cave vault. Namely, it was accelerated in the lower part of the profile by the larger entrance and slowed down in the upper part by the smaller entrance.

Since the inflow of underground water in Divje babe I was recorded even during prolonged winter periods of drought and low temperatures, there was at least just enough water, if not abundant, also during the days of frost under glacial climatic conditions. The measured minimum in the central part of the cave, at the end of a one-month period of extremely cold and dry conditions by Slovenian standards in the winter of 1999/2000, was 1.05 litres/m^2 in 24 hours. At the end of an even drier and colder two-month period with below-average temperatures and, above all, below-average precipitation in the winter of 2001/2002, the absolute minimum was measured at 0.68 litres/m^2 in 24 hours. In both cases, icicles formed on the floor but not on the ceiling, up to 19 metres from the

[8] OIS 4 is poorly represented by finds due to interrupted sedimentation. Completely without sediments (and consequently without finds) are OIS 2 and the younger part of OIS 3.

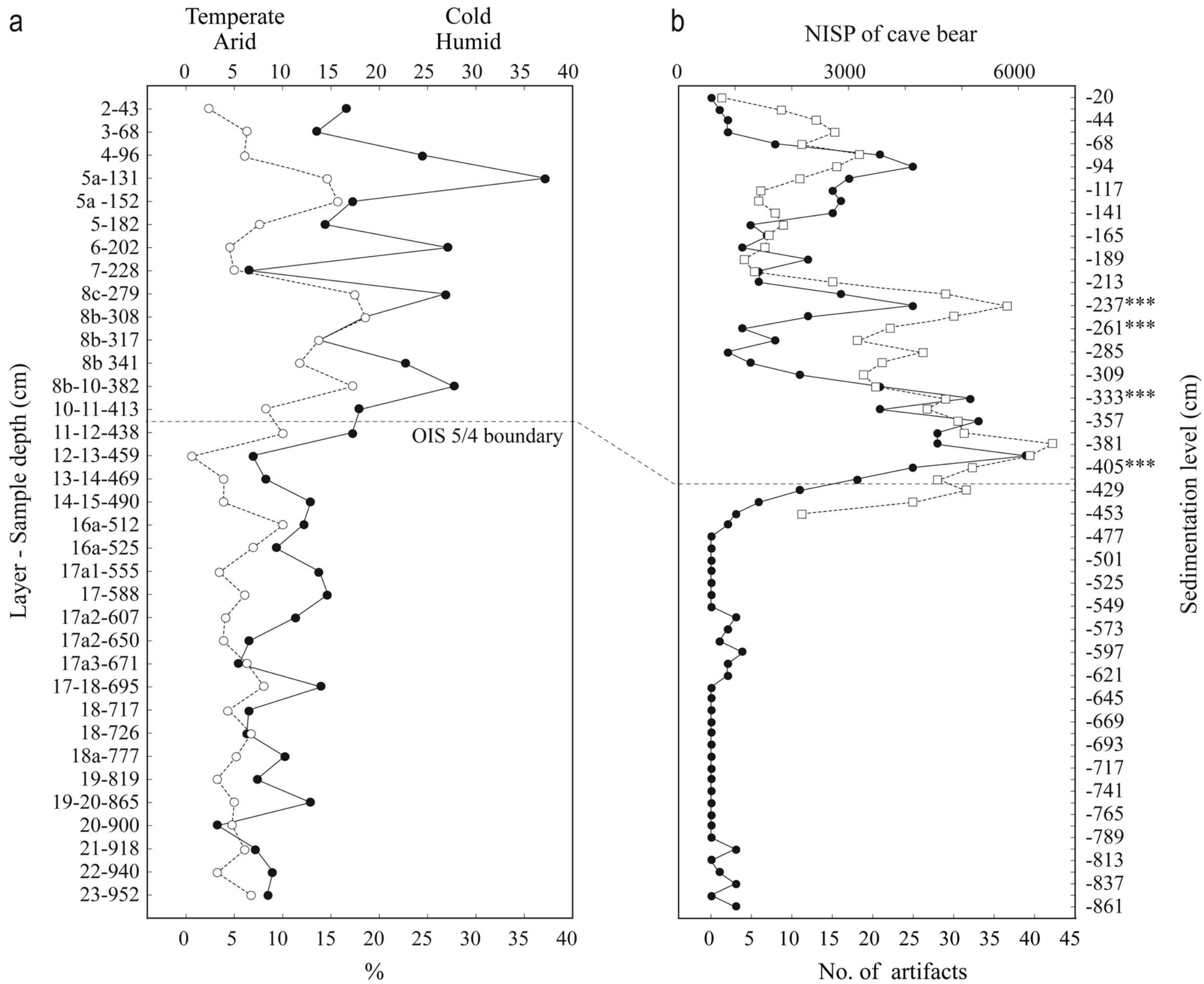

Fig. 6: The relation between palaeoclimate and the presence of humans and cave bears in Divje babe I: ***a*** – palaeoclimate reconstructed on the basis of the percentage (%) of congelifracts (●) and cavernously corroded clasts (○) (see I. Turk *et al.* 2005; Skaberne *et al.* 2015a); ***b*** – human and cave bear presence defined on the basis of the number of artefacts (●) and all determinable cave bear remains (□) (NISP) (I. Turk, Dirjec 2007, Tab. 12.4.1; I. Turk 2014b, Fig. 3.2, Tab. 3.1). Sedimentation levels with hearth remains are marked with three asterisks (***).
Sl. 6: Odnos med paleoklimo ter prisotnostjo ljudi in jamskega medveda v Divjih babah I: ***a*** – paleoklima, rekonstruirana na podlagi številčnih deležev (%) kongelifraktov (●) in reliefno korodiranih klastov (○) (glej I. Turk *et al.* 2005; Skaberne *et al.* 2015a); ***b*** – prisotnost ljudi in jamskega medveda, opredeljena na podlagi števila artefaktov (●) in vseh določljivih ostankov jamskega medveda (□) (NISP) (I. Turk, Dirjec 2007, tab. 12.4.1; I. Turk 2014b, sl. 3.2, tab. 3.1). Sedimentacijski nivoji z ostanki ognjišč so označeni s tremi zvezdicami (***).

entrance. If the ice surrounded the cracked, more or less corrosively rounded pieces of gravel on/in the ground only once per winter, they turned into congelifracts in ten to twenty winters. Then, at temperatures above 0°C, the process of re-rounding the fresh edges of the newly created clasts on/in the ground began. Rounding and congelifraction kept alternating until new sediments covered the ground and both processes slowed down considerably or even stopped. Only congelifracts with fresh fractures surrounded by sharp edges formed just before the coverage by new sediments were used for the approximation of the negative temperature.

3 – The proportion of structural aggregates in the sandy fraction, simplified expressed by volumetric mass, has been related to precipitation by ground moisture. In both chronostratigraphically delineated profile parts, the proportion is significantly different ($p > 0.05$) (Skaberne *et al.* 2015a, Fig. 7). The difference in the volumetric mass of the sandy fraction between the upper and lower parts of the profile was reasonably explained by the globally

drier and warmer climate in the lower (OIS 5) and the globally more humid and colder climate in the upper part of the profile (OIS 3) (I. Turk *et al.* 2005). Since the formation of structural aggregates and the corrosion agency in the ground inevitably requires water in the form of ground moisture, it is important that the distribution of structural aggregates matches the distribution of corroded clasts as well as corroded bones, in the sediments of the stratigraphic sequence. The rough correspondence of the distribution of structural aggregates with congelifracts could be the result of the formation and consolidation of aggregates due to the segregation of ice in the ground (Williams, Smith 1989, 42, 46). Aggregates compressed in this way are more resistant than unconsolidated aggregates from warmer climatic periods and could therefore be preserved in larger quantities.

Fossilised cave bear hair and hair imprints were discovered for the first time in larger structural aggregates (*Fig.* 7) (I. Turk *et al.* 1995). The discovery was later independently confirmed with similar finds of the Pleistocene age at Ozark Cave in the USA (Schubert, Kaufmann 2003). The Iron Age find from Čadrg near Tolmin (Kavkler 2016) with identical mineralised structures of wool fibres, such as fossilised hair (*Fig. 7*), showed that two-and-a-half millennia are sufficient for hair fossilisation. From this, we can conclude that the fossilised hairs and their associated aggregates in Divje babe I originated syngenetically (i.e., almost contemporaneously with sediment deposition) rather than epigenetically.

4 – The distribution of the fossil remains of the cave bear, which with regard to the mortality rate in the cave den could have depended on the duration and characteristics of a winter (humid, dry), is clearly different between the upper part and the lower part of the profile (*Fig. 6b*). The remains are much more numerous in the upper part of the profile, deposited in a cold and humid climate. Since the land was covered with mixed forests at that time (OIS 3), as indicated by the analyses of charcoal and pollen (Šercelj, Culiberg 1991; Culiberg 2007; 2011), living conditions were favourable for the cave bear population during the warm season. It might have been different in the cold season, when mainly female bears with cubs and older, weaned cubs stayed in the cave. When winter conditions were unfavourable (at the time of increased humidity), rivalry for cave dens could have occurred between male bears on one side and female bears with cubs on the other. The mortality rate was the highest among cubs up to one year old, which constitute 70% or more of the fossil population in the upper part of the profile, excavated in 1989–1999 (Debeljak 2002).

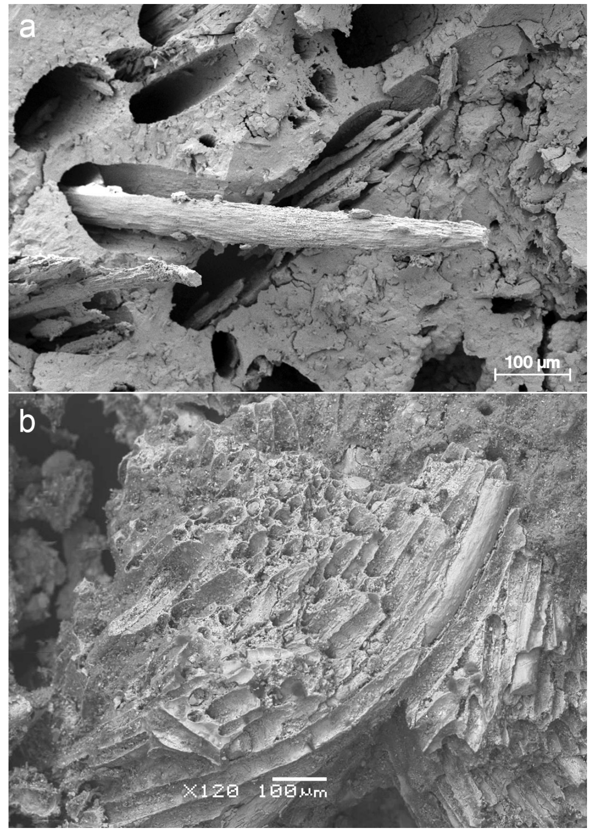

Fig. 7: ***a*** – examples of fossilised hair and hair impressions from Divje babe I (Turk *et al.* 1995, Fig. 5); ***b*** – examples of wool fibres of Iron Age textile from Čadrg (Kavkler 2016, Fig. 3).
Sl. 7: ***a*** – primerki fosiliziranih dlak in odtisov dlak iz Divjih bab I (Turk *et al.* 1995, sl. 5); ***b*** – primerki volnenih vlaken železnodobne tkanine iz Čadrga (Kavkler 2016, sl. 3).

5 – A similar pattern as with cave bears is seen in the distribution of Palaeolithic artefacts (*Fig. 6b*). These show the intensity of cave visits by the local Neanderthal population and their use of the cave as a shelter from bad weather. Thus, the cave visits correspond well with the approximate values for temperature and humidity (*Fig. 6*). The archaeological remains, such as artefacts and fireplaces/hearths, roughly reflect the density of the local Neanderthal population. In the harsh Glacial climate, they were forced to retreat from central Europe toward the Mediterranean. This led to a greater population density and also to increased visitation to caves in the area. It is well known that in the warm Interglacial climate finds in the open

predominate, while in the cold Glacial climate finds in caves are much more numerous. This pattern is now clearly expressed and confirmed also in Divje babe I.

6 – Analysis of the rich stratified microfauna revealed that the climate was more humid at the time of sedimentation in the upper part of the profile (OIS 3) than at the time when the layers of the lower part of the profile (OIS 5) were deposited (Toškan, Kryštufek 2007; Toškan, Dirjec 2011). As these are discontinuous data, it was not possible to compare the results in detail with the sedimentological results.

7 – The findings from the microfauna remains were supplemented by palaeobotanical analyses of stratified pollen and several thousand charcoal pieces. They confirmed that the climate at the time of deposition of certain layers in the upper part of the profile (OIS 3) was colder than at the time of deposition of the layers in the lower part (OIS 5) (Šercelj, Culiberg 1991; Culiberg 2007; 2011). Again, these are discontinuous data that cannot be compared in detail with sedimentological data.

The first natural science synthesis of the multidisciplinary analysis of an individual Palaeolithic site in Slovenia yielded consistent results. Numerous collected data from different fields of natural science create a uniform system. Divje babe I can therefore rightly be regarded as one of the key cave sites for the OIS 5 and OIS 3 stage, which are little known in terms of environment and Palaeolithic finds. In the second half of OIS 3, there was a complete replacement of the human population in Europe, with the arrival of new species and associated cultural changes, which was not the case at any earlier or later time.

CONCLUSIONS

Based on the synthesis of the results of all the analyses carried out on the sediments of Divje babe I and their content, we come to these reliable conclusions:

1 – The analysed profile of Divje babe I, although incomplete due to hiatuses, is currently the most illustrative profile for the major part of the Late Pleistocene in Slovenia (I. Turk 2006; I. Turk 2007c, Fig. 4.1b). It is certainly more illustrative than the profiles of Črni Kal and Betalov spodmol, which have long been considered reference profiles for this period (M. Brodar 2009). Its potential is far from exhausted, for the sediments on the slope below the cave, whose entrance was once moved far forward, are probably 50 m deep and reach far back into the Pleistocene. It need not be particularly emphasised that caves with such thick sediments containing archaeological and palaeontological finds are an extreme rarity. Moreover, most of the cave interior has not been excavated, while the sediments of Črni Kal have been completely removed and only a small part has been preserved in Betalov spodmol.

2 – The sediments excavated in Divje babe I were formed under the influence of individual cave microenvironments in the microenvironment of a cave as a whole. Cave microenvironments, including sedimentary environments, are primarily shaped by unevenly distributed underground water in all aggregate states, which depend on temperature. The latter can be generalised to all horizontal caves. In Divje babe I, cave microenvironments are expressed in a mosaic image. This was established on the basis of a comprehensive spatial analysis of various data recorded during the excavations and afterwards using samples of sediment fractions. The mosaic environment is thus conditioned by space and time. When solving problems of the cave sedimentary environment, it is therefore essential that these two dimensions are taken into account. Traditional approaches that consider almost exclusively the dimension of time on a given vertical of a given profile in a cave would have been appropriate if the same conditions, expressed by temperature and humidity, were present in the entire ground plan, or if there were no microenvironments. Otherwise, misleading interpretations may result, especially if generalised to the entire site.

3 – A microenvironment forms and changes due to the influence of various factors (global climatic, microclimatic, etc.) that are constant or change over time. One of the most important factors is certainly the atmospheric climate, which is known to be constantly changing on a global scale.

4 – The most important factors affecting the microenvironment in Divje babe I are the parent rock, the global climate, the presence of cave bears, and the volume of the cave. None of these factors was constant in time and space. The main characteristics of the parent rock (cracking, porosity) could have changed from one rock layer to another. The global climate was certainly not the same all the time (i.e., for 90,000 years

Fig. 8: Distinct cryoturbation in the transverse profile x = 10 m.
Sl. 8: Izrazita krioturbacija v prečnem profilu x = 10 m.

of sedimentation). The visits of cave bears and Neanderthals who used Divje babe I as a den and shelter fluctuated. The cave entrance and geometry of the cave gradually changed, and the cave volume constantly decreased. This had a direct impact on the microclimate in the cave. Before the Last Glacial Maximum (OIS 2) the entrance was only 1 m high. Due to this, and the northern position of the entrance, a deeply frozen ground without an active layer, which normally thaws in summer, gradually formed in the cave during the period of the glacial maximum. During the formation of permafrost, strong cryoturbation of the sandy-silty sediments occurred (*Fig. 8*). Since the temperature in the cave thus remained negative throughout the year, the cave was no longer a suitable shelter for humans and animals, even if the low entrance was not closed by perennial snow and ice. Such a condition lasted several thousand years, possibly even several tens of thousands of years, and caused a long hiatus in sedimentation and the complete absence of any kind of finds from this period, due to the extremely hostile living environment.

5 – Diagenetic-pedogenetic processes that occur in a cave environment are processes of transformation of rock clasts, processes of transformation of organic remains, and migration processes. Among the latter, migrations of uranium are especially analytically significant (Skaberne *et al.* 2015b). In the cave ground, there was no biological circulation of minerals between the animate and inanimate nature, which is typical of ordinary pedogenetic processes. The transformation processes occurred differently in a cave than in the open. In the cave, the regolith was formed by the weathering of the parent rock on the ceiling and walls rather than by the weathering of the bedrock, which was protected from weathering by thick layers of detrital and other sediments because there was no major erosion. The processes of transformation of parent rock and minerals are mainly secondary in nature, as they took place almost exclusively in the regolith in/on the cave ground.

The processes of transformation of organic remains resulted at best in the formation of a parahumus horizon, but not humus horizons. The organic remains were mainly represented by mass remains of animal origin and remains introduced from the outside.

The migration processes transferred products of transformation by leaching or accumulation, and corresponding (para-)horizons (cambic, eluvial, illuvial) were formed in the cave sediments. The migration processes were more complicated in the cave than in the open air, because the transformation products from the ground and the rock strata above the cave could be leached and accumulated in the cave sediments. Fine particles could also be brought into the cave by the wind, as revealed by chemical analysis of the sediments (Skaberne *et al.* 2015b). Leaching was unevenly distributed across the space. Migrations within the profile were confirmed by analysis of uranium content, which migrated from the upper part of the profile to the lower part (*ibid.*), as well as within individual layers, due to breaks in sedimentation.[9] In Divje babe I, this affected the dating of the upper and lower part of the profile based on uranium series, meaning that certain dates from the lower part of the profile were younger than the dates from the upper part of the profile, giving the impression of a reversed stratigraphy (Ku 1997).

6 – Processes associated with the activities of particular factors also took place in the cave ground. These processes included cryoturbation and oxidation associated with the presence of stagnant water in the sediments. In caves with sandy-silty sediments, cryoturbation is particularly strong between the lateral walls. Walls prevent the lateral expansion of the frozen sediments, whose volume expands greatly (*Fig. 8*). Cryoturbation is often mistakenly associated with the mixing of sediments and finds from different layers. In reality, no mixing occurs, as confirmed by distinct boundaries between cryoturbated layers. Finds are not mixed earlier than during excavations because it is not possible to reliably follow the cryoturbatic folds according to layers.

[9] In preparation: I. Turk, J. Turk, M. Turk, Uran (U) in torij (Th) v sedimentih Divjih bab I, dinamika sedimentacije in ESR kronologija. / Uranium (U) and thorium (Th) in Divje babe I cave sediments, sedimentation dynamics and ESR chronology.

The excavations of 1989–1999 have by far not exhausted the potential of the site. They provided guidelines for possible further exploration of this promising site and reliably achievable goals were defined. With the application of the presented new methods and approaches to all sediments excavated in the future, it would be possible to verify and improve the existing findings. The proposed new standards would be strengthened and in time they would bring new insights into the Palaeolithic in Slovenia and into the Palaeolithic in general.

The main goal remains to obtain as detailed and reliable a chronological sequence of climatic events as possible, to determine sedimentation hiatuses, and to find out how these hiatuses and the climate influenced the formation of the site. New excavations could further improve the field method of sediment sampling and test the credibility of the results of the 1989–1999 excavation campaign and their definitions obtained on the basis of the new model to explain the cave clastic sediments.

Acknowledgement

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Translation: Maja Sužnik

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O pomenu jame Divje babe I za stratigrafijo, sedimentologijo in kronologijo jamskih paleolitskih najdišč v Sloveniji

Prevod

Paleontološko in arheološko jamsko najdišče Divje babe I leži v zahodni Sloveniji, v predalpskem hribovju, pod robom Šebreljske planote (*sl. 1*). Jama, izoblikovana v dolomitu, se odpira na strmem severnem osojnem pobočju nad dolino reke Idrijce, na nadmorski višini 450 m. Najdišče je znano predvsem po najdbi nenavadno preluknjane stegnenice mladega jamskega medveda, interpretirani kot neandertalsko glasbilo (M. Turk *et al*. 2018). Vendar je najdišče zanimivo še zaradi drugih pomembnih odkritij in inovativnih raziskovalnih pristopov (I. Turk 2007a; 2014a).

V Divjih babah I je v letih 1978–1986 sistematično izkopaval Mitja Brodar. Izkopavanje sta v letih 1989–1999 nadaljevala Ivan Turk in Janez Dirjec. Njuno izkopavanje je prineslo nekatere povsem nove pristope za razlago jamskih klastičnih in kemičnih sedimentov. Njihov idejni tvorec je bil I. Turk. Zaradi pomembnosti izsledkov teh pristopov za raziskovanje jamskih najdišč sva avtorja v pričujočem članku pripravila povzetek z dodatno razlago njegovih zamisli in izsledkov proučevanj, objavljenih v številnih člankih. Nekateri doslej neobjavljeni podatki in izsledki pa so povzeti po obsežnem elaboratu, ki ga hrani arhiv ZRC SAZU Inštituta za arheologijo.[1]

Pleistocenski jamski sedimenti so pomembni tako zaradi arheološke in/ali paleontološke vsebine kot tudi zaradi možnosti, ki jih ponujajo za različne druge interdisciplinarne raziskave. S proučevanjem sedimentov ugotavljamo njihov nastanek, izvor in diagenezo. Vse to lahko spremljamo bolj ali manj zvezno – odvisno od prekinitev v sedimentaciji – v določenem profilu. Takšno spremljanje običajno ni mogoče pri arheoloških in paleontoloških najdbah, in sicer zaradi prisotnosti sedimentov brez najdb. Ker so jamski sedimenti zaradi posebnega sedimentnega okolja spremenljivi glede na njihovo mikrolokacijo, je treba pri razlagah izsledkov sedimentoloških raziskav nujno upoštevati tudi njihovo prostorsko variabilnost, čemur pa se je doslej namenjalo bistveno premalo pozornosti (glej Farrand 2001).

Proučevanje pleistocenskih sedimentov v paleolitskih jamskih najdiščih ima v Sloveniji dolgo tradicijo (S. Brodar 1939; 1958; 1966; M. Brodar 1959; Osole 1961; 1968; 1986). Omejeno je bilo predvsem na kraške jame, ki so se izoblikovale v apnencu. Zato je jama Divje babe I, ki je nastala v dolomitu, zaradi drugačnih sedimentov na začetku izkopavanj M. Brodarja pomenila izjemo brez ustrezne primerjalne prakse (M. Brodar 1999, 39). Divje babe I so tako začasno postale na videz nerešljivo ali vsaj težko rešljivo vprašanje s področja pleistocenske jamske sedimentologije v Sloveniji. Postavljalo se je celo vprašanje, kakšen smisel bi v tem posebnem primeru imela tedaj veljavna rutinska sedimentološka analiza. Ko je I. Turk leta 1997 dobil novo priložnost za sistematično radiometrično datiranje profila Divjih bab I z elektronsko spinsko resonanco (ESR),[2] se je odločil izvesti vzporedno pilotsko analizo sedimentov vseh s to metodo ponovno datiranih plasti. Po zaključku sistematičnih izkopavanj leta 1999 se je lotil temeljite analize vseh odkopanih sedimentov po lastni zamisli in se pri tem povezal z geologom Dragomirjem Skabernetom z Geološkega zavoda Slovenije.[3]

RAZISKOVALNE METODE IN NJIHOVA UPORABA V SLOVENSKIH PALEOLITSKIH JAMSKIH NAJDIŠČIH S POUDARKOM NA NOVI METODI, UPORABLJENI V DIVJIH BABAH I

Naj najprej predstaviva glavne značilnosti prvotne metode dela v sedimentologiji paleolitskih najdišč v Sloveniji do leta 1999. Rezultati proučevanja jamskih sedimentov v paleolitskih najdiščih Slovenije so bili običajno sestavni del kronologije najdišč

[1] Turk, I. 2002, Elaborat Divje babe I. Izkopavanja 1989–1999, Arhiv ZRC SAZU Inštitut za arheologijo.

[2] Prvič je bilo najdišče datirano leta 1990 s tedaj novo metodo AMS ^{14}C, ki jo je s svojo ekipo razvil D. E. Nelson (1991; 1997), kar Divje babe I uvršča med prva s to metodo datirana paleolitska najdišča v Evropi.

[3] Projekt analize sedimentov ni bil odobren. V okviru omejenih finančnotehničnih možnosti je bila analiza sedimentov vseeno opravljena v letih 1999–2014.

in paleolitskih najdb. Pri raziskavah se je skoraj izključno uporabljala kvalitativna in deduktivna metoda, ki je predpostavljala določene zakonitosti v sedimentaciji (npr. menjavanje gruščnatih in ilovnatih plasti) na podlagi hipotez. Tako se je npr. predpostavljalo, da so jamski grušči značilni za hladnejšo klimo in jamske ilovice za toplejšo (S. Brodar 1958; M. Brodar 1959, 438; Osole 1961), kar je v osnovi zmotno mišljenje (White 2007). Temeljna domneva, da je bila v pleistocenu klima glavni dejavnik, ki je vplival na jamske sedimente, se od najdišča do najdišča ni preverjala. Tako se ni ugotavljalo odstopanje vrednosti analiziranih atributov (parametrov) – predvsem velikosti zrn (klastov) – v pleistocenskih sedimentih od vrednosti atributov v holocenskih sedimentih, ki so nastali v bolj ali manj poznani klimi. Tudi drugod ni poznan niti en primer takšnega preverjanja. Se je pa samo izjemoma preverila ponovljivost rezultatov tehničnega dela metode v okviru posameznega najdišča z vzorci iz različnih profilov (M. Brodar 1959; Farrand 1975 in drugi). Iz množice sedimentoloških atributov, ki so lahko – ali pa tudi ne – povezani s klimo, se ni nikoli izločil najvplivnejši atribut ali najvplivnejši atributi z dosledno uporabo metode abstrakcije. Zato se po opravljeni analizi določenega atributa – običajno je bila to porazdelitev velikosti drobnih zrn, analiziranih s kvantitativno metodo – tega ni poskušalo povezati z drugimi sedimentološkimi atributi z metodo sinteze. Dejansko to ni bilo mogoče, ker drugi atributi niso bili ustrezno količinsko ovrednoteni, temveč v najboljšem primeru zgolj opisno navedeni.

Po skoraj 70 letih obsežnih, tudi multidisciplinarnih raziskav (Stritar *et al.* 1967) v številnih paleolitskih jamskih najdiščih po Sloveniji so premik v novo smer prinesla prav izkopavanja v Divjih babah I in Turkova inovativna študija sedimentov (Skaberne *et al.* 2015a; 2015b). Domnevamo, da so njegove temeljne ugotovitve uporabne tudi na drugih najdiščih s podobnim sedimentnim okoljem in podobnimi pojavi, kot so zmrzlinski klasti (kongelifrakti), reliefno korodirani klasti in fosfatni agregati. Takšna najdišča so v Sloveniji Jama pod Herkovimi pečmi, Matjaževe kamre, Mokriška jama, Njivice in Potočka zijalka. I. Turk je za analizo sedimentov Divjih bab I uporabil empirično metodo, podprto s statistiko. Pri tem pa ni zanemaril kvalitativnih znakov atributov, ki jih je kombiniral s kvantitativnimi. Vsako prevzeto ali lastno hipotezo je preveril v okviru danih možnosti, tudi eksperimentalno, če je bilo mogoče. Z namenom preverjanja stare kronološke sheme za umeščanje srednjepaleolitskih najdišč v Sloveniji je z neformalno pomočjo tujih sodelavcev postavil temelje neodvisne radiometrične kronologije (Nelson 1997; Ku 1997; Lau *et al.* 1997; Blackwell *et al.* 2007; 2009). V okviru možnosti je uporabljal metodo abstrakcije, s katero je odstranil vse za klimatski model nebistvene sedimentološke atribute, med katere sodi tudi porazdelitev velikosti drobnih zrn. Med terenskimi raziskavami je I. Turk razvil nov model poteka sedimentacije v jamskem okolju. Ta je osnovan na spletu med seboj povezanih sedimentoloških atributov, izbranih z metodo abstrakcije, ki odslikavajo tako klimatske razmere kot hitrost sedimentacije. Slednja je bila v starem modelu premalo ali pa sploh ni bila upoštevana. Pomembni so samo tisti atributi, ki so nesporno povezani s klimo in ki na najdišču nastopajo zvezno v času (navpična razsežnost) in prostoru (bočna razsežnost). Zbiranju in statistiki zveznih podatkov, ki se nanašajo na lastnosti sedimentov in njihovo prostorsko variabilnost, se je v preteklosti posvečalo premalo pozornosti. V večini primerov se obojega, kljub možnosti, ki jo ponujata vsako večje izkopavanje in računalniška podpora za obdelavo podatkovnih množic, ni izkoristilo. Glavni razlog za to je bil v izkopavalni metodi čelnega izkopavanja po plasteh od profila do profila in pobiranja najdb brez sejanja sedimentov. Nov model sedimentacije je bilo mogoče razviti šele na podlagi izkopavanj po režnjih in kvadratih ter mokrega sejanja vseh, tudi arheološko sterilnih sedimentov.

Navpično razsežnost

so v Divjih babah I predstavljali v prvi vrsti režnji, izkopi enake debeline, s katerimi so se odstranjevali sedimenti. Debelina režnjev je bila po letu 1989 stalno 12 cm, kar je optimalna debelina glede na teksturo sedimentov, ki vsebujejo veliko klastov, večjih od 10 cm. Režnje lahko enačimo s sedimentacijskimi nivoji, stratigrafsko kategorijo, ki jo je v Divjih babah I uporabil in opredelil I. Turk. Sedimentacijski nivoji sledijo naklonu plasti, če meje med plastmi niso vodoravne v prečni in/ali vzdolžni smeri. Več zaporednih sedimentacijskih nivojev lahko po potrebi združimo v večjo celoto, kot je npr. plast, več plasti pa v njihovo zaporedje (glej Skaberne *et al.* 2015a).

Po definiciji je geološka plast homogena celota, ki je (teoretično) nastala pod enakimi fizikalno-kemičnimi pogoji pri enotnih procesih in njihovem enotnem zaporedju. Plast je ločena od podlage in krovnine glede na eno (ali več) osnovnih značilnosti sedimentov. Na značilnosti plasti vplivajo fizikalni, kemični, biološki (vključno z antropološkimi), geološki in diagenetski pogoji. Plastnatost nastaja v sedimentu praviloma ob spremembah v materialu, ki se odlaga. To v jamskem okolju, kjer prevladujejo klastični sedimenti, ni ravno pogosto. Nevidne sedimentacijske vrzeli med plastmi (hiati), ki vplivajo na popolnost kronološkega zapisa, nastanejo zaradi prekinitve v sedimentaciji, delovanja erozije ali sprememb pogojev pri sedimentaciji. Če nam uspe ugotoviti hiate na podlagi datacij in sedimentoloških raziskav, lahko razlikujemo več sedimentacijskih ciklusov, ki so med seboj ločeni s prekinitvami v odlaganju sedimentov (glej Blackwell *et al*. 2020; J. Turk 2011). Med odkopavanjem vedno novih plasti vsega tega seveda ni mogoče sproti ugotavljati na terenu. Zato so na terenu ugotovljene t. i. geološke plasti samo začasni delovni pripomoček za stratigrafsko in kronološko razvrščanje najdb, ki nima bistveno večje teže od arbitrarnih režnjev, dokler ne ugotovimo prave narave vsake posamične plasti ali zaporedja določenih plasti z rutinskimi analitskimi postopki. Plast lahko vsebuje arheološke in druge najdbe. Te so bodisi razpršene po celotni debelini plasti bodisi zgoščene v enem ali več horizontih (I. Turk 2003).

Tako plasti kot sedimentacijski nivoji pripadajo različno dolgim časovnim intervalom, saj hitrost sedimentacije ni enakomerna. Sedimentacija v jamskem okolju poteka ali pa ne, odvisno od različnih notranjih in zunanjih pogojev, lokalne in/ali globalne narave. Hitrost sedimentiranja je torej zelo pomembna spremenljivka. Od nje sta odvisni stopnja preoblikovanosti sedimentov ter zastopanost in časovna enotnost oziroma neenotnost arheoloških in drugih najdb (I. Turk 2003). Časovna enotnost ni nujno zagotovljena s pripadnostjo najdb določeni plasti. Zaradi zastoja v sedimentaciji lahko namreč pride do mešanja različno starih najdb.

Kronologija je poleg določitve plasti in sedimentacijskih vrzeli med plastmi ključnega pomena pri vsaki raziskavi. Zato je nadvse pomembna stratigrafija, ki jo predstavlja navpična razsežnost proučevanega pojava. I. Turk je v Divjih babah I opredelil navpično razsežnost (profil) kvantitativno-kvalitativno na dva načina (*sl. 2* in *3*):

1 – S pomočjo srednjih vrednosti množice podatkov določenega sedimentološkega atributa v primerno velikem volumnu stratificiranega jamskega zasutja s tlorisno površino, ki je obsegala 15 % (83 m^2) celotne današnje površine jame (550 m^2) (I. Turk 2003, sl. 6a). Podatki so bili razporejeni po sedimentacijskih nivojih, ki so jih predstavljali 12-centimetrski režnji. Ti so bili po končanih izkopavanjih razvrščeni tako, da so v grobem sledili padcu plasti v smeri vzdolžne osi jame. *Sl. 2* ter tudi že objavljeni sl. 6a in 7a (I. Turk 2003) kažejo, da se srednje vrednosti sedimentoloških atributov spreminjajo s spreminjanjem deleža vzorčene površine od celotne tlorisne površine in da so tem bolj zanesljive, čim večji je delež vzorčene površine.

2 – S pomočjo dveh profilov iz razpoložljive množice profilov določenega sedimentološkega atributa, ki sta se maksimalno razlikovala ter tako predstavljala obe skrajnosti stratigrafskega niza: a) profil, ki je najmanj odstopal od vseh razpoložljivih profilov, in b) profil, ki je od teh najbolj odstopal (*sl. 3*). Oba sta bila tem bolj zanesljiva, čim večja je bila množica profilov, izmed katerih sta bila izbrana, vizualno ali računsko. Profil, ki najmanj odstopa od vseh razpoložljivih profilov, predstavlja t. i. tipični profil (I. Turk 2003). Na *sl. 3* je razvidna znatna variabilnost proučevanega atributa v prostoru (kvadratih), kar je pričakovano za jamsko okolje. Zato zelo natančna in sofisticirana analiza na določeni mikrolokaciji ne pomeni, da so tako dobljeni rezultati reprezentativni tudi v primeru celote, ki ni bila podvržena takšni analizi. Gre za bližnjico, ki jo lahko uporabimo tudi pri reviziji določenega najdišča, in pri tem lahko dobimo bistveno drugačen rezultat od prvotnega. Pri tem pa še vedno ne vemo, kateri rezultat je bolj pravilen in kateri manj.

Bočno razsežnost

so predstavljali v Divjih babah I kvadrati velikosti 1×1 m. Jamsko sedimentacijsko okolje je mozaično okolje, sestavljeno iz mikrookolij. Ta se spreminjajo že s samo velikostjo vhoda in oddaljenostjo od njega, tako da prihaja do pojava gradienta ali postopnega zmanjševanja zunanjih vplivov sorazmerno z oddaljenostjo od vhoda in njegovo velikostjo. Sočasno lahko na spremembe vplivajo tudi drugi dejavniki, ki niso neposredno odvisni od velikosti in oddaljenosti vhoda. Ti zlasti vplivajo na fosilne ostanke in podzemno vodo, pri čemer ni mišljena podtalnica, temveč prenikajoča voda in z njo povezana večja ali manjša prisotnost vlage v sedimentih. Posledica delovanja različnih dejavnikov je variabilnost jamskih sedimentov. Velika variabilnost pa je temeljna značilnost jamskih sedimentov. Zaradi vsega naštetega je dokumentiranje in analiziranje značilnosti sedimentoloških atributov v bočni smeri lahko prav tako pomembno kot dokumentiranje in analiziranje njihovih navpičnih značilnosti.

Vseh novih metodoloških prijemov seveda ni bilo mogoče izpeljati brez prilagajanja arheološke terenske metode novim zahtevam, ki jih prinaša uporaba drugačnih poizkopavalnih analitskih metod in postopkov, kot so bili pri nas v rabi do konca prve faze izkopavanj v Divjih babah I leta 1986. Raziskava sedimentov Divjih bab I je v osnovi potekala tako, da je poleg naštetega sproti preverjala natančnost in zanesljivost podatkov, od katerih je odvisna verodostojnost oziroma točnost razlage.

– Natančnost zbranih podatkov je odvisna predvsem od metode, vloženega časa in natančnosti tistih, ki metodo izvajajo. Nujne so kontrole natančnosti, ki dajo oceno napake.

– Zanesljivost podatkov ni vedno odvisna od natančnosti, s katero so podatki zbrani. Pomembno je tudi število podatkov. Veliko število manj natančnih podatkov lahko da bolj zanesljiv rezultat kot skromno število zelo natančnih podatkov. Oceno zanesljivosti lahko naredimo samo na podlagi množice podatkov, ki se nanašajo na posamezne proučevane atribute.

– Verodostojnost oz. točnost razlage zbranih podatkov je odvisna od tega, kako zanesljivi so podatki. Vendar zanesljivost podatkov ni sama po sebi porok za verodostojnost interpretacije. Zato je vsaka razlaga samo hipotetična, dokler je ne potrdimo ali ovržemo na podlagi preverjanja z drugimi neodvisnimi podatki in metodami. Preverjena trditev ostane veljavna, dokler jo ne nadomestimo z drugo dobro utemeljeno trditvijo ali dokažemo, da je napačna. Verodostojnost razlage še ne pomeni, da je razlaga pravilna. Vsaka razlaga bi morala temeljiti na analizi natančnosti in zanesljivosti izhodiščnih podatkov (dejstev). Tega načela se je v Sloveniji poskusil držati le M. Brodar (1959) pri analizi zrnavosti sedimentov Mokriške jame.

Pri proučevanju problemov, povezanih s preteklimi dogodki in pojavi, običajno iz posledic (dejstev) sklepamo na vzroke in procese, ki so privedli do določenega aktualnega stanja. Težava je v tem, da imajo različni vzroki in procesi lahko podobne posledice. To pomeni, da je vsaka razlaga in vsako sklepanje povezano z določenim tveganjem, da ni pravilno. Tveganje lahko zmanjšamo, če dejstva ne obravnavamo posamično, temveč skupaj z drugimi razpoložljivimi dejstvi, tako da analiziramo njihove medsebojne odnose in ugotavljamo smiselne povezave, ki pripeljejo do sistemskih rešitev.

Če povzamemo, lahko rečemo, da je I. Turk stare metode, ki so temeljile na logičnem razmišljanju, intuiciji in izkušnjah, nadgradil z raziskovalnimi metodami, ki kvaliteto črpajo iz kvantitete. Pri tem se je omejil na avtohtone jamske sedimente in na najdišče Divje babe I, kjer je imel na voljo največ osebno zbranih podatkov in možnost maksimalnega preverjanja rezultatov analiz. Razumljivo je, da se njegovi novi izsledki niso vedno skladali z izsledki, pridobljenimi z drugačnimi metodami. Tudi tistimi, ki jih je prej sam uporabljal po zgledu svojih predhodnikov, in z izsledki analiz alohtonih primesi v jamskih sedimentnih okoljih. Slednje se pogosto obravnavajo prednostno, čeprav predstavljajo neznaten delež v jamskih sedimentih.

CILJ IN INOVATIVNE METODE SEDIMENTOLOŠKIH RAZISKAV V DIVJIH BABAH I

Proučevanje pleistocenskih sedimentov ima v paleolitskih najdiščih določen cilj. To je običajno ugotoviti izvor in predvsem starost sedimentov. Oboje je bilo pri sedimentih Divjih bab I bolj ali manj pojasnjeno. Zaradi sedimentnega okolja in posebne skeletne zgradbe sedimentov ni dvoma o skoraj izključno avtohtonem izvoru večine sedimentov. Številni radiometrični datumi so pojasnili tudi osnovna kronološka vprašanja, ki jih je postavil M. Brodar (1999). Ostalo je torej vprašanje dodatnih (alternativnih) ciljev sedimentološke analize (za rutinske postopke glej Farrand 2001; Woodward, Goldberg 2001). Ti so bili:

– ugotoviti dejavnike, odgovorne za odlaganje sedimentov (vključno z najbolj drobno frakcijo), preperevanje in nadaljnjo diagenezo sedimentov;

– po možnosti določiti kazalnike temeljnih klimatskih parametrov.

Tako bi skupaj s palinološkimi, antrakotomskimi, makro- in mikrofavnističnimi podatki prispevali k rekonstrukciji paleoklime, ki je poleg radiometričnih podatkov trenutno edina podlaga za kolikor toliko zanesljivo klimatokronološko umestitev najdišča v shemo sodobne globalne kronologije mlajšega pleistocena, saj t. i. popolna členitev Würma že dolgo ni več aktualna (glej I. Turk, Verbič 1993).

V zasledovanju zastavljenih ciljev je I. Turk analiziral vzorce sedimentov iz profilov in vzorce sedimentov, odvzetih po režnjih in kvadratih v prostoru, na katerem so potekala izkopavanja.[4] Natančna analiza sedimentov iz profila je sicer reprezentativna predvsem ali samo za določen odsek profila, vendar ima tudi širši pomen, ker vsaka posamezna analizirana vrednost določene značilnosti sedimentov v profilu nedvomno pripada množici z določenim razponom vrednosti. Na podlagi podatkov iz posamičnih profilov *sensu stricto* lahko tako primerjamo izsledke analize množic sedimentoloških podatkov, ki so bili zbrani po režnjih in pozneje združeni v sedimentacijske nivoje, s t. i. geološkimi plastmi, kot so bile določene vizualno v profilih. Podatki, zbrani po režnjih, so se nanašali na naslednje kategorije:

– maso dolomitnih blokov in frakcij od vključno drobnega grušča do melja;
– na volumsko maso peščene frakcije;
– na fosilne ter arheološke ostanke.

Čeprav sedimentološki podatki niso bili v nobenem pogledu tako natančni kot ustrezni podatki iz profilov, so bili zaradi svoje številnosti (od nekaj 100 do ok. 2500 arhiviranih in neobjavljenih podatkov[5] za posamezno kategorijo od plasti 2 do vključno plasti 16a ali povprečno 150 podatkov za vsako odkopano plast) statistično zanesljivi in so tako omogočili spoznati variabilnost zbranih podatkov po omenjenih kategorijah. Ker so bili stratigrafsko objektivno opredeljeni z natančnostjo 12 cm, jih je bilo mogoče dosti dobro vzporediti s stratigrafsko domnevno primerljivimi podatki iz profilov, narediti primerjalno analizo in preveriti korelacijo med sedimentacijskimi nivoji in geološkimi plastmi. Da bi bolje spoznal celoten potek sedimentacije in preobrazbe sedimentov, je I. Turk s sodelavci sistematično proučil:

a – porazdelitev velikosti zrn (klastov in agregatov) različnih frakcij;
b – povprečno velikost zrn v posameznih frakcijah klastov;
c – posedimentno fragmentiranje klastov (t. i. zmrzlinske klaste ali kongelifrakte);
d – korozijsko razjedenost klastov (t. i. reliefno korodirane klaste);
e – volumsko (specifično) maso drobnih sedimentnih frakcij;
f – kemično sestavo posameznih sedimentnih frakcij s poudarkom na drobni frakciji.[6]

Pri tem se je osredotočil na nekatere univerzalne značilnosti klastičnih sedimentov (preperelost, kongelifrakcija, korozija, cementacija), za katere je domneval, da so neposredno povezane s klimatskimi parametri (temperaturo, vlago). Na podlagi radiometričnih datumov mu jih je uspelo neposredno korelirati z globalnimi klimatskimi nihanji temperature (Blackwell *et al.* 2007; I. Turk 2007b), medtem ko se pri modernih paleoklimatskih in paleookoljskih raziskavah to počne na podlagi drugačnih parametrov (Ellwood *et al.* 2004; Spötl *et al.* 2006; Aubry *et al.* 2010), ki se jih lahko samo posredno primerja z datiranimi klimatskimi krivuljami. Visoko korelativni s temperaturo naj bi bili zmrzlinski klasti (kongelifrakti), z vlago oziroma padavinami pa korozijsko razjedeni klasti in različni strukturni agregati s cementnim vezivom. Korozijsko razjedene klaste je lahko zanesljivo povezal tudi z zastoji v pretežno mehanskem preperevanju jamskega svoda. Ti se odslikavajo tudi v diskontinuitetah datumov ESR v profilu Divjih bab I. Doslej ni bil nihče posebej pozoren na povezavo med hiati in korozijsko razjedenimi klasti, vključno z avtorji, ki so se posebej ukvarjali s stratigrafskimi hiati v jamskih najdiščih (Campy, Chaline 1993). Tudi strukturni agregati niso bili nikdar analizirani tako, kot je bilo to storjeno v Divjih babah I.

V analizi sedimentov Divjih bab I je I. Turk izhajal iz splošnega znanja o preperevanju in cementiranju sedimentnih kamnin (kamor prištevamo tudi dolomit) ter lastnih terenskih opažanj iz obdobja 19-letnih izkopavanj v Divjih babah I. Temeljne zamisli o povezavi preperevanja in cementiranja s klimo je dobil pri mokrem sejanju in pregledovanju vseh odkopanih sedimentov v letih 1990–1999. Vendar žal šele proti koncu izkopavanj, zato mu kongelifraktov in korozijsko razjedenih klastov ni uspelo preveriti v njihovi bočni razsežnosti tako, kot je to storil s strukturnimi agregati.

Preperevanje

je kombinacija neločljivo povezanih mehanskih in kemičnih procesov, ki privedejo do razkroja kamnine (I. Turk 2006, 21). Preperevanje matične dolomitne kamnine je bilo lahko primarno, *sinsedimentno, singenetsko* (na stropu, stenah in policah jame) in/ali sekundarno, *posedimentno, postgenetsko* (na/v jamskih tleh). Masa posedimentne preperine je enaka masi sinsedimentne preperine, če ni nobenega transporta preperine iz

[4] Vzorce sedimentov skupaj z drugimi najdbami hrani Narodni muzej Slovenije.

[5] Turk, I. 2002, Elaborat Divje babe I. Izkopavanja 1989–1999, Arhiv ZRC SAZU Inštitut za arheologijo.

[6] Slednje v sodelovanju z geologom D. Skabernetom.

jame ali izdatnejšega dotoka alohtone preperine. Pri obeh vrstah preperevanja gre za podobna procesa, ki potekata pod različnimi sedimentacijskimi pogoji (vlaga, temperatura, transport). Zato so lahko končni proizvodi različni. Vendar proizvode enega in drugega preperevanja lahko razlikujemo samo izjemoma.

Tako sinsedimentno kot posedimentno preperevanje potekata neprekinjeno, razen v primerih nabiranja zaščitnega sloja preperine (na policah in na tleh) ali kemičnih sedimentov, kot je siga (na stropu, stenah, policah in na tleh). Preperevanje je lahko enakomerno ali neenakomerno. Do kakšne mere je preperevanje neenakomerno, je odvisno predvsem od stopnje anizotropnosti (pretrtosti idr.) kamnine. Ob daljšem zastoju v primarnem preperevanju nastanejo na stropu in stenah korozijske razjede. Ko se tako preoblikovan jamski svod začne ponovno krušiti, se v sedimentih nabirajo reliefno korodirani klasti. V podobnih okoliščinah lahko ti nastanejo tudi v tleh.

Erozija, ki ima pomembno vlogo pri preperevanju usedlin na prostem, je bila v Divjih babah I bolj izjema kot pravilo. V poštev pride le pri najdrobnejših sedimentih, ki jih je podzemna voda spirala v pore in vakuole med klasti, lahko pa tudi iz jame ob površinskem curljanju. Dokazi za erozivno soliflukcijo so samo na pobočju pred jamo in pod njo, kjer evidentno manjka neznan del pleistocenskih sedimentov. Delno odstranjeni (antropogeno?) so bili tudi sedimenti plasti 2 pri sedanjem jamskem vhodu (I. Turk 2007c, sl. 4.1b).

Sinsedimentno preperevanje, ki poteka na majhni površini, ki jo predstavljata jamski svod in police, spremlja stalna erozija preperine zaradi delovanja težnosti. Ta je največja na stropu in najmanjša na policah. Količinsko gledano, so rezultat sinsedimentnega preperevanja predvsem debele frakcije, pogojene s primarnimi makrorazpokami v matični dolomitni kamnini. Delež drobnih frakcij, pogojenih s primarnimi mikrorazpokami in kristalinsko zgradbo dolomita, je kljub potencialno večjemu številu mikrorazpok relativno majhen zaradi relativno majhne površine, ki preperava.

Posedimentno preperevanje, ki poteka na veliki površini, ki jo predstavljajo površine vseh klastov, in vključuje tudi nastajanje sekundarnih razpok, je obratno sorazmerno s sinsedimentnim preperevanjem, ker hitro odlaganje vedno novih usedlin z jamskega svoda zavira preperevanje prej odloženih sedimentov. Nasprotno počasno odlaganje novih usedlin z jamskega svoda omogoča močnejše preperevanje prej odloženih sedimentov. Posedimentno preperevanje pa ni odvisno samo od klime in hitrosti sedimentacije gravitacijskega drobirja, ki zadržuje za preperevanje nujno potrebno vlago, temveč tudi od količine biomase. Rezultat posedimentnega preperevanja so predvsem drobne frakcije, ki so običajno predmet analize porazdelitve velikosti zrn in mikromorfologije. Poskusi I. Turka so pokazali, da je delovanje zmrzali (gelifrakcija) najučinkovitejše, če je sediment dobesedno zalit z vodo. To je seveda mogoče predvsem v/na tleh, če so za to izpolnjeni potrebni pogoji (prisotnost manj propustnega sloja v obliki zahojene površine). V takšnih pogojih se najprej odkrušijo klasti v velikosti melja in drobnega peska. Nato začne odpadati debelejši pesek in tako naprej do velikih odlomkov, ki lahko dosežejo polovico velikosti zamrznjenega klasta. Veliki odlomki, ki so nastali zaradi delovanja zmrzali, so t. i. zmrzlinski klasti ali kongelifrakti.

Na podlagi temeljne zakonitosti sin- in posedimentnega preperevanja je bila razložena porazdelitev velikosti zrn v profilu Divjih bab I, predvsem najdebelejše in najdrobnejše frakcije (Skaberne *et al.* 2014, sl. 17.2.1). Ti nista tako izrazito povezani s klimo, kot so predpostavljali M. Brodar in nekateri drugi avtorji. Obe frakciji sta obratno sorazmerni in večinoma različni po izvoru. Najdebelejša frakcija je, kot rečeno, nastala pretežno sinsedimentno v povezavi z nestabilnim jamskim svodom. Najdrobnejša frakcija je nastala predvsem posedimentno v povezavi z zastoji v sedimentaciji najdebelejše frakcije v obdobjih stabilnega jamskega svoda. Predstavlja gravitacijsko najbolj mobilno frakcijo, ki lahko sčasoma zapolni vse pore med klasti.

Hitrost sedimentacije vseh gravitacijskih jamskih sedimentov je odvisna od klime (temperature, vlage, sezonske razporeditve padavin), narave kamnine (stopnje pretrtosti in zgradbe), medzrnske poroznosti klastičnih sedimentov in potresne dejavnosti. Zgodnja kemična diageneza (nastanek kemičnih usedlin) je odvisna od fizikalnih in fizikalno-kemičnih lastnosti sedimenta in raztopin, ki se pretakajo skozenj. Te lastnosti pa so odvisne od sestave okolnih kamnin in sedimentov ter eksogenih pogojev (klima, rastlinske in živalske primesi, živo okolje). Pri razlagi rezultatov analize sedimentov je bilo zato nujno upoštevati vse te dejavnike. Nekateri so med seboj povezani. Tako npr. siga ni mogla nastati brez rastlinskega pokrova nad jamo. Velikost populacije rastlinojedega jamskega medveda, ki je prispevala k organski komponenti sedimentov, je bila odvisna od hrane oziroma vegetacije. Ta pa je bila spet povezana z višjimi temperaturami, večjo vlago in daljšimi poletji.

MODEL, UPORABLJEN ZA RAZLAGO IZBRANIH ZNAČILNOSTI KLASTIČNIH SEDIMENTOV V DIVJIH BABAH I

Model temelji na naslednjih splošnih dejstvih

Ker v podzemnih jamah ni direktnega sončnega obsevanja, je v njih posebna mikroklima, na katero lahko vpliva še mikroklima v neposredni okolici jame. Na jamsko mikroklimo vplivajo velikost vhoda, temperatura tal (vključno in predvsem jamskih sedimentov), prisotnost človeka (ogenj) in vegetacija nad jamo in pred njo (drevje, grmovje, goličava). Vsi ti dejavniki se lahko spreminjajo soodvisno, nekateri tudi neodvisno od klimatskih sprememb v povezavi z naravnimi katastrofami (gozdni požari, ledolomi ipd.). Medtem ko vpliva mikroklima na jamske sedimente kratkoročno in specifično za posamezno najdišče, vpliva atmosferska klima dolgoročno in globalno, kar omogoča primerjave na globalni ravni.

Vlaga v jamah nastopa kot kondenz in kot podzemna (talna) voda. Podzemne vode so vse vode pod površino zemlje, vključno z vodo v porozni sredini jamskih sedimentov. Tako kondenzna vlaga kot podzemna talna voda sta odvisni od zunanje temperature zraka in padavin. Vlaga v jamskem okolju je močno povezana z razlikami med jamskimi in zunanjimi temperaturami, ki so v negativni korelaciji z velikostjo vhodne odprtine (glej *sl. 4*).

Podzemni dotok vode, kot je prenikajoča voda v horizontalnih jamah, je odvisen od padavin. Na *sl. 5* so prikazani izsledki občasnih meritev podzemnega dotoka (prenikajoče vode) s stropne površine 91 m^2 v Divjih babah I od januarja 2000 do februarja 2001. Povprečje meritev je 22,7 litra v eni uri ali 0,25 litra na 1 m^2 v eni uri, če bi bil podzemni dotok vode enakomerno razporejen po površini 91 m^2. Največja vrednost za površino 91 m^2 je bila 112 litrov na uro, najmanjša pa 2 litra. V enem letu bi lahko tako na 1 m^2 jamskih tal pricurljalo 2190 litrov vode, kar je malo več od lokalnega povprečja padavin za obdobje 1961–1990, ki znaša 2098 litrov (Nadbah 2012). Podzemni odtok je v nasprotju s padavinami stalen. Po padavinah hitro naraste, potem pa pade v obliki eksponencialne krivulje. Ta se najprej hitro spušča, od določene točke pretoka pa zelo počasi in se verjetno nikoli ne spusti na vrednost 0. Podzemni odtok je odvisen od ločevanja padavin na površinski in podpovršinski odtok ter evapotranspiracije (izhlapevanja vode z zemeljskega površja).

Za razlago humidnosti v jamskem okolju Divjih bab I se je I. Turk oprl na naslednji mikroklimatski model:

– *Pri nižjih temperaturah* je v zraku manj, v tleh pa več vlage zaradi manjše evapotranspiracije. Ta pri 30-letni povprečni letni temperaturi 10 °C in 1800 mm padavin, oboje izmerjeno v okolici jame, znaša 572 mm na leto (primerjaj Verheye *et al.* 1991, tab. 1). Pri znižanju povprečne letne temperature za 5 °C in nespremenjenih padavinah bi se evapotranspiracija zmanjšala za 35 %, tako da bi znašala 372 mm na leto. V jamskem okolju to dolgoročno pomeni manj kondenzne vlage in več podzemne vode. Slednja je zaradi nižje temperature agresivnejša in lahko v tleh proizvede več reliefno korodiranih klastov, ki se jim lahko pridružijo klasti z reliefno korodiranega jamskega svoda iz predhodnega toplejšega obdobja, ko je bilo več kondenzne vlage in korozije (glej I. Turk *et al.* 2005, sl. 7). Padavine povečajo predvsem dotok podzemne vode, ker nimajo večjega vpliva na evapotranspiracijo. Pri povprečnih letnih padavinah 2500 mm, ki so verjetno blizu možnega maksimuma za to območje, in povprečni letni temperaturi 5 °C bi bila letna evapotranspiracija 425 mm, kar je le 12 % več kot pri 1800 mm padavin. Travniška vegetacija, značilna za hladnejšo klimo, povečuje navpično prepustnost tal, kar ugodno vpliva na pretok podzemne vode, ta se lahko tako poveča tudi do 50 % (Ćirić 1986, 123s). Po drugi strani je dnevno-nočna temperaturna amplituda pri nižjih temperaturah manjša kot pri višjih temperaturah. Manjša amplituda pomeni tudi manj kondenzne vlage. V jami so temperaturne amplitude manjše pri manjšem vhodu. To se je lepo pokazalo med izkopavanji v Potočki zijalki, ki so potekala poleti v letih 1929–1935 in so jih spremljale dnevne meritve temperature v jami in zunaj nje (S. Brodar 1934) (*sl. 4*). Pred povečanjem vhoda je bilo z nihanji zunanje temperature zraka leta 1929 pojasnjene samo 13 % variacije temperature zraka za vhodom ($n = 87$, $p = 0{,}001$) in 24 % variacije temperature zraka na koncu jame ($n = 87$, $p < 0{,}001$). Po povečanju vhoda z izkopavanji je bilo z nihanji zunanje temperature zraka leta 1935 pojasnjene že 64 % variacije temperature zraka za vhodom ($n = 107$, $p < 0{,}001$) in 72 % variacije temperature zraka na koncu jame ($n = 107$, $p < 0{,}001$). Pri 95-odstotnem zaupanju se je povprečna temperatura zraka za povečanim vhodom leta 1935 zvišala za 1,3–1,5 °C, na koncu jame pa za 0,8–1,0 °C, in to kljub padcu povprečne zunanje temperature zraka za 1,8–2,0 °C istega leta v primerjavi z letom 1929, ko vhod še ni bil povečan. Če upoštevamo še razliko v povprečni zunanji temperaturi zraka, je bilo največje povprečno povišanje 3,5 °C za vhodom in 3,0 °C na koncu jame. Analogno zvišanju poletnih temperatur bi bilo znižanje zimskih temperatur v jami zaradi večjega vhoda.

– *Pri višjih temperaturah* je v zraku več vlage, v tleh pa manj zaradi večje evapotranspiracije. V jamskem okolju to dolgoročno pomeni več kondenzne vlage in nekoliko manj podzemne vode. Padavine povečajo dotok pozemne vode, vendar bistveno manj kot pri nižjih temperaturah. Pri povprečnih letnih padavinah 2500 mm in temperaturi 10 °C bi bila letna evapotranspiracija namreč samo za 2 % večja kot pri enaki temperaturi in 1800 mm padavin. Odtočni deficit (razlika med količino vode, ki je padla na določeno območje, in količino vode, ki je s tega območja odtekla ob iztoku – v grobem je enak evapotranspiraciji) povečuje tudi gozdna vegetacija, ki je v toplejši klimi pričakovano bolj razvita kot v hladni klimi. Zato padavine pri višjih temperaturah tudi bolj povečujejo kondenzno vlago kot pri nižjih temperaturah. Količina kondenzne vlage se poveča tudi zaradi večje temperaturne amplitude, ki je posledica višjih temperatur. Večjo temperaturno amplitudo lahko povzroči tudi manjši jamski vhod (*sl. 4*).

– Ker kondenzna vlaga pospešuje korozijo jamskega svoda, lahko po toplejših obdobjih teoretično pričakujemo v sedimentih več reliefno korodiranih klastov kot po hladnejših obdobjih. Obseg korozije pa je odvisen predvsem od stabilnosti jamskega svoda in delno od količine padavin. Jamski svod destabilizirajo potresi in zmrzal. Ker je zmrzal odvisna od temperature in podzemne (prenikajoče) vode, je manjša pri višjih povprečnih letnih temperaturah. To ugodno vpliva na razvoj stenskih in stropnih korozijskih tvorb.

– Ker podzemna voda pospešuje nastanek agregatov, breč in sig, lahko te tvorbe pričakujemo tako v hladnih kot toplih obdobjih. Zmrzovanje tal z meljasto-peščeno osnovo, kot jo imamo v sedimentih Divjih bab I, je dodatno prispevalo k nastanku in konsolidaciji strukturnih agregatov (Williams, Smith 1989, 42, 46). Obseg in razvitost teh tvorb pa sta odvisna od količine padavin, ki bolj ali manj direktno vpliva na količino podzemne (prenikajoče) vode. Nižje temperature in več vode pospešujejo delovanje zmrzali, ki destabilizira jamski svod in povečuje posedimentno razpadanje klastov (gelifrakcija) ter nastanek reliefno korodiranih klastov in agregatov v jamskih tleh. Nestabilnost jamskega svoda samo še zmanjšuje možnosti za že tako omejeno učinkovitost korozije. Povečajo se tudi možnosti za pobočno erozijo. Če erozija uniči vegetacijo nad jamo, kar se je v primeru Divjih bab I v preteklosti lahko dogajalo zaradi izredno strmega, slemenasto oblikovanega terena nad jamo, ni več pogojev za nastajanje sige. Erodirana pobočja tudi povečajo površinski odtok, zaradi česar se (lahko) zmanjša dotok podzemne vode. Na današnjem erozijsko nestabilnem pobočju nad Divjimi babami I ne moremo pričakovati debelejših nanosov ilovice, ki bi jo voda izdatneje splakovala v jamo. Ker v pleistocenskih sedimentih Divjih bab I praktično ni ilovice, lahko sklepamo, da je bilo podobno strmo in nestabilno kot sedanje tudi pleistocensko pobočje nad jamo.

Predlagani mikroklimatski model je primerljiv s klimatskimi modeli, ki temeljijo na spremembi temperature. Dolgoročna sprememba povprečne letne temperature ne pomeni, da bi se enakomerno spremenila tudi poletna in zimska temperatura. Nasprotno temu je verjetneje, da bi se precej bolj kot poletne spremenile zimske temperature. Posledica temperaturnih sprememb bi bila spremenjena količina padavin, ki bi bile spet drugače razporejene pozimi in poleti. To bi vplivalo na debelino snežne odeje, ki je eden glavnih regulatorjev temperature tal v hladni klimi (prim. Williams, Smith 1989, 81).

Ker sta vlaga in temperatura na podlagi predlaganega modela v jamskem okolju soodvisna klimatska parametra, se je lahko preverilo, kako se medsebojno ujemajo izsledki, dobljeni na podlagi domnevnih sedimentoloških atributov za temperaturo in vlago, ki jih predstavljajo zmrzlinski klasti, korozijsko reliefno razjedeni klasti in agregati. Te za zdaj domnevne klimatske atribute so predstavljali povsem neodvisno pridobljeni zvezni sedimentološki podatki, ki so se nanašali na singenetske in različne postgenetske procese. Ker se rezultati analiz izbranih sedimentoloških podatkov dobro ujemajo, lahko zaupamo razlagi klime, ki temelji na predlaganem modelu. Ker gre za univerzalno delovanje temperature in vlage na karbonatne kamnine, se da metodo I. Turka uporabiti v vseh podobnih sedimentnih okoljih s podobnimi posledicami posedimentnih procesov.

SINTEZA

Sinteza pionirskih sedimentoloških raziskav v Divjih babah I je bila mogoča šele na podlagi številnih datacij plasti z metodo elektronske spinske resonance (ESR).[7] Na podlagi datacij plasti in primerjanja analitskih izsledkov s temperaturno krivuljo kisikovih izotopskih stopenj (OIS) in njej podobnih krivulj za obdobje mlajšega pleistocena (glej I. Turk, Verbič 1993) je bilo mogoče v krivuljah kongelifraktov, reliefno korodiranih klastov in strukturnih agregatov prepoznati mejo med toplim zgodnjim glacialom (OIS 5) in hladnim visokim glacialom (OIS 4).[8] Ta meja, ki je po dogovoru postavljena 74.000 let pred sedanjost (I. Turk 2007b), deli profil Divjih bab I v dva dela s statistično različnimi značilnostmi klastičnih in kemičnih sedimentov (Skaberne *et al.* 2014; 2015a; 2015b). Spodnji del profila predstavlja topel in suh zgodnji glacial, zgornji del pa hladen in vlažen visoki glacial (pleniglacial). Znotraj obeh delov se v sedimentih odslikavajo še večje ali manjše tisočletne spremembe klime, opredeljene s temperaturo in vlago (I. Turk *et al.* 2001; 2005; J. Turk, M. Turk 2010; Skaberne *et al.* 2014; 2015a; 2015b; Blackwell *et al.* 2009). Izsledki I. Turka o vlagi v obdobjih zgodnjega glaciala in visokega glaciala so nasprotni od splošno sprejetega mnenja o vlažnih toplih in suhih mrzlih obdobjih zgodnjega in visokega glaciala. To mnenje temelji predvsem na puhličnih sedimentih, ki so značilni za glacialno klimo. Vendar so za nastanek in rast ledenikov pogoj izdatne snežne padavine, povezane z bolj vlažno klimo in nižjimi poletnimi temperaturami.

Gradniki sinteze I. Turka

1 – Delež reliefno korodiranih klastov (*sl. 6a*), ki jih je povezal s kondenzno in talno vlago, je v obeh kronostratigrafsko razmejenih delih profila statistično značilno različen (p < 0,05) (Skaberne *et al.* 2014, sl. 17.2.2). Razlike v amplitudi in deležu reliefno korodiranih klastov med zgornjim (OIS 3) in spodnjim delom profila (OIS 5) so se zato lahko smiselno razložile s stabilno in globalno suho klimo v spodnjem delu profila in nestabilno globalno vlažno klimo v zgornjem delu. Oziroma z manjšimi in večjimi temperaturnimi razlikami med zrakom zunaj jame in v njej za stropne korozijske tvorbe in s povečanimi padavinami za talne (I. Turk *et al.* 2001; 2005). Stropnih korozijskih tvorb je bilo več v topli klimi. Vendar so bile zaradi večjega vhoda temperaturne razlike med zrakom zunaj jame in v njej manjše. Talnih pa je bilo več v hladni klimi pri enaki količini padavin. Zaradi krioklastične sedimentacije, ki je v obdobju hladne klime zmanjšala velikost vhoda, so se večale temperaturne razlike, kar je imelo za posledico tudi večjo stropno korozijo. Ker sta kondenz in talna voda odvisna od temperature, je pomembno, da se je porazdelitev deležev reliefno korodiranih klastov v splošnem ujemala s porazdelitvijo deležev posedimentnih fragmentov (Skaberne *et al.* 2014, sl. 17.2.2).

2 – Delež kongelifraktov z ostrimi robovi (*sl. 6a*) in svežimi (nepreperelimi) prelomnimi ploskvami se v obeh kronostratigrafsko razmejenih delih profila statistično značilno razlikuje (p < 0,05) (Skaberne *et al.* 2015a, sl. 7). Zastopanost deležev kongelifraktov je bila povezana s številom dni v letu, ko zmrzuje, oziroma s povprečno zimsko temperaturo v relativno kratkem časovnem obdobju pred zasutjem z novimi sedimenti (I. Turk *et al.* 2001). Razlike v amplitudi in deležu posedimentnih fragmentov med zgornjim in spodnjim delom profila so bile lahko smiselno razložene s stabilno, globalno toplejšo klimo v spodnjem delu profila (OIS 5) in nestabilno, globalno hladnejšo v zgornjem (OIS 3) oziroma z višjimi in nižjimi temperaturami. Velikost vhoda je vplivala na kongelifrakcijo obratno, kot na korozijo jamskega svoda. V spodnjem delu profila jo je zaradi večjega vhoda pospeševala, v zgornjem pa zavirala.

Ker je bil v Divjih babah I zabeležen dotok podzemne vode tudi v daljših zimskih obdobjih suše in nizkih temperatur, je bilo vode v dneh, ko zmrzuje, tudi v pogojih glacialne klime vsaj za silo dovolj, če ne v izobilju. Izmerjeni minimum v osrednjem delu jame na koncu enomesečnega za slovenske razmere skrajno mrzlega in suhega obdobja pozimi leta 1999/2000 je bil 1,05 l/m^2 v 24 urah. Na koncu še bolj suhega in mrzlega dvomesečnega obdobja s podpovprečnimi temperaturami in predvsem podpovprečnimi padavinami pozimi leta 2001/2002 pa je bil izmerjen absolutni minimum 0,68 litra/m^2 v 24 urah. V obeh primerih so nastale na tleh, ne pa tudi na stropu, ledene sveče

[7] Datacije je po letu 1999, ko je stekel neformalni projekt sedimentoloških analiz, ljubeznivo priskrbela Bonnie A. B. Blackwell (MA lab: Dept. Of Chemistry, Williams College, RFK Research Instiute, Williamstown, MA, USA) (Blackwell *et al.* 2007; 2009).

[8] OIS 4 je z najdbami slabo zastopan zaradi prekinjene sedimentacije. Popolnoma brez sedimentov (in posledično najdb) je OIS 2 in mlajši del OIS 3.

v oddaljenosti do 19 m od vhoda. Če je led samo enkrat na zimo vklenil že napokane bolj ali manj korozijsko zaobljene kose grušča v tleh, so se ti v desetih do dvajsetih zimah spremenili v kongelifrakte. Potem pa se je začel proces ponovnega zaobljevanja svežih robov na novo nastalih klastov na/v tleh pri temperaturah nad 0 °C. Zaobljevanje in kongelifrakcija sta se izmenjavala še naprej, vse do zasutja z novimi sedimenti, ko sta se oba procesa močno upočasnila ali celo ustavila. Za približek negativni temperaturi so služili izključno kongelifrakti s svežimi odlomi, obkroženi z ostrimi robovi, ki so nastali tik pred zasutjem z novimi sedimenti.

3 – Delež strukturnih agregatov v peščeni frakciji, poenostavljeno izražen z volumsko maso, je bil prek talne vlage povezan s padavinami. Delež je v obeh kronostratigrafsko razmejenih delih profila statistično značilno različen ($p > 0,05$) (Skaberne *et al.* 2015a, sl. 7). Razlika v volumski masi peščene frakcije med zgornjim in spodnjim delom profila je bila smiselno razložena z globalno bolj suho in toplo klimo v spodnjem (OIS 5) in globalno bolj vlažno in mrzlo klimo v zgornjem delu profila (OIS 3) (I. Turk *et al.* 2005). Ker je za nastanek strukturnih agregatov in za delovanje korozije v tleh nujno potrebna voda v obliki talne vlage, je pomembno, da se je porazdelitev strukturnih agregatov ujemala s porazdelitvijo korodiranih klastov, pa tudi korodiranih kosti, v sedimentih stratigrafskega niza. Grobo ujemanje porazdelitve strukturnih agregatov s kongelifrakti pa je lahko posledica nastajanja in konsolidacije agregatov zaradi segregacije ledu v tleh (Williams, Smith 1989, 42, 46). Tako stisnjeni agregati so odpornejši od nekonsolidiranih iz toplejših klimatskih obdobij in so se zato lahko ohranili v večjem številu.

V večjih strukturnih agregatih so bile prvič odkrite fosilizirane dlake in odtisi dlak jamskega medveda (*sl. 7*) (I. Turk *et al.* 1995). Odkritje je bilo pozneje neodvisno potrjeno s podobnimi najdbami pleistocenske starosti v jami Ozark v ZDA (Schubert, Kaufmann 2003). Železnodobna najdba iz Čadrga nad Tolminom (Kavkler 2016) z enakimi mineraliziranimi strukturami volnene tkanine, kot so fosilizirane dlake (*sl. 7*), je pokazala, da za fosilizacijo dlak zadostuje že poltretje tisočletje. Zato lahko sklepamo, da so fosilizirane dlake in z njimi povezani agregati nastali v Divjih babah I singenetsko, tj. skupaj z odlaganjem sedimentov, ne pa epigenetsko.

4 – Porazdelitev fosilnih ostankov jamskega medveda, ki je bila, ko gre za smrtnost v jami-brlogu, lahko odvisna od trajanja in značaja zime (vlažna, suha), je v zgornjem delu profila bistveno drugačna kot v spodnjem (*sl. 6b*). Ostankov je precej več v zgornjem delu z znaki hladne in vlažne klime. Ker je bila v tem obdobju (OIS 3) pokrajina poraščena z mešanim gozdom, kot kažejo analize oglja in peloda (Šercelj, Culiberg 1991; Culiberg 2007; 2011), so bile življenjske razmere za populacijo jamskega medveda v toplem delu leta ugodne. Drugače je lahko bilo v mrzlem delu leta, ki so ga zlasti medvedke z mladiči in že samostojni mladiči prebili v jami. V neugodnih zimskih razmerah, kot je povečana vlaga, je lahko prihajalo tudi do tekmovanja za jamske brloge med samci na eni strani ter samicami in mladiči na drugi strani. Smrtnost je bila največja med mladiči do enega leta starosti, ki predstavljajo 70 % in več fosilne populacije v zgornjem delu profila, raziskanega v letih 1989–1999 (Debeljak 2002).

5 – Podoben vzorec kot pri jamskem medvedu se je ponovil tudi pri porazdelitvi paleolitskih artefaktov (*sl. 6b*). Ti predstavljajo intenzivnost obiska lokalne populacije neandertalcev v jami in njene uporabe kot zavetišča pred vremenskimi neprilikami. Zato se obiskanost jame dobro ujema s približki temperature in vlage (*sl. 6*). Arheološke ostaline, kot so artefakti in ognjišča/kurišča, v grobem odslikavajo številčno stanje lokalne populacije neandertalcev. V zaostreni glacialni klimi so bili ti prisiljeni umakniti se iz srednje Evrope proti Sredozemlju. To je imelo za posledico večjo gostoto poseljenosti in tudi večji obisk jam nasploh na tem območju. Znano je, da v topli interglacialni klimi prevladujejo najdbe na prostem, v mrzli glacialni klimi pa najdbe v jamah. Ta vzorec je zdaj jasno izražen in potrjen tudi v Divjih babah I.

6 – Analiza bogate stratificirane mikrofavne je pokazala, da je bilo podnebje v času odlaganja plasti zgornjega dela profila (OIS 3) vlažnejše kot v času nastanka plasti spodnjega dela profila (OIS 5) (Toškan, Kryštufek 2007; Toškan, Dirjec 2011). Ker gre za nezvezne podatke, izsledkov ni bilo mogoče podrobno primerjati s sedimentološkimi rezultati.

7 – Izsledke na podlagi ostankov mikrofavne so dopolnile paleobotanične analize stratificiranega peloda in več tisoč primerkov oglja. Te so potrdile, da je bilo podnebje v času odlaganja določenih plasti zgornjega dela profila (OIS 3) hladnejše kot v času nastanka plasti spodnjega dela (OIS 5) (Šercelj, Culiberg 1991; Culiberg 2007, 2011). Tudi v tem primeru gre za nezvezne podatke, ki jih ne moremo podrobno primerjati s sedimentološkimi.

Prva naravoslovna sinteza multidisciplinarne analize posameznega paleolitskega najdišča v Sloveniji je dala skladne rezultate. Številni zbrani podatki iz različnih področij naravoslovja tvorijo enovit sistem. Divje babe I lahko zato upravičeno štejemo za eno redkih tipskih jamskih najdišč za slabo poznano stopnjo OIS 5 in OIS 3, ko gre za okolje in paleolitske najdbe. V drugi polovici OIS 3 je prišlo v Evropi do popolne zamenjave človeške populacije z novo vrsto in s tem povezanih sprememb, kar se ni zgodilo ne kdaj prej ne pozneje.

SKLEPI

Na podlagi sinteze izsledkov vseh analiz, izvedenih na sedimentih Divjih bab I in njihove vsebine, lahko naredimo nekaj zanesljivih sklepov:

1 – Analizirani profil Divjih bab I je zaradi sedimentacijskih hiatov sicer nepopoln, vendar trenutno še vedno najbolj izpoveden za večji del mlajšepleistocenskega obdobja v Sloveniji (I. Turk 2006; I. Turk 2007c, sl. 4.1b). Vsekakor je izpovednejši od profila Črnega Kala in Betalovega spodmola, ki sta dolgo veljala za referenčna profila tega obdobja (M. Brodar 2009). Njegov potencial še zdaleč ni izčrpan, saj so sedimenti na pobočju pod jamo, katere vhod je bil nekoč pomaknjen daleč naprej v smeri pobočja, domnevno debeli 50 m in segajo globoko v pleistocen. Da so jame s tako debelimi sedimenti ter pripadajočimi arheološkimi in paleontološkimi najdbami velika redkost, ni treba posebej poudarjati. Poleg tega je nedotaknjen večji del notranjosti jame, medtem ko so sedimenti Črnega Kala v celoti odstranjeni, v Betalovem spodmolu pa jih je ohranjen le manjši del.

2 – Sedimenti, odkopani v Divjih babah I, so nastali pod vplivom posamičnih jamskih mikrookolij v mikrookolju jame kot zaključene celote. Jamska mikrookolja, vključno s sedimentnimi, oblikuje predvsem neenakomerno razporejena podzemna voda v vseh agregatnih stanjih, ki so odvisna od temperature. Slednje lahko posplošimo na vse vodoravne jame. Jamska mikrookolja se v Divjih babah I izražajo v mozaični sliki. To smo ugotovili na podlagi izčrpne prostorske analize različnih podatkov, zabeleženih med izkopavanji ali po njih na podlagi vzorcev sedimentnih frakcij. Mozaično okolje je torej pogojeno s prostorom in časom. Pri reševanju problemov jamskega sedimentnega okolja je zato nujno treba upoštevati ti dve dimenziji. Običajni pristopi, pri katerih se je upoštevala skoraj izključno dimenzija časa na določeni vertikali določenega profila v jami, bi bili ustrezni, če bi v tlorisu povsod vladali enaki pogoji, podani s temperaturo in vlago, oziroma če ne bi bilo mikrookolij. V nasprotnem primeru lahko pride do zavajajočih razlag, zlasti če jih posplošimo na najdišče kot celoto.

3 – Mikrookolje se oblikuje in spreminja zaradi vpliva različnih dejavnikov (globalnih klimatskih, mikroklimatskih idr.), ki so stalni ali pa se v času spreminjajo. Eden glavnih dejavnikov je nedvomno atmosferska klima, za katero vemo, da se nenehno spreminja na globalni ravni.

4 – Glavni dejavniki, ki so vplivali na mikrookolje v Divjih babah I, so matična kamnina, globalna klima, prisotnost jamskega medveda in prostornina jame. Nobeden od teh dejavnikov ni bil stalen v času in prostoru. Glavne lastnosti kamnine (razpokanost, poroznost) so se lahko spreminjale od ene kamninske plasti do druge. Globalna klima zanesljivo ni bila ves čas, tj. 90.000 let, enaka. Obisk populacij jamskega medveda in neandertalcev, ki so uporabljale Divje babe I za svoj brlog in zavetišče, je doživljal vrhunce in padce. Jamski vhod in konfiguracija jame sta se postopno spreminjala, prostornina jame pa se je vztrajno zmanjševala. To je neposredno vplivalo na jamsko mikroklimo. Pred glacialnim vrhuncem (OIS 2) je bil vhod visok samo še 1 m. Zaradi tega in severne lege so v času glacialnega vrhunca v jami postopno nastala globoko zamrznjena tla brez aktivnega sloja, ki se sicer odtaja čez poletje. Med nastajanjem permafrosta je prišlo do močne krioturbacije peščeno-meljastih sedimentov (*sl. 8*). Ker je bila posledično temperatura v jami vse leto negativna, jama ni bila več primerno zatočišče za ljudi in živali, tudi če nizkega vhoda nista zaprla večni sneg in led. Takšno stanje je trajalo več tisoč let, lahko tudi več deset tisočletij in povzročilo dolgotrajen zastoj v sedimentaciji ter popolno odsotnost vseh vrst najdb iz tega obdobja, zaradi skrajno neprijaznega bivalnega okolja.

5 – Diagenetsko-pedogenetski procesi, ki pridejo v poštev v jamskem okolju, so procesi transformacije kamninskih klastov, procesi transformacije organskih ostankov in procesi migracije. Pri slednjih so analitsko pomembne predvsem migracije urana (Skaberne *et al.* 2015b). V jamskih tleh ni bilo biološkega kroženja mineralnih snovi med živo in neživo naravo, značilnega za običajne pedogenetske procese. Procesi transformacije so potekali v jami drugače kot na prostem. V jami je nastajala preperina (regolit) s preperevanjem stropne in stenske

matične kamnine namesto s preperevanjem talne matične kamnine, ki je bila pred preperevanjem zaščitena z debelimi sloji detritičnega in drugega sedimenta, ker ni bilo izdatnejše erozije. Procesi transformacije matične kamnine in mineralov so večinoma sekundarne narave, ker so potekali skoraj izključno v regolitu v/na jamskih tleh.

Procesi transformacije organskih ostankov so pripeljali kvečjemu do nastanka parahumusnega horizonta, ne pa do humusnih horizontov. Organske ostanke so predstavljali predvsem množični ostanki živalskega izvora in nanosi od zunaj.

S procesi migracije so se premeščali proizvodi transformacije, tako da so se izpirali ali zbirali, pri čemer so tudi v jamskih sedimentih nastajali ustrezni talni (para)horizonti (kambični, eluvialni, iluvialni). Procesi migracije so bili v jami kompleksnejši kot na prostem, ker so se v jamske sedimente lahko spirali in zbirali tudi proizvodi transformacije iz tal in kamninskih skladov nad jamo. Z delovanjem vetra so v jamo drobni delci lahko prišli tudi z oddaljenih lokacij, kar je pokazala kemična analiza sedimentov (Skaberne *et al.* 2015b). Samo spiranje pa je bilo neenakomerno razporejeno v prostoru. Migracije znotraj profila je potrdila analiza vsebnosti urana, ki je iz zgornjega dela profila migriral v spodnjega (*ibid.*), in tudi znotraj posameznih plasti, zaradi zastojev v sedimentaciji.[9] To je v Divjih babah I vplivalo na datacije zgornjega in spodnjega dela profila na podlagi uranovih serij. Nekatere datacije spodnjega dela profila je toliko pomladilo, da je nastal vtis obrnjene (inverzne) stratigrafije (Ku 1997).

6 – V jamskih tleh so potekali tudi procesi, povezani z delovanjem posebnih dejavnikov. Takšna procesa sta bila npr. krioturbacija in oksidacija, povezana z zastajanjem vode v sedimentih. Krioturbacija je v jamah s peščeno-meljastimi sedimenti posebno močna med stranskima stenama, ki preprečujeta bočno raztezanje zamrznjenih sedimentov, ki se jim močno poveča volumen (*sl. 8*). Krioturbacija se pogosto zmotno povezuje z mešanjem sedimentov in najdb iz različnih plasti. Dejansko ne prihaja do mešanja, kar je potrjeno z razločnimi mejami med nagubanimi plastmi. Najdbe se pomešajo šele pri izkopavanjih, ker ni mogoče zanesljivo slediti zapletenim gubam po plasteh.

[9] V pripravi: I. Turk, J. Turk, M. Turk, Uran (U) in torij (Th) v sedimentih Divjih bab I, dinamika sedimentacije in ESR-kronologija. / Uranium (U) and thorium (Th) in Divje babe I cave sediments, sedimentation dynamics and ESR chronology.

Z izkopavanji v letih1989–1999 potencial najdišča še zdaleč ni bil izčrpan. Podane so bile zgolj smernice za morebitne nadaljnje raziskave tega vsestransko obetavnega najdišča in opredeljeni zanesljivo dosegljivi cilji. Z uporabo predstavljenih novih metod in pristopov na vseh v prihodnje izkopanih sedimentih bi bilo mogoče preveriti in izpopolniti dosedanje izsledke. Utrdili bi predlagane nove standarde, ki bi sčasoma prinesli nova spoznanja o paleolitiku v Sloveniji in o paleolitskem obdobju nasploh.

Glavni cilji ostajajo ugotoviti čim bolj podrobno in zanesljivo kronološko zaporedje klimatskih dogodkov, ugotoviti zastoje/prekinitve (hiate) v sedimentaciji in to, kako so hiati in klima vplivali na celotno podobo najdišča in na naše predstave o njem. Z nadaljevanjem izkopavanj bi se dalo izboljšati terensko metodo vzorčenja sedimentov in preveriti zanesljivost rezultatov izkopavanj v letih 1989–1999 in njihovih razlag, pridobljenih na podlagi novega modela za razlago jamskih klastičnih sedimentov.

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Illustrations: Fig. 1 (photo: Carmen Narobe). – *Fig. 8* (photo: Ivan Turk).
Slikovno gradivo: Sl. 1 (foto: Carmen Narobe). – *Sl. 8* (foto: Ivan Turk).

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