4 Significant Findings from Karst Sediments Research

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About 44% of Slovenia's surface consists of carbonate rocks. Karst geomorphology and over 13,000 known caves represent a significant proportion of its landscape. Various sediments present on the karst surface in the form of clastic or precipitated deposits can cover or fill smaller or extended areas and they can also accumulate in the caves.

In the last decades, study and interpretations of the karst sediments in Slovenia went through different stages in accordance with various theoretical models and were recently upgraded, especially by development of dating methods and by improved knowledge about karst processes.

Karst surface sediments are mechanical or chemical deposits (Fig. 4.1). Mechanical sediments on the karst surface represent all kinds of clastic material deposited by surface processes such as: fluvial (e.g. gravel, sand, silt, clay); conglomerate forming for instance alluvial fans, terraces; lacustrine; glacial, fluvioglacial and periglacial material (e.g., till forming moraines, diamicton and diamictite); and slope material (e.g. talus cones, rockfalls). Chemical deposits related to environment and climate factors (e.g. tufa, travertine), different carbonate crusts (e.g. calcrete, caliche) and calcite cements in bulk material are also represented. Various soils may be formed due to development from insoluble residues (e.g. in situ pedogenesis) or clastic allochthonous sediments (e.g. fluvial, eolian). Former cave sediments from unroofed caves, such as clastic sediments and speleothems can also be found on the surface.

Cave sediments represent all types of mechanical and chemical depositions in the caves (Fig. 4.2). According to their origin, they are divided into allochthonous and autochthonous sediments (Ford and Williams 2007). Allochthonous deposits were brought into caves from outside and represent all kinds of clastic sediments, such as gravel, sand, silt, clay (when cemented: conglomerate, sandstone, siltstone, claystone) or organic matter such as plant debris, coarse woody debris and bones. The most common allochthonous cave deposits are allogenic sediments which are brought into caves by sinking rivers. Most common are gravel, sand, silt and clay size materials originating from weathered bedrocks and sediments of the sinking river catchment area. Infiltration sediments which are brought into a cave through open fissures or cave entrances and are composed of various surface clastic sediments and soils (e.g. "terra rossa") are also allochthonous, as are eolian and glacial or periglacial materials which can be present at the entrance areas of the caves (e.g. loess, till, lacustrine sediments).

Autochthonous clastic sediments are all deposits formed in caves. These include breakdown and crumbled wall materials as well as chemical deposits like secondary cave minerals and speleothems.

Chemical deposits precipitate from a supersaturated solution in the form of various speleothems; they differ in shape, mineral composition, colour and age. The shape is determined by the mode of water inflow which can include dripping, flowing, seeping, pooled and capillary water. Speleothem mineral composition and colour depend on the composition of bedrock and vegetation above the cave. The most common minerals that form speleothems in limestone caves are calcite ($CaCO_3$), aragonite ($CaCO_3$) and gypsum ($CaSO_4 \times 2H_2O$). Speleothem colour depends on the mineral composition, metal impurities, soil and surface vegetation cover. Speleothems are of different ages, ranging from

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Fig. 4.1 Various sediments on karst surface: **a** lacustrine sediments in the dry bottom of Cerknica polje; **b** tufa barriers on Krka river; **c** red soil above subsoil karren in Dolenjska region may be infiltrated deep into the karst underground; **d** stalagmite surrounded by cave allogenic sediments in an unroofed cave above Škocjanske jame

the youngest which are still growing to those millions of years old.

Karst sediments, both on the surface and in caves, represent an important source of information on the evolution of tectonic and geomorphological units of different sizes. Fluvial sediments, for instance, indicate the abundance of precipitation and hydrological characteristics. The shapes of speleothems made of secondary calcite specify the way of water percolation. The mineral composition, various inclusions and stable isotope geochemistry indicate physio-chemical conditions at the time of their precipitation. The dynamics of sedimentation is mainly controlled by climate and hydrology (e.g. glaciations, floods, precipitation), by changes in river catchment and by the evolution of cave networks.

Protected in caves, sediments are generally well preserved and reveal exceptionally good, multi-proxy records of surface environmental conditions at the time of their deposition; they can cover time spans from several million years up to the present (Bosák 2002). Cave sediments represent traps of past geologic and environmental records in spite of the fact that they mostly represent the latest episodes of deposition. Many times sediments from diverse karst environments are the only sediments representing terrestrial phases of landscape evolution and they indirectly indicate the age of speleogenesis and surface evolution.

The question concerning the time span of karst evolution in Slovenia, the age of karst surfaces and speleogenesis and, consequently, the rates of processes, have been an important issue in most of the previous karst studies and syntheses. The majority of dating of karst sediments has been recently carried out in SW Slovenia (i.e. in the NW part of the Dinaric Karst) which is known as the Kras. Eocene flysch rocks are the last marine deposits preserved in the geologic record. Oligocene to Quaternary rocks represents a terrestrial period where surface denudation and erosion processes prevailed. Karst sediments preserved on the surface are therefore rare; but caves have functioned as traps of clastic, chemical and organic sediments derived from local as well as more distant environments during the life of a cave. The position and composition of cave fill, including fossil remains, tends to be preserved for great time spans and can offer useful information on the evolution of surface geology, morphology and also a cave itself.

Fig. 4.2 Characteristic cave sediments: **a** various speleothems in Tartarus (Postojnska jama); **b** aragonite crystals from Bevkova jama; **c** river sediments (pebbles) from Škocjanske jame; **d** bones and teeth of *Ursus spelaeus* from Križna jama

4.1 Karst Sediments Research in Slovenia

The territory of Slovenia, with its numerous karst regions from the Alps to the Mediterranean, long history of karst evolution and relatively good knowledge of karst sediments, represents an ideal place for studies and dating of cave sediments with different research methods. The results obtained have been used for interpretation of sediment origins, deposition time as for time of caves and karst evolution of selected Slovenian regions.

The first estimates of the age of the karst in Slovenia were made by geologists and karst geomorphologists. They utilized geologic data such as the age of the last marine sedimentation and the tectonic evolution of the Dinaric Mountains and the Alps (e.g. Grund 1914), sediments on the karst surface and some distinct forms of the relief. Roglić (1957), Melik (1961) and Radinja (1972, 1986) defined a pre-karst phase when rivers were flowing across the karst surface and deposited fluvial sediments, and the karstification phase when rivers began to sink at the edges of the karst.

The early systematic studies of cave sediments were carried out during archaeological excavations of sediments in the entrance parts of some caves (Brodar 1952, 1966). Gospodarič (1972, 1976, 1981, 1988) started with more extensive and detailed studies of cave sediments; but he suspected that the cave sediments were not much older than 350 Ka. It was suspected that the karst started to evolve during Pliocene times (e.g. Brodar 1966; Gospodarič 1988; Habič 1992). A better understanding of cave sediments and their age and the chronological sequence of speleological events was achieved by more concentrated dating by the Th/U method (Zupan 1991; Zupan Hajna 1996; Mihevc and Lauritzen 1997; Mihevc 2001a). The application and interpretation of paleomagnetic analysis and magnetostratigraphy of the cave sediments, both clastic and chemogenic, began in 1997, suggested substantial changes in the lower limiting ages of cave fill deposition (Bosák et al. 1998, 1999, 2000a, b, 2004; Šebela and Sasowsky 1999, 2000; Audra 2000; Mihevc et al. 2002; Zupan Hajna et al. 2008a, b, 2010; Knez et al. 2016). The study of cave deposits in Alpine caves and in unroofed caves of the Kras provided entirely new insights into the age of cave and karst sediments and introduced new ideas concerning the development of karst.

Presented here are some examples of recent findings during karst sediment research and their interpretations which sometimes have come into conflict with existing karst concepts.

4.1.1 Surface Clastic Sediments and Red Soil

One of the characteristics of the Slovenian karst is red soil—terra rossa-type, although the colour of clastic sediments includes all varieties from yellow to red. In general, not a lot of soil is on the karst surface with the exception of accumulations in dolines or depressions. On the other hand, there are thick sediment/soil covers present in some areas of Southern Slovenia which is the most northern part of the Dinaric Karst. Terra rossa-type red soils are composed of reddish clayey to silty material covering karst landscapes in hot/warm climates (Fedoroff and Courty 2014), such as those in the Mediterranean part of Dinaric Karst. The origin of red soil in Slovenia was at first attributed to insoluble remains of limestone, especially those containing cherts (Gregorič 1967; Culiberg et al. 1997; Rejšek et al. 2012). In the Kras Plateau in SW Slovenia, red soil is called “jerovica” (Fig. 4.3a); jerovica is a characteristic soil developed on Cretaceous limestone with chert, such as the Komen limestone of the Sežana Formation and the Tomaj limestone of the Lipica Formation (Jurkovšek et al. 1996). Different opinions were related to the nature of its parent material and origin. Red soil in Slovenia was studied from different aspects, including its composition and origin by Hrovat (1953), Gregorič (1967, 1969) and its accumulation in dolines by Gams (1974, 2004). Later, a possible eolian origin as loess sedimentation during Pleistocene was considered (Šušteršič et al. 2009). Red soils origin and their relationship to underlying carbonates and existing karst relief have been, and still are, the subject of discussion.

Recent research on red soils from different parts of Slovenian karst found that they originate in weathered remains of limestones rich in chert, in weathered remains of flysch rocks, in local weathered noncarbonate rocks (Zupan Hajna et al. 2019), or even from the alluvium of unroofed caves and they are almost negligible in eolian sediments (Zupan Hajna 2000, 2005; Zupan Hajna et al. 2017). Red soils on the karst surface may differ in respect of mineral composition and thus also by their origin and time of development (Zupan Hajna 2000, 2005; Zupan Hajna et al. 2017). For instance, most of the red clays and soils around Divača village (south part of Kras Plateau) have their origin in weathered flysch rocks (Zupan Hajna 1992, 1998a, b, 2000, 2002; Fig. 4.5). Minerals such as microcline and plagioclase found in those red soils prove that they cannot be insoluble remains of limestone. In sediments from caves close to the surface and from unroofed caves sediments, no minerals indicating loess origin were found (e.g. amphiboles which are typical of loess sediments in Istria; Durn 2003), thus eolian origins can be excluded; even some of them from unroofed caves there were dated to 5–4 Ma (Zupan Hajna et al. 2008a, 2010). Some of the red coloured sediments and red soil passed through weathering in a period of tropical climate what is indicated by presence of bauxite minerals; examples are red clasts from cave sediments in Trhlovca Cave (Fig. 4.5).

Some red clays on the surface (e.g. on the Kras Plateau, Dolenjska region) in the dolines and in the caves are not soils; they are actually clastic sediments which have had contact with percolating water from the surface and changed their colour during diagenesis in the oxidation zone from yellow to red due to the oxidation of goethite to hematite in clay pigment coatings (rubification) (Mihevc and Zupan Hajna 1996; Zupan Hajna 1998a, 2000; Knez et al. 2016; Zupan Hajna et al. 2017, 2019; Fig. 4.5). The study of the

Fig. 4.3 **a** Red soil composed of unsoluble remains of limestones with chert, Komen (Kras); **b** unroofed cave with quartz pebbles and sand on Slavenski ravnik

mineralogical composition of yellow and red sediments from dolines around Divača village also showed that yellow colour is usually an indicator of sediments of Eocene flysch origin which were weathered in different degrees and after deposition in caves or karst depressions were protected against atmospheric influences (e.g. oxidation). If those yellow sediments were in contact with percolating meteoric water, they may have changed colour to red. The same process may occur in the caves.

Occurrences of quartz pebbles and sands (Fig. 4.3b) on the karst surface were at first all attributed to fluvial transport of weathered remains of flysch rocks over karst in the so-called "pre-karst" phase (Melik 1961; Radinja 1972; Habič 1992). With further research and the discovery and geomorphological explanation of denuded caves, many of those sediments have since been determined to be surface exposures of cave sediments (Mihevc 1996; Mihevc and Zupan Hajna 1996; Zupan Hajna 1998a; Mihevc 2001a, 2007; Knez et al. 2016).

4.1.2 Cave Clastic Sediments

Clastic sediments in caves differ in size, shape, colour, texture, mineral composition and therefore they have various proveniences. Mechanical cave sediments are categorized in terms of their autochthonous or allochthonous origins. Autochthonous mechanical cave sediments are due to weathering processes on cave ceilings and walls, allochthonous sediments are clay, silt, sand, and gravel originating from outside of the caves. In these sediments, various minerals are accumulated. From original rock to mechanical sediment in the cave, the minerals may be lost or changed. The changes of mineral composition occur either due to chemical weathering of the original rock, or during the transport or at later diagenesis of mechanical sediments in the cave. How many minerals and which of them are lost during the transport, is especially dependent on duration of transport. With respect to chemical and mechanical weathering, only the most resistant minerals remain as heavy minerals and quartz. The most important factors for the determination of the origin of cave mechanical sediments are the invariable mineral association and also the presence of some typical residual minerals. Less resistant minerals are replaced by clay minerals, chlorites, iron hydroxides, etc.

4.1.2.1 Cave Sediment Facies

From a sedimentological point of view, the cave environment can be divided into an entrance facies and an interior facies. The farther away cave sediments are from cave entrances, the less they are subjected to environmental changes on the surface after deposition. During several years of research, we found that sediments in a cave could remain completely unchanged for millions of years. In the vicinity of cave entrances, deposited sediments are influenced mainly by diurnal and seasonal changes in temperature and water intake (precipitation, floods), which can greatly alter the chemical and mechanical properties of existing sediments.

The entrance facies includes fine-grained sediments transported from the vicinity of the cave by wind and water, coarser clasts transported into the cave by slope processes, or autochthonous sediments produced by frost action or other mechanical and chemical processes on the cave walls. The cave entrance contains pollen as well as datable archaeological and paleontological remains that are protected from surface erosion, weathering and biochemical alteration (Ford and Williams 2007). Entrance zones of caves are often exposed to seasonal freezing that causes spalling of cave walls and formation of fragments of various sizes which accumulate on the cave floor. Resulting sediments are often subject to creeping due to cryoclastic processes.

Cryoturbated cave sediments in Slovenia were usually attributed to Pleistocene climates (e.g. Brodar and Brodar 1983; Turk et al. 2001), but a recent patterned ground formation was first described in the cave Skednena jama by Gams (1963). Accumulations due to frost action are now known and described from many cave entrances in Slovenia, especially from higher elevations but also from lower elevations. Examples include caves Potočka zijalka and Snežna jama on Raduha Mountain in the Savinja Alps (Mihevc 2001b), Divje babe (Turk et al. 2001) and Skednena jama in the central part of Slovenia, and Barka rock shelter on the slopes of Snežnik Mountain (Zupan Hajna 2007). In the Barka rock shelter, rock fragments produced by gelifraction are accumulated on the cave floor; in the wintertime freezing causes development of sorted (polygons; Fig. 4.4a, b) and nonsorted patterned ground (Zupan Hajna 2007). Elongated polygons (Fig. 4.4b) are formed where the frost rubble covers the cave floor which is inclined and material may move down the slope due to thawing. In the caves Skednena jama and Ulica pečina, movement of individual marked rocks was measured against the ceiling (Mihevc 2009) and later were compared with Lidar scanograms of the floor. Seasonal vertical displacements due to freezing and thawing were found to be 5–15 cm, and in extreme cases up to 30 cm. Observations show that there are several caves where the cave morphology enhances the periglacial process and sediment creeping and patterned ground formation (Fig. 4.4; Zupan Hajna 2007; Obu et al. 2018), and that freezing causes creeping of the whole sediment body. This can be observed in Bestažovca and Potočka zijalka caves; in both caves these processes interfere with formation of the Palaeolithic and Neolithic archaeological strata (Mihevc 2009) and are still active today.

The interior facies develops in those parts of the cave that are more remote from the surface (Fig. 4.1a, b, and d). The

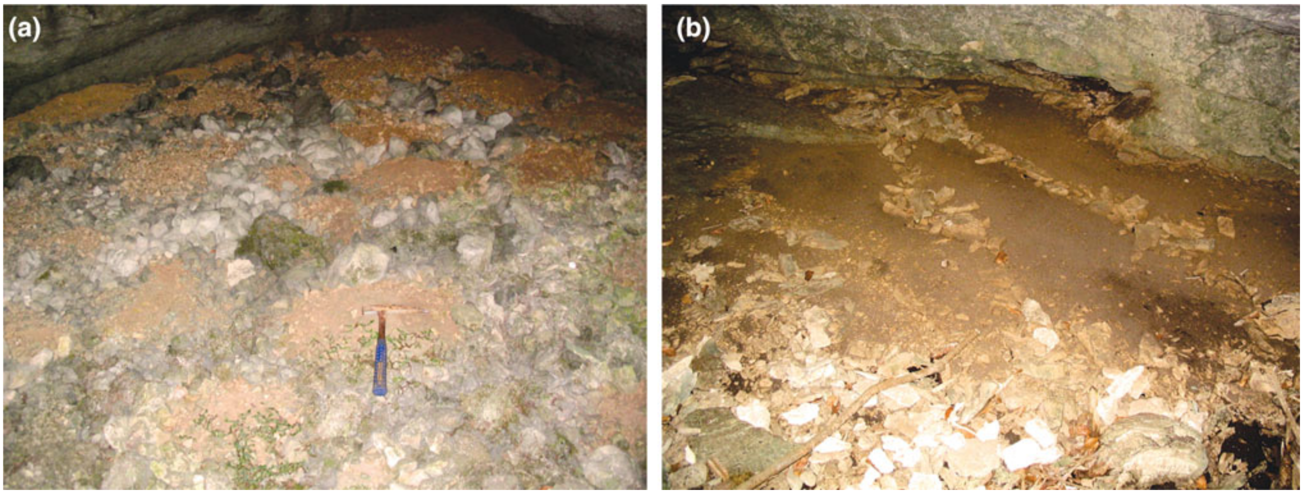

Fig. 4.4 Polygons of seasonal frost; frost rubble covers the floor and patterned ground are developed (cave shelter in Barka Cave, Mt. Snežnik, SW Slovenia)

composition, mineralogy and lithology of cave clastic sediments depend on the material available in the source areas, but the deposition in the cave depends on the internal dynamics of the conduit system (White 2007). Bosch and White (2004) described facies according to particle size and the degree of sorting as channel, thalweg, slackwater, diamicton, backswamp facies. The channel facies with the widest range of particle size and particle sorting occurs in the most common stream deposits in caves and thalweg facies are the coarse cobbles that form the beds of many active cave streams. Slackwater facies are the thin layers of fine-grained silt and clay forming the final top of clastic deposits. Diamicton facies is the result of debris flows and backswamp facies is locally derived (residual insoluble or infiltrated material).

Although we worked with all the types of facies listed during the exploration of sediments in Slovenian caves, slackwater and channel facies were the most represented and dated in our studied cases (e.g. Zupan Hajna et al. 2008a, 2010). Due to the dynamic environment of cave interiors and periodicity of events, sedimentary sequences often represent a series of depositional and erosional events (sedimentary cycles); they are separated by unconformities in which substantial time spans can be hidden (e.g. Bosák et al. 2000b, 2003; Bosák 2002).

4.1.2.2 Infiltrated Sediments

By weathering and erosional processes on the surface and percolating water through open fissures and vadose shafts, a lot of different materials (like "terra rossa" or weathered residues of various rocks) can be infiltrated into the karst (Ford and Williams 2007). Mineral composition in such cases depends on the composition of rocks from where the weathering remains originated. Open fissures and shafts filled with sediments were always of interest to Slovenian researchers (e.g. Šušteršič 1978; Kogovšek and Zupan 1992); their composition and origin were interpreted differently. For a long time, a prevailing opinion was that in all fissures (and also along faults) in karst, red or yellow clays and silts are either "terra rossa" infiltrated into the karst from the surface (Fig. 4.1c), infiltrated eolian deposits, or remains of flood sediments in underground open fissures or cavities. All of the sediment types listed above contain quartz as a dominant mineral among various clay minerals (e.g. Figure 4.5; DHrs). Research of mineral composition of sediments in fissures and fault zones (e.g. Figs. 4.7 and 4.8) has since proven that those are not allochthonous sediments, but tectonic clays formed in situ (Zupan 1989; Zupan Hajna 1997), described in the continuation of this chapter.

4.1.2.3 Allogenic Sediments

Major sources of sediments in caves are allogenic sinking streams, bringing sediments into the underground from eroded noncarbonated rocks (Ford and Williams 2007; White 2007). Allogenic cave sediments are particularly important for understanding the environment of their formation before transport and storage in the cave. The same rocks on the surface weather in different ways under different environmental conditions (T, amount of precipitation, pH, Eh) (e.g. Zupan Hajna 1992). Different clay minerals are produced and the colour of the product depends on the type of iron minerals and pigment (e.g. hematite, goethite). Allogenic sediments with almost the same mineral composition but differences in colour are found in the Slovenian river caves Postojnska jama (Figs. 4.5 and 4.8) and Škocjanske jame (Fig. 4.8).

Most of the clastic cave sediments in SW Slovenian karst originate from weathered remains of Eocene flysch rocks.

Fig. 4.5 Fluvial sediments from Postojnska jama: **a** yellow and red clay, silt and sand from a relict passage consist of quartz and clay minerals with feldspars in traces; **b** yellow allogenic sediment laminas filled in fissure in artificial tunnel. Allogenic sediments in both cases originate from weathered flysch rocks; they differ in colour and age, but are of almost the same mineralogical composition

Allogenic rivers flowing into the caves, such as the Pivka River (which sinks into Postojnska jama) and the Reka River (which sinks into Škocjanske jame), bring the sediments from weathered flysch rocks of the Pivka Basin and Brkini Hills. For example, among fluvial sediments of active, relict and unroofed caves of the active and relict allogenic Reka River, the mineral composition of all studied sediments is very similar (Fig. 4.8, samples SCfl–DFys). In almost all samples relatively equal mineral composition prevailed, indicating the main source was from flysch rocks which were differentially weathered. The samples contained quartz, clay minerals, microcline, plagioclase and heavy minerals (e.g. goethite, tourmaline, rutile), which are typical of Eocene flysch rocks in the Reka River catchment area. The process of flysch transport into the caves continued for a few million years, but the intensity varied over time (Zupan Hajna et al. 2008a, b, 2010, 2017). Large accumulations of allogenic cave sediments having their origin in flysch rocks show that in some period flysch rocks weathered intensively and the sediments were transported to the existing caves. The erosion of flysch rocks was probably accelerated in the colder climate and due to increased rainfall or/and due to tectonic uplifting of the landscape.

Through studies of the mineral composition of alluvial cave sediments, it was also noticed that in many cases a high amount of carbonate clasts was significant (Zupan Hajna 1992, 1998b, 2002). Examples are sediments in the bottom of deep shafts in Alpine caves of the Kanin Plateau (Črnelsko brezno; Fig. 4.8, sample CHs). It was recognized that the origin of the carbonate clasts (clay, silt and sand size) is the selective and incomplete solution of limestones and dolomites of the caves walls where weathered carbonate rocks were eroded by flowing water (Zupan Hajna 2002). The solution is very similar to the subsoil corrosion on the karst surface, except that the carbonate particles are not mechanically eroded and transported. From the presence of undissolved carbonate particles, it can be concluded that the removal of the limestone from its primary place is not always conditioned merely by dissolution, but also by mechanical erosion. The process of the fine-grained carbonate particles formation is explained below.

4.1.2.4 Accumulations of Fine Carbonate Clasts

The presence of a soluble residue of incomplete limestone solution is in disagreement with classical theories of karst origin, which predicts that limestone, when affected by an aggressive solution, will dissolve completely. According to these theories, only insoluble residues will remain after carbonate rock has been dissolved. The way in which the carbonate rock is carried away from its primary site depends mostly on its chemical and mineral composition and on the chemical and hydro-mechanical characteristics of the water; water in a karst environment is a natural solvent as well as the erosive and alluvial agent. Rock may be carried away from its primary site in the form of solution or mechanical particles (by means of chemical or mechanical erosion, or in some cases by a combination of both).

The literature mentions occurrences of carbonate particles in the suspended load of subterranean streams (Newson 1972) and in trickling percolation water (e.g. Kogovšek and Habič 1981; Kogovšek and Zupan 1992). The suspended particles were attributed to carbonate rock weathering on the surface and the transport of the weathered rock particles through open fissures into the cave. It was also found that clastic sediments could be enriched on calcite or dolomite (e.g. Zupan 1989; Zupan Hajna 1997, 1998b, 2002); those are actually small particles of limestone or dolostone derived from weathered walls of the underground water passages. The content of carbonate minerals in allochthonous material has been presumed to be low but the X-ray analyses and analyses in thin sections have shown that the carbonate content in a lot of samples could increase to high values, from less than 5% to more than 80%. The proportion of carbonates in cave sediments may increase with the depth of the cave, and dolomite clasts may occur where a cave is formed in dolomite beds. Weathered cave walls present the source for the carbonate grains found in cave sediments due to incomplete dissolution of carbonate rock (Zupan Hajna 2002).

The weathered part of limestone is almost identical to the parent rock in its mineral and chemical composition, yet it is much more porous. In limestone different degrees of weathering are seen. Weathered zones pass from wholly weathered limestone to unweathered limestone one through few steps of weathering. Fresh limestone first becomes slightly discoloured and, after weathering progresses, becomes totally discoloured (white) and porous (Fig. 4.6a, b). Ions such as Mg^{2+} and Sr^{2+} are leached from the calcite structure, so the calcite is purified during the weathering. In this case, it is not going on to the dissolution of the limestone and then precipitation of cleaner calcite crystals. Weathered limestone becomes more and more porous and develops a “sponge-like” texture. When weathered limestone is wet, the water is in its pores. If there is no source of moisture, the weathered wall of the cave becomes dry.

Mechanical erosion takes place where weathered carbonate rock is in contact with flowing or dripping water (Fig. 4.6c). After weathered carbonate rocks are eroded, transportation and accumulation of carbonate particles as cave clastic sediments begin. Water washes the exposed particles from the wall, carries them away and finally accumulates them in the cave sediment in particle sizes ranging from clay, silt or fine sand (Fig. 4.6d). Carbonate particles are deposited either as independent sediments or they may mix with the allochthonous deposits. The result is the production of carbonate fines (silt and clay size particles) which accumulate as autochthonous clastic cave sediments (Zupan Hajna 1998a, 2002).

4.1.2.5 Tectonic Clays

Very high contents of carbonate minerals can be detected in tectonic clays if they were formed in fault zones situated in carbonate rocks. This clay size material is formed by tectonic compression of carbonate rocks. Tectonic clay consists almost entirely of calcite or dolomite. Their admixture depends on mineral composition of the parent rocks. Studies of materials from selected locations found that red clays/silts often were actually tectonic clays (mylonite, cataclastite) of the inner fault zones, with mineral compositions mostly of calcite in clay or silt size clasts (or dolomite; depending on the parent rock) where clay minerals, goethite and hematite, were present only in traces (Zupan 1989; Zupan Hajna 1997).

Tectonic clay develops in limestone due to cataclastic deformation such that under pressure the limestone recrystallizes and becomes more porous, especially close to the active fault plane. Directly at the fault a collapse of solid limestone structure appears. At first, solution occurs on the borders of the grains; later sparitic grains collapse and soft, unconsolidated clay occurs. Due to its origin, controlled by tectonic pressures, it is called tectonic clay. This term is not yet entirely clear, as occasionally in literature the expression “mylonite” is used for technical crushed rock.

Tectonic clays may be either yellow or red in colour. Goethite gives the clay a yellow colour, while a red colour is due to hematite present in the places where the water had been squeezed out of goethite and it was transformed into hematite. This clay impedes drainage within the fault zone. This is why no karstification was recorded in such fault zones.

4.1.2.6 Colour, Mineral Composition and Origin

The colour of sediments depends on their mineral composition, the presence of various pigments, and on physical and

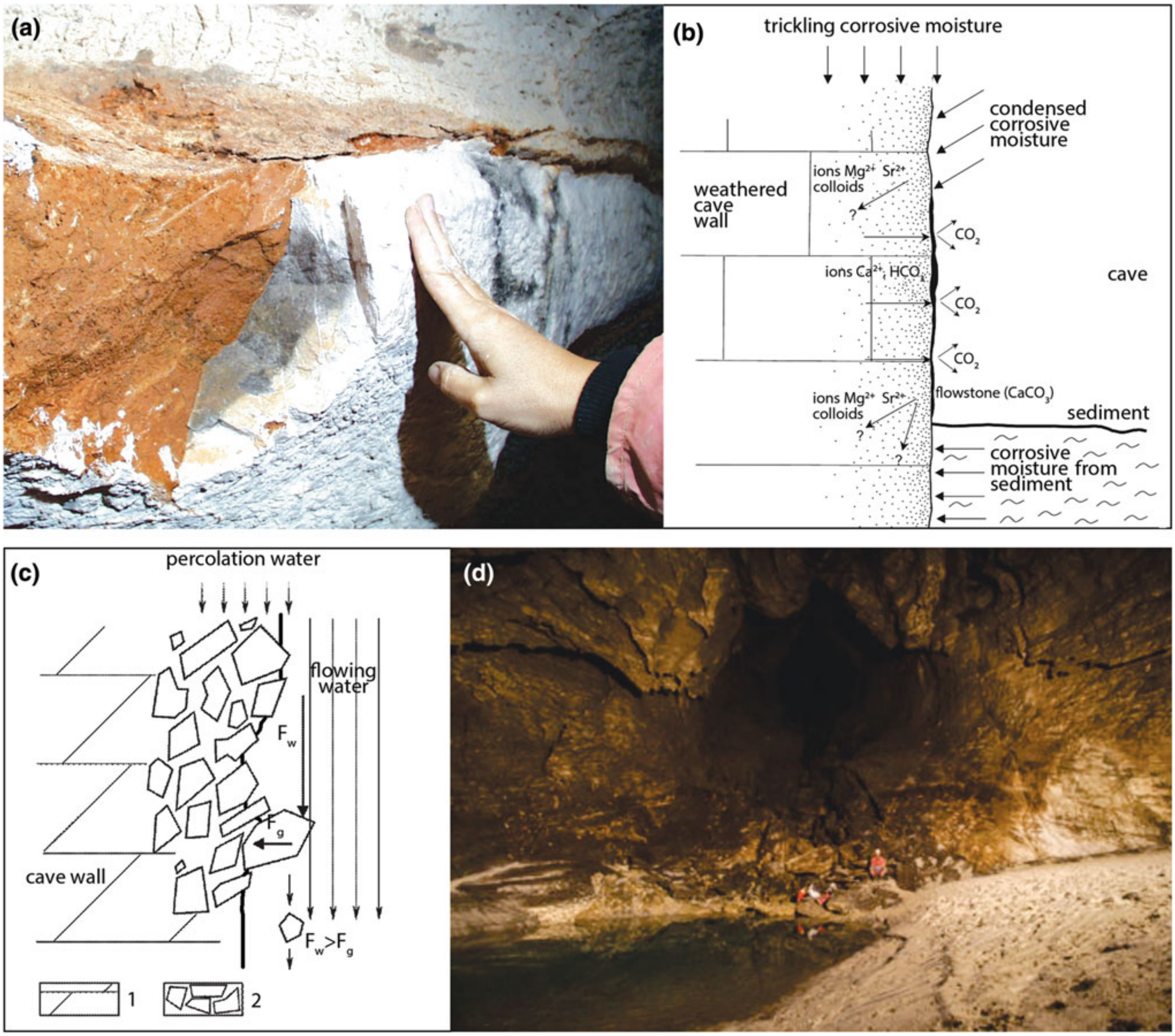

Fig. 4.6 **a** Weathered limestone on cave wall in Martinska jama; **b** process of weathering and incomplete solution in the cave; **c** mechanical erosion of exposed limestone or dolomite particles (1. fresh limestone, 2. weathered limestone); **d** accumulation of dolomite clasts (silt size) in Renejevo brezno shaft (photo M. Blatnik)

chemical conditions in the environment. But the same colour of sediments doesn't mean that the same mineral composition and knowledge of the mineral composition is not enough to declare the origin of the clastic sediments. This is because at the end of the weathering only the most resistant minerals, and also the distinctive secondary minerals for certain environments, are present, which reflect the diagenesis of mechanical sediments in the cave. The sediments' colour in Slovenia includes all varieties from grey, yellow to red and brown. Red colour is usually linked to mineral hematite and thus to oxidation processes, while yellow and grey colours are controlled by humid and reduction conditions within the environment and black by organic matter. The mineral composition of cave mechanical sediments does not reflect just the climatic conditions at the time of their deposition in caves but also reflects the mineral composition of the original rocks. However, it is not always possible to determine the original rock due to long lasting weathering which may disintegrate a lot of the primary minerals. Heavy minerals are very important for determining origin because they are resistant to weathering and transport due to their mechanical and chemical properties. It is easiest to determine the origin of cave mechanical sediments when their composition entirely reflects the mineral association of the original rock. Quartz is a very resistant mineral in respect to weathering and transport and because of this quartz may be detritus of weathering of various rocks, and its presence does not tell much.

In Slovenian caves, different types of fine-grained clastic material may be distinguished based on their origin (Fig. 4.8). From the original rock to the mechanical sediment in the cave, minerals can be lost or changed. The cave allogenic deposits are clastic materials brought into the caves by sinking rivers, where their composition corresponds to the rock composition of the water flow watershed (catchment). In SW Slovenia, they most often are weathered remains of Eocene flysch rocks (Zupan Hajna 1992, 1998a, b, 2000, 2005; Zupan Hajna et al. 2017) which were brought into the caves through a few million years time span. The final products of flysch weathering are most often quartz, various clay minerals and iron minerals; both groups of minerals, however, reflect the environment of original rock weathering. Figure 4.8 (samples SCfl, DCys, Tys, Trc, DFys, PRyl, DHys, DOys, PCfl) shows examples of the mineralogical composition of allogenic cave sediment samples brought into the caves by allogenic rivers from flysch catchments. In all cases quartz prevails; besides clay minerals, microcline and plagioclase are also present, reflecting the original component of flysch rocks in SW Slovenia. Clay minerals differ due to the environmental conditions on the surface during weathering. However, at the end of cave existence, cave sediments may come into the contact with the surface due to the denudation of the karst surface; as a consequence, original cave sediments may be found on the karst surface in unroofed caves (samples PRyl, DHys) or even in the bottom of dolines (samples DOys, DOrs).

The infiltrated material is brought into the open fissures and caves from the surface (Fig. 4.1c). Mineral composition in that case depends on composition of rocks and soils from where the weathering remains originated; usually most red soils originated from flysch residue or other surface sediments were brought into the caves as infiltrated material (Fig. 4.8; samples Trc, DHrs and DOrs) and are usually red in colour due to oxidation of iron minerals in them.

Clastic material consisting of autochthonous carbonate particles of various sizes originating from cave walls are rare, but may be found in various caves where incomplete solution of cave walls is present (e.g. Figs. 4.6 and 4.8, sample CHs). Silt- and clay-sized clastic carbonate sediments may be found in caves as an addition to allogenic sediments or they may accumulate as autochthonous sediments (Fig. 4.6d) in the cave depositional environment.

Sometimes cave passages may cut the fault zone(s) full of cataclastic material, which is significant for the inner part of fault zones (Fig. 4.7). Clay or larger-sized material, formed by tectonic compression of carbonate rocks (limestone or dolomite), consists mainly of calcite or dolomite (Fig. 4.8, sample PCtc).

4.1.3 Important Palaeontological Findings

Palaeontological material in caves can belong to cave animals that lived in caves and their skeletons are preserved in the conservative environment. More common are remains of surface animals which used caves as dwellings, were washed in, or fell into vertical cave entrances.

Remains of fossil cave animals have been found in several caves in Slovenia. The most important is the discovery of the fossil aquatic cave animal *Marifugia cavatica* (Fig. 4.9) in two locations. The first is located in SW Slovenia where a sediment-filled cave was exposed by the Črnotiče Quarry operations (Mihevc 2000). In the cave filled by allogenic sediments, the calcareous tubes of Marifugia were found both in fine fluvial sediment and also in original positions attached to the cave wall. Sediments were dated by small mammal faunal remains present in sediments and by palaeomagnetic dating method to about 1.8–2.2 Ma (Mihevc et al. 2002; Horáček et al. 2007; Bosák et al. 2004). The animal lived in a cave river that later filled the cave with sediments. At present, *Marifugia cavatica* lives in spring caves which are about 400 m below and 3 km away from the quarry. The second locality with *Marifugia cavatica* is the relict cave Velika Pasica in the Central part of Slovenia, which is located about 300 m above the present underground water level. Broken-off tubes were found in the coarse fluvial sediment that is preserved in some parts of the cave. The sediment was dated by fossil mammal remains to about 2 Ma (Mihevc et al. 2017). In both cases, remnants of Marifugia give important information about former elevation of karst water levels and younger relief evolution. Fossil remnants of invertebrates, some of them most likely cave animals, were found in clay layers in the caves Trhlovca and Račiška pečina (Moldovan et al. 2011). Their age was defined by position in the sediment profile position by palaeomagnetic dating to Pre-Qaternary (Zupan Hajna et al. 2010).

Cave bear (*Ursus spelaeus*; Fig. 4.2d) remains are the most abundant Pleistocene fossil mammals in Slovenia; findings were documented in over 90 caves. The most complete dating of them was done on the Divje Babe I. site where cave bear remains (*Ursus spelaeus* s.l.) were dated (^{14}C and ESR) from 40 to 115 Ka (Turk 2007).

Fossil remains of small mammals were found in several Slovenian caves or karst fillings (Aguilar et al. 1998; Sigé et al. 2003). A quarry at Črni kal cut an infilled shaft with large Pleistocene fauna and in Pirešica Quarry small passages filled with sediments revealed small mammals. Among them was an extinct species of dormouse—*Glis* sp. (Aguilar and Michaux 2011; Sigé et al. 2003). Those palaeontological findings helped to calibrate the palaeomagnetic results of studied sediment sections in Črnotiče Quarry and Račiška

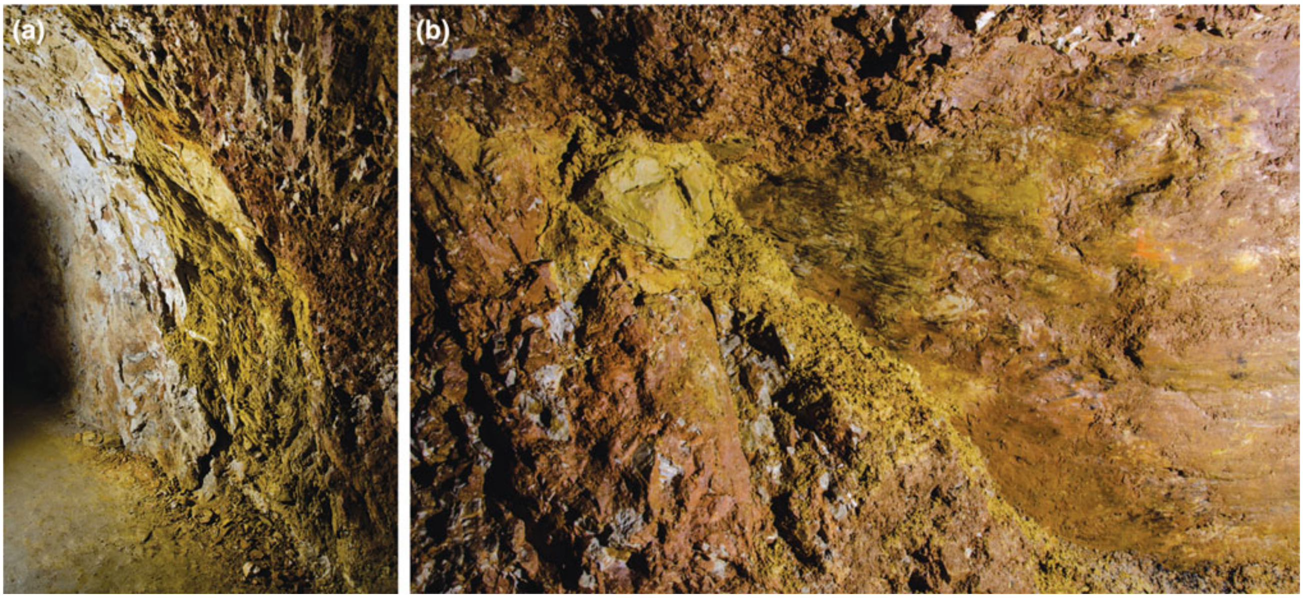

Fig. 4.7 **a** Tectonic clay from a fault zone in Pivka jama (Postojnska jama); **b** tectonic clay at fault plane; it consists almost 100% of calcite particles of silt and clay size (Fig. 4.5). The colour is the same as allogenic flood loam brought into the cave by river (in Fig. 4.5b), but the mineral composition is different

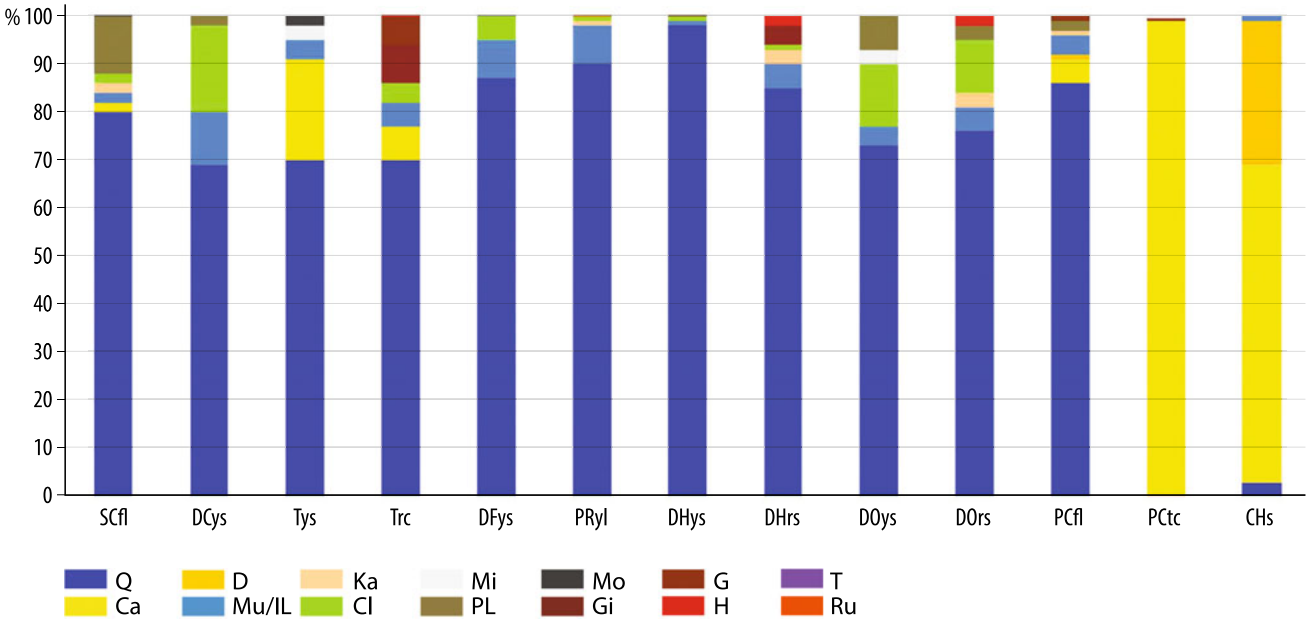

Fig. 4.8 Comparison of selected cave sediment sample mineralogical compositions originating from underground Reka and Pivka rivers, fault zone in Pivka jama and from the Alpine cave Črnelsko brezno, Slovenia. Legend: *SCfl* Škocjanske jame recent flood loam; *DCys* Divaška jama relict laminated yellow sand; *Tys* Trhlovca relict yellow sand; *Trc* Trhlovca red clasts; *DFys* Divača relict yellow sand and clay; *PRyl* Povir (roofless cave) yellow loam; *DHys* Divaški hrib (relict filled cave) yellow sand; *DHrs* (relict filled cave) infiltrated red sediment; *DOys* Divača 1 (doline) yellow sediment; *DOrs* Divača 1 (doline) red sediment; *PCfl* Pivka jama (active cave) flood loam; *PCtc* Pivka jama (fault zone) tectonic clay; *CHs* Črnelsko brezno (deep shaft) clastic sediment; *Q* quartz; *Ca* calcite; *D* dolomite; *Mu/IL* muscovite/illite minerals; *Ka* kaolinite; *Cl* chlorite; *Mo* montmorillonite group of minerals; *Mi* microcline; *Pl* plagioclase; *Gi* gibbsite; *G* goethite; *T* tourmaline; *Ru* rutile

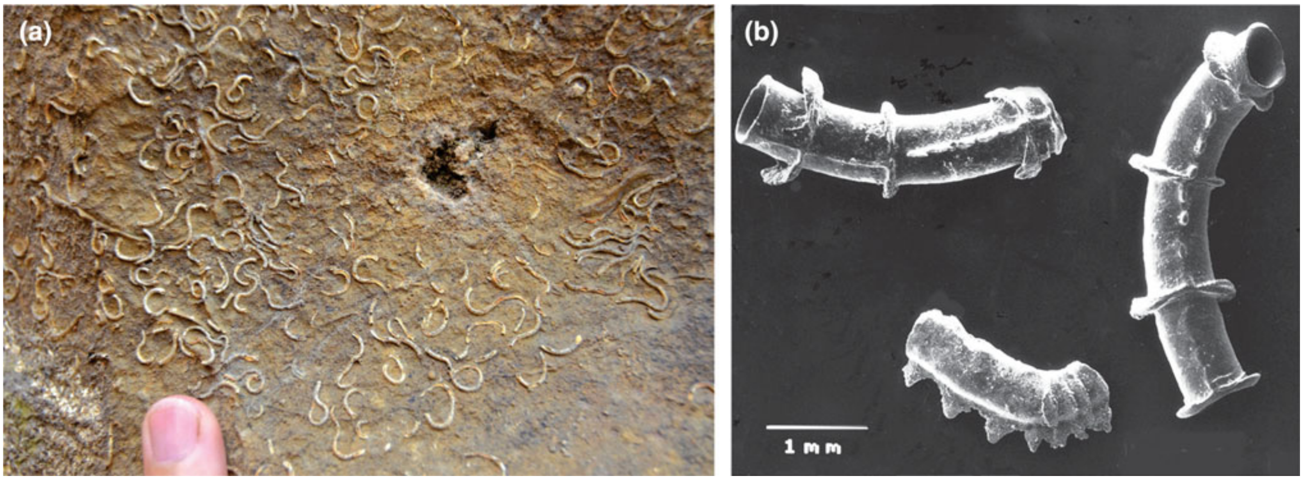

Fig. 4.9 Tubes of *Marifugia cavatica* on the unroofed cave in Črnotiče Quarry

pečina and Snežna jama caves. For the first time in Slovenia, biostratigraphic data helped to correlate magnetostratigraphy logs with the GPTS and to allocate the ages of cave fill more precisely to pre-Quaternary times (Horáček et al. 2007). Palaeontological finds in the Račiška pečina and Črnotiče Quarry confirmed the age interpreted from magnetostratigraphy. Cave fills are often Pliocene in age and even older (Zupan Hajna et al. 2008a, 2010).

4.1.4 Age of Cave Sediments

The first studies of cave sediments in Slovenia were carried out during archaeological and palaeontological excavations of sediments in cave entrances (e.g. Brodar 1952, 1966) where they interpreted all sediments with alternation of cold and warm periods during Pleistocene, disintegration of cave walls and the sliding of the slope materials into the cave. Detailed studies of cave sediments were later done by Gospodarič (1972, 1976, 1981, 1988) in the 70s and 80s of the last century. Gospodarič (1988) applied a relative dating method, comparing cave sediments from different sites to establish the age of deposits and also used available dating methods. He suspected that the cave sediments were not much older than 350 Ka, although it has been already noted that some dating results were beyond this time. In his geochronology of cave sediments based on recognition and descriptions of several profiles from various caves, he classified different deposition phases in the subsurface and linked them to sea-level oscillations and climate changes during the Pleistocene (Franke and Geyh 1971; Ikeya et al. 1983; Ford and Gospodarič 1989). In the Kras region (SW Slovenia), Gospodarič (1988) linked the karstification of the area with glacio-eustatic oscillations of the Adriatic Sea and the global palaeoclimate evolution during the Pleistocene.

Later U-series dating indicated that speleothems from different caves in Slovenia must be older (Zupan 1991; Zupan Hajna 1996; Mihevc and Lauritzen 1997; Mihevc 2001a). Results indicated that speleothem growth corresponded to warmer periods during the Pleistocene; but nevertheless there were large numbers of speleothems older than the limit of the method (350 Ka in the 1990s). These results proved that the cave sediments were older than had been previously thought.

The application and interpretation of palaeomagnetic analysis and magnetostratigraphy of cave sediments, both clastic and chemogenic, which began in 1997, suggested substantial changes in the lower limiting ages of cave fill deposition (e.g. Bosák et al. 1998, 1999, 2000a, b, 2002, 2004; Šebela and Sasowsky 1999, 2000; Audra 2000; Mihevc et al. 2002; Horáček et al. 2007; Zupan Hajna et al. 2008a, b, 2010; Knez et al. 2016).

Systematic studies of cave sediments in Slovenian caves in the last 20 years using different dating methods showed that the sediments were much older than had been originally assumed, as the identified ages cover not only the entire periods of the Pleistocene and Pliocene but also reach into the Miocene. In SW Slovenia, in the area of the Classical Karst, the last evidence of marine sedimentation exists since the Eocene, when flysch sediments were deposited. Palaeomagnetic dating in combination with other methods, especially U-series dating and biostratigraphy, have shifted the possible beginning of cave infilling processes and speleogenesis in Slovenia below the Tertiary/Quaternary boundary. Sediment sections from about 30 studied caves were divided into segments according to palaeomagnetic polarity, NRM, MS, lithology and age. Mean palaeomagnetic declination and inclination were then calculated for each segment (Vrabec et al. 2018). Where possible, age determination was augmented with absolute ages obtained from speleothems interbedded with or covering the sediments, and with biostratigraphical (Horáček et al. 2007) or archaeological data. We found that cave sediments were predominantely deposited in three distinct episodes: 5.4–4.1 Ma, 3.6–1.8 Ma, and 0.78 Ma–present, reflecting regional-scale environmental and tectonic forcing (Zupan Hajna et al. 2010) as the cessation of Miocene deposition in the Pannonian Basin in the Central, E and SE Slovenia and post-Messinian evolution in the SW and W Slovenia. These sedimentation phases in the underground suggest climatic changes on the surface with possible flood events and/or changes of the tectonic regimes during Neogene and Quaternary. It was also evident that all studied sediments were deposited within one post-Eocene karstification period. However, since the processes of sedimentation in the caves are very complex and strongly influenced by local factors, with sediment profile thicknesses of usually only a few metres and interrupted by several unconformities, the interpretation of cave sediments and the resulting data of the surface and subsurface processes is very complex. Calibrated data contributed to reconstruction of the speleogenesis, deposition in caves, and indirectly to evolution of karst surfaces and succession of tectonic displacements (Häuselmann et al. 2015; Vrabec et al. 2018; Zupan Hajna et al. 2017).

The research of cave sediments has not been finished yet; the interpretation of obtained data regarding tectonic, climate, geomorphological and speleological evolution of specific karst areas is in progress.

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