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Marjan Temovski

Evolution of Karst in the Lower Part of Crna Reka River Basin

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Marjan Temovski

Evolution of Karst in the Lower Part of Crna Reka River Basin

Doctoral Thesis accepted by
the University of Nova Gorica, Slovenia

Springer

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Supervisors' Foreword

The thesis of Marjan Temovski is an important milestone, not only regarding the knowledge of the karst of Macedonia especially lower part of Crna Reka River Basin, but also more generally regarding advances in karst science.

Firstly, this pioneer work now represents an essential work about the caves and karst in this lesser studied karst region and using classical and modern methods gives many new surprising data and details not forgetting the whole picture, the morphology, and the evolution of karst landscape.

The author's aim is to give a general overview of the spatial and temporal evolution of the chosen karst terrain. As the karst surface is missing distinctive morphology and correlative sediments, the only place to search for the evidence of the past evolution were caves.

His comprehensive cave inventory with new surveys is integrated within the most updated approaches in geomorphology. Since this terrain is extremely difficult to access without any access to huge areas and deep wild gorges, it will be for decades a founding contribution that may be used by scientist, such as archeologists and hydrogeologists, and by land managers.

One can find in this book all types of the cave genesis that are studied presently worldwide.

The *per ascensum* speleogenesis, evidenced by 100-m-high rising phreatic shafts, is related to an important base-level rise occurring during the Pliocene with the filling of basins by volcaniclastic materials. It implies first that 1000-m-deep gorges preexisted before this burying event and that the current landscape dynamic corresponds to an ongoing exhumation and rejuvenation of the paleolandscape. The problematic of the possible influence of the Messinian Salinity Crisis that triggered the incision along the neighboring Vardar valleys is under investigation. The occurrence of deep phreatic "vauclusian" springs along the Vardar and its tributaries and the evidence of a major pre-Pliocene incision phase point toward an important impact of the Messinian event in the landscape building. Ongoing thoughts are currently orientated to include this geomorphologic process for the understanding of the Neogene basins evolution, which were only considered before from the tectonic point of view. This base-level rise is not only responsible of the origin of deep phreatic cave passages: Aggradation phases first filled caves producing paragenetic features before complete burying, and then, new cave systems developed from allogenic runoff onto volcano-clastic covers following the progressive clearing of the thick plio-quaternary covers. Timing of main events is based on dating (Ar/Ar, U/U, paleomagnetism), allowing not only to date Provalata cave activity and Budimirica cave filling, but also helping to track the main phases of landscape evolution connected to the Crna valley incisions and fillings, especially the Mariovo Lake draining.

The genesis of caves by ghost-rock weathering is a hot subject within the karst community, where specialists are debating about the origin of the fluids responsible of this weathering, i.e., from the surface or from deep origin. Marjan Temovski displays here an important example of hypogene ghost-weathering in dolomitic marbles, where rising hydrothermal fluids first weathered the rock along fractures producing ghost-rock, before this soft material has been washed away by turbulent flow to produce the cave as it can be observed now. It will be an important contribution to the ongoing debate.

The most outstanding result concerns the sulfuric acid speleogenesis (SAS) in Provalata Cave, which has been dated using Ar/Ar method on alunite and jarosite byproducts of SAS.

Numerous other results are important and some have to be published. Several aspects are announcing future major advances, namely the hypogenic speleogenesis around sulfidic ores, the tracking of the Messinian Crisis milestones, and the corresponding outlooks on Macedonian geomorphology which has been deeply renewed.

Postojna
Nice
May 2015

Prof. Andrej Mihevc
Prof. Philippe Audra

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Contents

Chapter 1
Introduction

1.1 Foreword

Karst terrains in Republic of Macedonia, considering the area of karst rock outcrops, represent 12 % of its total area (Temovski 2012). Their distribution is in more or less isolated, generally smaller areas (karst oasis by Manakovik 1980), with largest areas and most of the karst terrains located in the western and central part of Republic of Macedonia. Consequently these areas were the main interest for karstological research in Republic of Macedonia (Kolčakovski 1989, 2005; Temovski 2008) (Fig. 1.1).

The research area is located in the southern part of Republic of Macedonia and is generally a harsh and hardly accessible, largely unpopulated (or depopulated) area, with karst terrains dispersed in several separated areas. The main characteristic of the area are the hilly and mountainous terrains cut by the deep valley of Crna Reka. It is one of the least studied karst areas in Macedonia, with only few published papers regarding karst and caves, and also some speleological exploration done by cavers. It is an area of highly complex geological and geomorphological evolution, yielding rocks from Precambrian to present age.

This thesis mostly represents a regional karstological work, giving first comprehensive information on the extension, development and evolution of the karst terrains in the lower part of Crna Reka river basin. Considering the size of the area, and the general lack of previous research, it represents a rather enthusiastic attempt.

Results of both epigenic and hypogenic karst development are presented here, with hypogenic speleogenesis first time registered in Republic of Macedonia. Hypogenic karst is mainly connected to hydrothermal speleogenesis due to increased geothermal gradient connected to Plio-Pleistocene volcanism. At places

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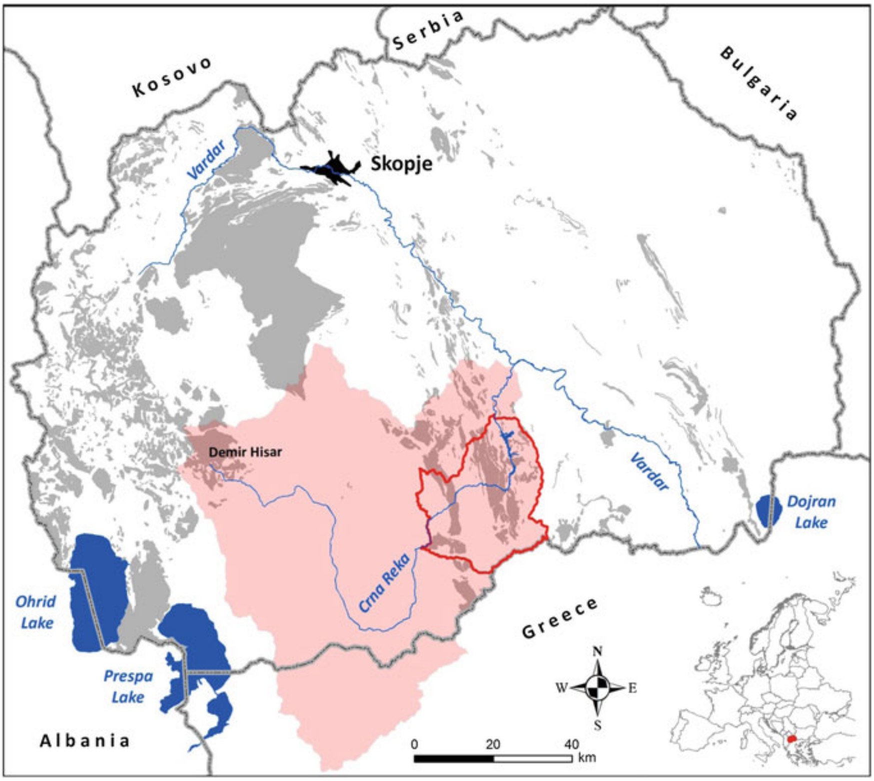

Fig. 1.1 Geographical situation of Republic of Macedonia with karst rock outcrops (*grey shade*), Crna Reka river basin (*red shade*) and location of research area (*red line*)

hydrothermal speleogenesis is converging with other hypogenic processes/mechanisms connected to local geological or lithological control, as a result of which sulfuric acid speleogenesis and ghost-rock weathering developed, both hot topics in today's karst science. Per ascensum epigenic development of caves, due to rise of base level, was also registered with implications pointing to possible impact of the Messinian Salinity Crisis on the deep incisions of Vardar River and its tributaries prior to the Pliocene filling of valleys and basins. The evolution of the sulfuric acid cave Provalata, allowed to determine the timing of the draining of Mariovo Lake between 1.8 and 1.6 Ma, a contribution to the understanding of the evolution of Macedonian Neogene-Quaternary lake system.

The results presented in this thesis are therefore a contribution to the general knowledge of karst development and evolution in this area, and in Republic of Macedonia, although some of the results carry a much wider regional and general scientific significance.

1.2 Goals, Objectives and Approach

The general aim or goal of this thesis is to understand and give a general overview of the spatial and temporal evolution of karst in the lower part of Crna Reka river basin.

From this general aim we can extract several main objectives, with regards to the characteristics of the research area:

(a) To determine the influence of the volcanism in the Kožuf area to the evolution of the karst.
(b) To determine the influence of the Cenozoic sediments to the evolution of the karst.
(c) To determine the influence of the incision of Crna River valley to the general evolution of the karst in the area.

Because of the lack of information from karst surface morphology, this work is based on the thesis, that it is possible to explain the evolution of the karst through the information that we get from the caves in the area. Therefor a speleogenetic approach is used to understand the karst evolution in the research area.

This approach includes undertaking several tasks:

- Systematic surface search.
  To make a systematic search for new caves, besides the already known caves.
- Detailed mapping of the caves.
  To map new caves and make new detailed maps of the known caves from which pattern and passage analyses can be made.
- Morphological analyses.
  To analyze the patterns, passage types, and the micro-forms imprinted on the walls of passages and cave rooms.
- Sedimentary analyses.
  To describe and analyze composition of cave deposits and correlate them with surface (and other) possible source of deposits.
- Comparison and correlation.
  To compare and correlate the caves with the local or regional relief evolution.

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Chapter 2
General Overview of the Research Area

2.1 Geographical Location

The researched area is located in the southern part of Republic of Macedonia, in the lower part of Crna Reka drainage basin.

Crna Reka is the second longest tributary to Vardar river (the biggest river and main drainage system in Macedonia) flowing with W–E direction in the southern part of Republic of Macedonia. Karst areas within its basin are located in the upper part in Demir Hisar area, and in the lower part in Mariovo and Tikveš Basins, and also in the basin of its major tributary Raec River (Fig. 1.1).

The lower part of the basin addressed in this research, is mostly hilly to mountainous area dissected by the deep river valleys of Crna Reka and its tributaries. Morphologically comprises parts of two tectonic basins: Mariovo Basin to the south, and Tikveš Basin to the north and north-east, separated by Kozjak Mountain. The north-eastern boundary of the researched area is on Vitačevo Plateau, a sedimentary volcanoclastic plateau; the north-western boundary is the Dren Mountain Massif (Suva Planina, Radobilska Planina and Orle); south-eastern boundary is on Kožuf Mountain and south-western boundary is Satoka River. Central part of the area is the deep valley of Crna Reka, with also deeply incised valleys of tributaries Buturica, Blašnica and Kamenica rivers (Fig. 2.1).

The area is situated on the boundary between the Pelagonian Massif and Vardar Zone, two major geotectonic units in Macedonia, and also comprises parts of two geographical and historical regions: Mariovo and Tikveš. It is mostly a remote area with small and mostly depopulated villages with lack of infrastructure, with rudimentary agriculture and mining as the main economy.

Karst here is found as several separated karst areas, which is a general characteristic of karst terrains in Republic of Macedonia (oasis karst type by Manakovik 1980).

It is developed on Precambrian and Cambrian marbles, Triassic marbly limestones (or marbles) and dolomites, Cretaceous limestones and Pleistocene travertine rocks, without well expressed karst surface, but with well expressed karst underground.

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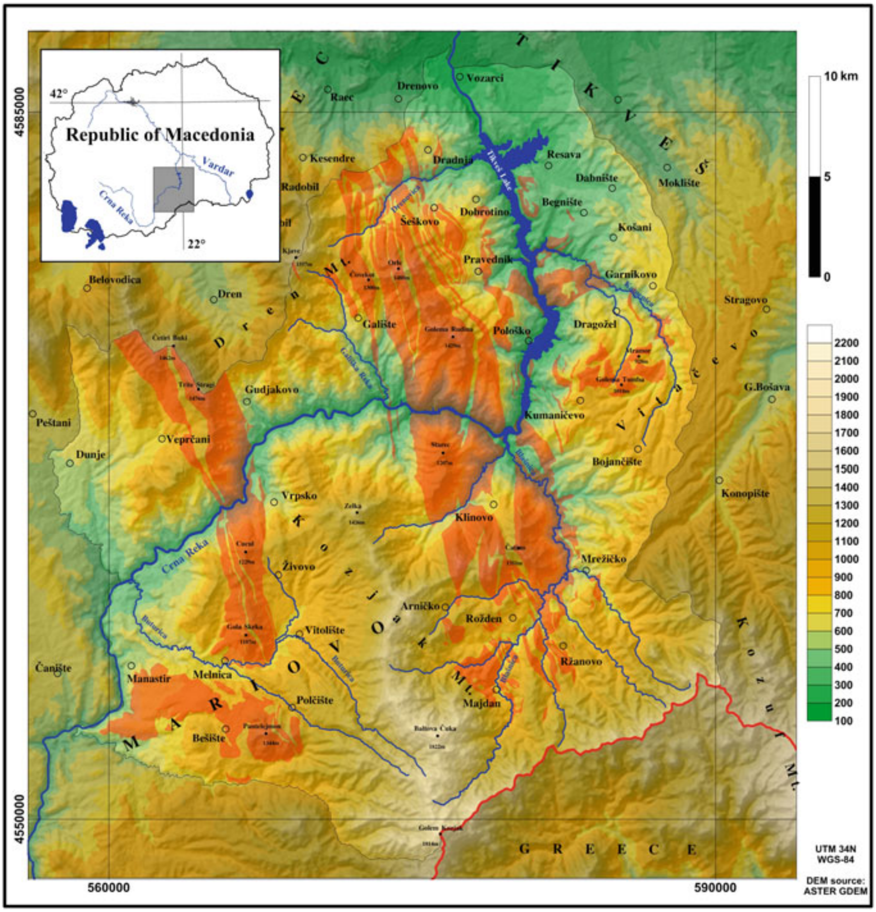

Fig. 2.1 Geographical situation of the research area. Karst rock outcrops are given in *red shade*

2.2 Previous Research

Previous research of karst in this area has been very scarce, mostly due to the generally harsh, hardly accessible and depopulated terrains.

Geological studies of the area included study of the carbonate rocks in the area, determining their spatial distribution, stratigraphy, age, structural characteristics and relations to the other rocks. Although geological research in the area has been conducted since the beginning of the twentieth century, the first comprehensive work is as part of the creation of the basic geological map of former Yugoslavia in scale 1:100 000, presented on sheets Vitolište, Kožuf, Prilep and Kavadarci

(Dumurdžanov et al. 1976; Hristov et al. 1965; Rakičević et al. 1965; Rakićević and Pendžerkovski 1970). The area is also included in the comprehensive work from Arsovski (1997) that gives an overall view to the tectonics and stratigraphy of Macedonia.

There are only few works dealing with the karst in the area. Manakovik (1971) publishes the first information about the caves in Kamenica River. He studied three caves: cave Aramiska Peštera, Buturica Cave and Crkviče Cave, explaining their evolution with the successive draining of Central Macedonian Lake and incision of Kamenica River in the limestone rocks, with Aramiska Peštera considered as the oldest, located in he upstream part with highest elevation of the three, with Buturica and Crkviče considered as younger, at lower elevations downstream along the valley of Kamenica River.

Small notes on the karst in Mariovo are given by Manakovik and Andonovski (1984) as part of the geomorphology of Mariovo. They only address the extension of carbonate rocks, and describe some karst surface features such as karren and dry valleys.

Kolčakovski et al. (2004) published first results about cave Provalata (named Gulabinka in the paper), giving morphometric information and noting the presence of gypsum deposits. Although contributing the presence of gypsum to dissolution of the marble by hydrothermal waters enriched with H_2S, they conclude that the cave is fossil ponor cave.

Speleological work in this area was also done by cavers, locating and mapping generally caves which were previously known to the local population. In the western part (Mariovo area), during the last 10 years, caving clubs SK Zlatovrv from Prilep and Ursus Speleos from Skopje have explored Pešti Cave and caves Melnička Peštera 1 & 2, while SD Peoni from Skopje has explored Provalata Cave and cave Živovska Propast (Propast Provala). In the eastern part, cavers from PSD Orle from Kavadarci have documented a number of caves, mostly in the 1960s and 1970s, describing location, general size and also mapping most of them. SD Peoni from Skopje also located and explored Čulejca Cave, and French cavers (ASBTP from Nice) in collaboration with PSD Orle and SD Peoni worked also in Gališka Peštera and Čulejca Cave.

2.3 Geological Setting

The research area belongs to two major Pre-Cenozoic tectonic structures: Pelagonian Massif and Vardar zone, overlaid by Cenozoic tectonic structures and sediments. It is composed of rocks from various ages from Precambrian to recent (Fig. 2.2).

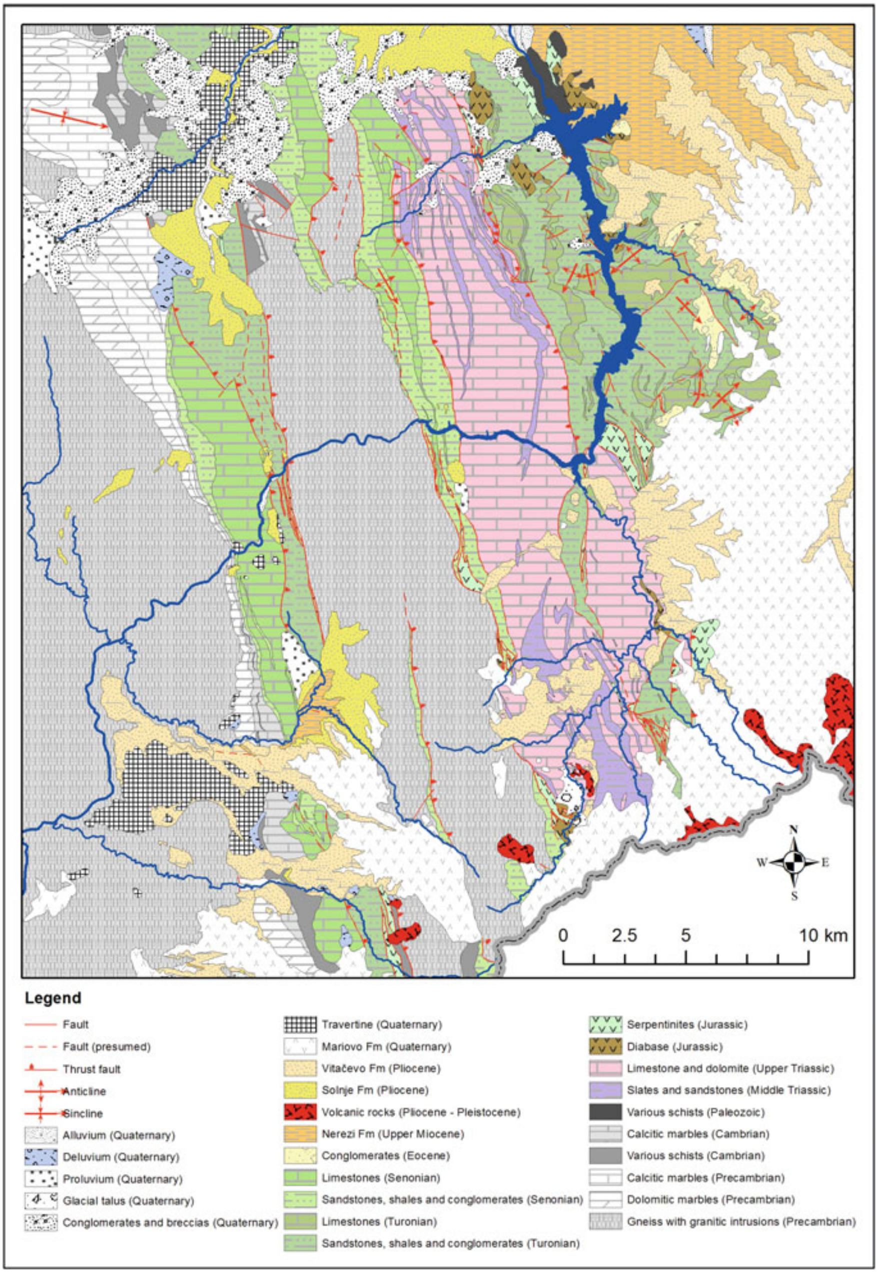

Fig. 2.2 Geological map of the research area, compiled from data after (Dumurdžanov et al. 1976; Hristov et al. 1965; Rakićević et al. 1965; Rakićević and Pendžerkovski 1970; Geološki Zavod—Skopje, unpublished)

2.3.1 *Pre-Cenozoic Stratigraphy*

Pelagonian Massif consists of Precambrian gneiss and schist rocks, covered by a thick section of dolomitic and calcitic marble in the upper part, and with abundant granitic plutons (Arsovski 1997; Dumurdžanov et al. 2005). Dolomitic marbles are mostly developed in the lower parts of the Precambrian marble series, and grade upwards to calcitic marble. They are found along the eastern border of the Pelagonian Massif, in a NNW–SSE stripe, with dolomitic marble more widespread in the southern parts (south from Crna Reka), and calcitic marble in the northern parts (north of Crna Reka). They are mostly white to gray, small grained to massive, highly fractured, and mostly pure carbonate rocks (Table 2.1) with less than 1 % silicate component (Stojanov 1974; Dumurdžanov et al. 1976).

Dolomitic marbles overlay gneiss rocks and dip to the ENE by 25°–50°, as part of the NNW–SSE oriented Veprčani Monocline. Precambrian gneiss and micaschist rocks, with granitoid plutons are also found in the Vardar Zone, as part of the Kozjak horst.

Paleozoic metamorphic rocks determined as Cambrian are developed in both the exterior and interior part of the Vardar Zone. The thickness of the complex it's not well determined because in most of the area, they are overlaid by Cenozoic deposits, but presumed to be around 1500 m. The Paleozoic complex is presented with different facies (Dumurdžanov et al. 1976): marbles; marbles and cipolin marbles; quartzite-sericite schists and quartzites; amphibolites and amphibole schists; phyllite-micaschists, greenschists and carbonaceous schists. A significantly thick mass of marbles lay along the eastern edge of the Pelagonian massif. At Pantelejmon (1344 m) in the southern parts, the Cambrian complex starts with schist in the lower parts, and through carbonaceous schists and cipolin marbles pass to medium bedded marbles. North of Melnica, the schists are found only as lenses within the Cambrian marbles which lay directly on top of the Precambrian marbles.

Triassic rocks are presented in form of a tectonic block with N–S direction, composed of terrigenous and carbonate sediments. They start with middle Triassic slate and sandstone deposits as the basal unit (Dumurdžanov et al. 1976;

Table 2.1 Chemical analysis of marbles from Pletvar, 20 km NNW from Crna Reka (Stojanov 1974)

	Dolomitic marble (%)	Calcitic marble (%)
CaO	32.50	54.35
MgO	19.63	1.02
SiO_2	0.27	0.50
FeO	0.10	/
Fe_2O_3	0.14	0.21
Al_2O_3	0.33	/
CO_2	49.96	43.80
$CaCO_3$	58.04	97.06
$MgCO_3$	41.05	2.13

Robertson et al. 2012), above which are deposited grey shallow-water Upper Triassic carbonates presented with limestones and dolomites, significantly metamorphosed, mostly platy and thick bedded, rarely massive (Dumurdžanov et al. 1976; Robertson et al. 2012). The upper part of the carbonate platform includes a thin interval of recrystallized chert, shale and thin bedded limestone which pass transitionally upwards into further thick-bedded, recrystallized limestone of possible Jurassic age (Robertson et al. 2012). They are locally highly deformed by isoclinal folding.

Jurassic ophiolitic rocks are found as elongated lenses along many tectonic structures, diapirically emplaced. They are localized in four main tectonic zones, along vertical or thrust faults (Dumurdžanov et al. 1976). The first is along many faults in the Upper Cretaceous rock delineating the west border of Kozjak block; the second is connected to the Galište–Arničko graben along NNW–SSE oriented faults; the third is along the faults forming the west border of Pološko–Ržanovo graben; and the fourth starts from Crna Reka trough Kumaničevo village and to the SSE below the tertiary-quaternary deposits. Lithologically they are composed of serpentinites and peridotites, gabbro and diabase.

Upper Cretaceous sediments are presented with thick section of Turonian and Senonian sediments (Rakićević and Pendžerkovski 1970; Dumurdžanov et al. 1976). Turonian sediments have thickness of around 2000 m and are localized in two zones. The first is on the western edge of the Vardar zone, as a part of the Dren-Vitolište graben. The sediments are overthrusted onto Senonian sediments to the west and have a fault connection with the Kozjak horst to the east. The second zone is in the inner part of the Vardar zone as part of the Pološko–Ržanovo graben. They are covered with pyroclastic sediments to the south, and have fault guided connection with the Triassic rocks. Three facies can be separated (Rakićević and Pendžerkovski 1970; Dumurdžanov et al. 1976): conglomerates and sandstones; sandstones, shales and conglomerates; limestones. The limestones are found in the upper layers of the Turonian sediments, and as layers and lenses inside the clastic sediments. They are massive, platy and thick bedded, micritic, gray to gray–white in color with sandy to marly alternations at places, containing numerous fossil fragments (Rakićević and Pendžerkovski 1970; Dumurdžanov et al. 1976).

In the Senonian sediments several facies are determined (Rakićević and Pendžerkovski 1970; Dumurdžanov et al. 1976): limestones; flysch: sandstones, siltstones, shales and limestones; sandstones, shales and conglomerates; and conglomerates and sandstones. Senonian limestones are found as the topmost formation of the Senonian sediments in the Dren-Vitolište graben and as part of the flysch deposits in the Galište–Arničko graben. They are platy to thick bedded, grey to white, rarely pinky and locally sandy or marly.

2.3.2 Main Tectonic Structures in the Pre-Cenozoic Rocks

Pre-Cenozoic rocks within the Vardar zone were strongly deformed in the latest Cretaceous to Paleocene time (Laramide phase), in number of folds and faults with NNW direction (Arsovski 1997; Dumurdžanov et al. 2005).

In Vardar zone we can separate two structural segments: Kozjak-Drenovo and Veles-Klepa-Tikveško Ezero segments (Fig. 2.3). Most of the area is part of the Kozjak-Drenovo segment, a system of horsts and grabens built from different complexes and formations divided by faults (Dumurdžanov et al. 1976; Arsovski 1997):

Kozjak horst extends in sub meridian direction over 30 km, starting from Raec Valley to the north, trough Dren and Kozjak to south, 4–6 km wide. It is settled between Dren-Vitolište graben to the west and Galište–Arničko graben to the east, divided by regional faults (Vrpsko reverse fault to the west and Kozarnički fault to the east), along which small lenses or bigger masses of tectonized serpentinites are found. It is composed of rocks from the gneiss and micaschists series, and granitoides of the Precambrian complex, and represents a cutoff part from the Pelagonian massif.

Dren-Vitolište graben, located to the west of the Kozjak horst, has system of longitudinal reversed faults (Vrpsko reverse fault) as part of the west border fault system of the Vardar Zone. In the middle of the graben the Turonian formation prevails, intensively dislocated, with lenses of serpentinites inserted along the faults. This middle part of the graben is overthursted on the west side over the Senonian flysch (Klen reverse fault), which overlays the Precambrian and Paleozoic complex of the Pelagonian massif.

Galište–Arničko graben lies to the east of the Kozjak horst, as a narrow graben, 2 km wide in the north part, and 1 km wide in the south. This graben is composed of Senonian flysch sediments, intensively folded into isocline folds. From the both sides the graben is isolated by regional faults (Kozarnički and Dračevički faults) alongside which lay elongated lenses of serpentinites.

Rožden horst lies to the east of the former graben. It is built from the Triassic sediments, intensively folded, mainly into isocline folds. In the north part the folds lean to the east, and the whole structure is overthursted trough the cretaceous sediments to the east, along the Smrdeliški fault. The south part of the horst is divided into two parts by the Pološko–Ržanovo graben.

Pološko–Ržanovo graben has N–S direction and is built of Turonian sediments, which form significantly big anticline (Crna Reka anticline) with axis parallel to the direction of Crna Reka. To the south, this anticline is deformed by the Čatenaški fault.

Veles-Klepa-Tikveško Ezero segment (Rakićević and Pendžerkovski 1970; Dumurdžanov et al. 1976; Arsovski 1997) here is presented with couple of folded structures in the Turonian sediments along the north part of the Tikveš Lake, in the

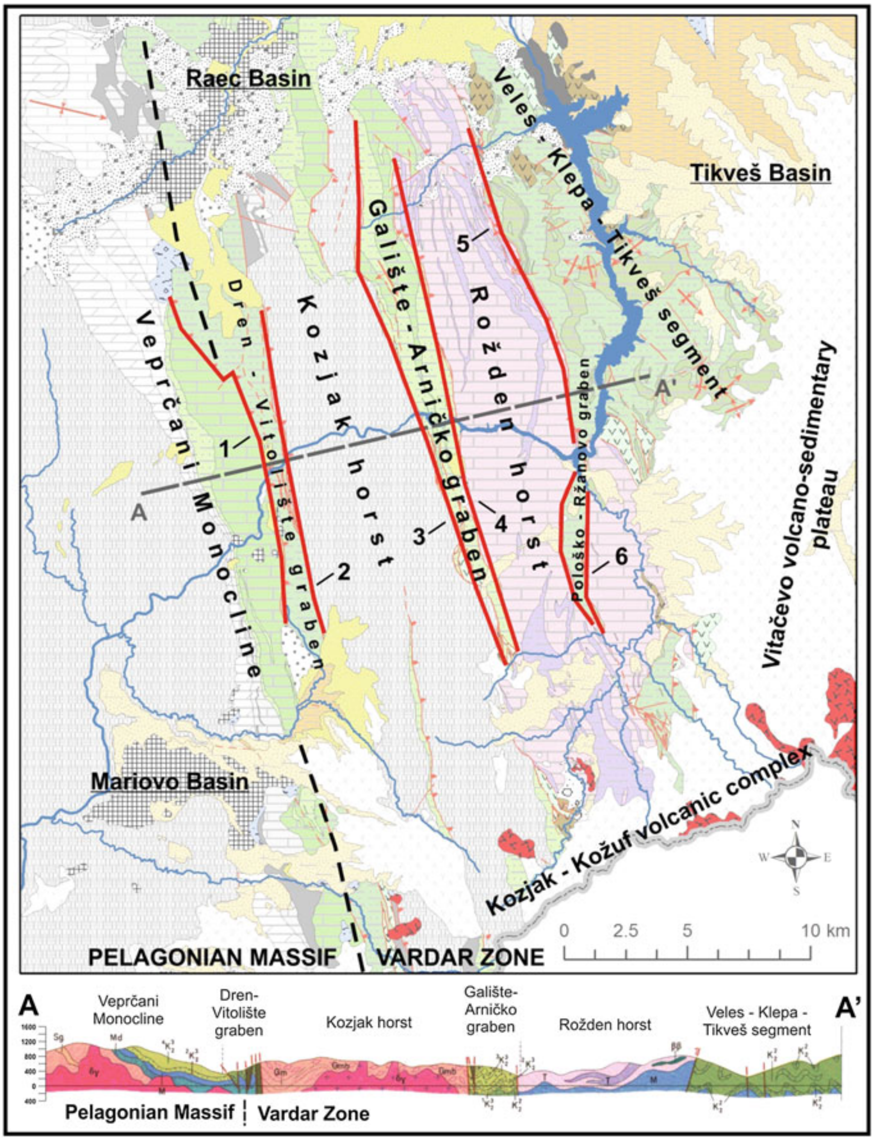

Fig. 2.3 Simplified structural map with main tectonic structures. *1* Klen reverse fault, *2* Vrspsko reverse fault, *3* Kozarnički fault, *4* Dračevički fault, *5* Smrdeliški fault, *6* Čatenaški fault. Note the difference in symbols between map and cross-section, with cross-section represented in original as given by Dumurdžanov et al. (1976)

western part of Vitačevo plateau. Main folds are the Kamenica Anticline and Dragozel Syncline, with NW oriented axis, cut by the NW–SE Dragozel fault, and several second order folds having NE oriented axis.

2.3.3 *Cenozoic Stratigraphy and Tectonics*

Cenozoic evolution is connected with two phases of basin development in late Eocene to recent time and reflects two major periods of extensional deformation separated by a short period of shortening (Dumurdžanov et al. 2004, 2005).

During the first period of extension in late Eocene, Tikveš-Ovčepole basin was formed as a forearc basin lying to the west of the regional magmatic arc. Five litozones are separated within the Paleogene sediments, of which basal conglomerates with fragments originating from Turonian sediments are found in the vicinity of Dragožel, Garnikovo and Kumaničevo villages (Rakićević and Pendžerkovski 1970; Petrov et al. 2010).

In the late Oligocene-Early Miocene, the strata in Tikveš basin were deformed as a result of two short periods of shortening (Pyrenian and Savian phases). These short periods of deformation were followed by a period of erosion that reduced the landscape to low relief and separated the first and second major periods of extension (Dumurdžanov et al. 2004, 2005; Petrov et al. 2010).

The second period of extension started in late early Miocene and became the dominant mode of deformation within Macedonia to the present. Basin formation in Macedonia during the second period is described in five cycles by Dumurdžanov et al. (2004, 2005). Tikveš and Mariovo Neogene grabens, which are located in the researched area, were formed during the second cycle (late Miocene: late Sarmatian —Meotian), partially controlled by N–S and NE–SW trending faults.

Mariovo Basin is located in the western part of the research area, and is filled with lacustrine and pyroclastic sediments deposited from Upper Miocene to Pleistocene (Dumurdžanov et al. 2004):

- ***Nerezi Formation*** (Upper Miocene)—gravel and sandstone; siltstone and silty claystone that grades upward into claystone and coal; and siltstone and sandstone followed by a hiatus.
- ***Solnje Formation*** (Pliocene)—poorly stratified gravel and sandstone, overlain by:
- ***Vitačevo Formation*** (Pliocene)—stratified tuff overlaid by sandstone and gravel interbedded with beds of diatomite, tuff, and sandy claystone; travertine deposits, tuff-agglomerate and sandstone.
- ***Mariovo Formation*** (Pleistocene)—pyroclastic rocks with nine travertine layers and a 20-m-thick travertine deposit on top.

Tikves Basin is bounded on its western side by normal faults of N–S and NW–SE strike, while two NE-striking parallel faults bound its northwestern and southeastern sides. Three formations are recognized in the central and southern part of the basin (Dumurdžanov et al. 2004):

- ***Nerezi Formation*** (Upper Miocene)—lies unconformably on Eocene rocks, starting with (the basal unit) basal conglomerate with gravel, sandstone, and brown claystone overlain by sandstone and mottled claystone; interbedded grey claystone, coal-bearing claystone and coal beds overlain by marl and marl-rich (the middle unit); interbedded sandstone, siltstone, and silty claystone (upper unit).

- ***Vitačevo Formation*** (Pliocene)—sandstone overlain by tuff and agglomerate with diatomite and tuff at the top; overlain by interbedded yellow sandstone, tuff, and agglomerate, locally containing travertine; with tuff agglomerate and tuff as the topmost part.
- ***Mariovo Formation*** (Pleistocene)—strata deposited in a lacustrine environment that was terminated during Pleistocene time by deposition thick beds of breccia conglomerate with volcanic material, above which lies agglomerate, tuff, volcanic breccias, and locally travertine.

Remnants of Pliocene deposits (Solnje Formation) as well as Pleistocene travertines (Mariovo Formation) are also found along the valley of Crna Reka, indicating possible connection of the Mariovo Lake with the Central Macedonian Lake (Dumurdžanov et al. 2003, 2004).

Dumurdžanov et al. (2004, 2005) interpret the evolution of the Neogene basins in Macedonia in 5 cycles, with Mariovo and Tikveš basins forming in cycle II (late Miocene: late Sarmatian-Meotian), with total hiatus at the end of cycle III (Pontian). In Pliocene—cycle IV (Solnje Formation and Vitačevo Formation in Mariovo; Vitačevo Formation in Tikveš) a transgression occurs, accompanied with volcanic activity in Kožuf and Kozjak Mts., which continued through Early Pleistocene (Mariovo Formation). With the draining of the lake system in central Macedonia (which started probably as late as Middle Pleistocene; Dumurdžanov et al. 2005) as a result of general uplift in Macedonia and subsidence in the Aegean Sea, Mariovo Lake also drained, thus Crna Reka established its fluvial basin.

New information regarding the Pliocene deposits invokes different interpretation to the evolution of the basins along the Vardar valley during the end of Miocene and in Pliocene time. A Gilbert-type fan delta, the postponed signature of the Messinian Salinity Crisis (MSC), has been documented in the Pliocene sediments southward of Skopje at Dračevo (Clauzon et al. 2008). It follows a previous phase of incision of deep valleys due to the lowering of base level as a result of almost complete desiccation of the Mediterranean Sea. Such results demonstrate that the MSC impacted the region of Skopje as it did for the northern Aegean region (Thessaloniki) and Western Dacic Basin (Turnu Severin). Hence, a marine gateway is considered to have connected the Aegean Sea and the Dacic Basin (Eastern Paratethys) through the Balkans Chain, replacing the generally suggested corridor in the present-day Bosphorus Strait area (Fig. 5.76).

Considering the location of the Tikveš Basin along the Vardar Zone between Skopje and Thessaloniki, MSC event must have impacted this area as well, with the hiatus at the end of Nerezi Formation (Upper Miocene) to be considered as a result of this event. The Pliocene deposits along the Crna Reka Valley also indicate valley incision prior to the Pliocene deposition, which might be connected to the MSC. Consideration of the possible MSC impact on the evolution of the area is of great importance, since such event would have had significant effect on the general relief formation, and also on karst development.

2.4 General Geomorphology

The base of the relief in the area is constituted by structural forms: horsts and grabens formed as part of the South-Balkan extensional system. The horst structures are Kozjak and Dren Mountains, and the grabens are Mariovo and Tikveš basins. Overprinted onto these macro-relief forms, as a result of fluvial-denudation, coastal, and karst erosion processes, are meso and micro-relief forms, different in shape and size.

Dren Mountain massive (Kjave, 1557 m) has a W–E direction and is composed of three morphological units. This is due to the lithology and older tectonic structure influencing the relief. To the west is the Suva Planina mountain with NW direction, built of Precambrian, Cambrian and Cretaceous rocks. In the middle is the main ridge of Dren Mountain, composed of Precambrian gneiss and Cretaceous sediments, and to the east lies Orle Mountain, containing Triassic and Cretaceous rocks.

Kozjak Mountain (Baldova Čuka, 1822 m) continues to the south of Dren Mountain and has an N–S general direction. It is composed of Precambrian to Cretaceous rocks. To the west it is highly eroded as part of the small Vitolište basin and Buturica valley, and borders the Mariovo basin. To the east it is separated from Vitačevo plateau by the valley of Blašnica.

Neogene lakes of Tikveš and Mariovo basin have left traces of lacustrine terraces. In Mariovo Manakovik and Andonovski (1984) determined two lacustrine terraces, at 1100–1150 m and at 1000–1050 m. Traces of the terrace at 1100–1150 m are found on the slopes of Pantelejmon, west side of Kozjak and on the ridge of Cucul (1229 m), Šipka (1182 m) and Gola Skrka (1187 m). The second terrace at 1000–1060 m is more pronounced in the area, and traces are found around Pantelejmon, Polčiško Pole, on the west side of Kozjak where it is more pronounced, also around Cucul (1229 m), Šipka (1182 m) and Gola Skrka (1187 m). The best preserved remnants are on Polčiško Pole. This terrace is considered as the central lake plain during Upper Pliocene by Manakovik and Andonovski (1984). In Tikveš, Manakovik (1971) found four lacustrine terraces, at 900 m, at 740–800 m (due to the pyroclastic sediments), at 660–700 m and at 600–620 m representing the former central lake plain. The biggest remnant of the lacustrine environment are the thick sediments, sands, clays, conglomerates, that are filling the Mariovo and Tikveš basins, which in Mariovo end with 20 m thick travertine deposit. They are deeply incised by valleys, and in the higher areas completely eroded.

The interpretations of the evolution of the Tikveš and Mariovo basins (Manakovik 1968; Manakovik and Andonovski 1984) should be revised, due to the new data on the sedimentation of the basins and age of sediments (Dumurdžanov et al. 2004, 2005). Also data (from south of Skopje) suggesting marine environment in upper Miocene, possible influence of the MSC and Pliocene marine transgression connecting the Aegean sea with the Dacic basin (Clauzon et al. 2008), which contradicts to the previous explanation of continuous lacustrine environment in the basins in Macedonia, events that surely influenced the valley of Crna Reka and Tikveš and Mariovo basins.

Fluvial relief covers most of the area, presented with the drainage of Crna Reka. The main form is the valley of Crna Reka that has gorge characteristics. It cuts through the area in W–E direction with a deeper valley segment separating Dren and Kozjak mountains. The upper parts of this gorge (on Dren and Kozjak Mountains) are wider and are remnants of old valley of Crna Reka, while at several locations along the valley in the lower parts Pliocene deposits are found, indicating Miocene age of the paleo Crna Reka Valley (Manakovik and Andonovski 1984). From the confluence with Blašnica, Crna Reka continues to the N, and also has gorge-like characteristics until Vozarci village where Crna Reka has formed a wider alluvial plain, continuing to the confluence with Vardar River.

Her tributaries have smaller drainage basins and smaller discharge than Crna Reka, so most of them did not managed to adjust its long-profile to the base level of Crna Reka. In the valley of Crna Reka, Manakovik and Andonovski (1984) determined fluvial terraces at different relative elevations (380–400 m, 310–340 m, 230–240 m, 200–210 m, 130–140 m, 115–120 m, 65–70 m, 40–55 m, 15–20 and 5 m).

2.5 Climate

As a result of the morphological configuration the area is characterized with local climate, with modified Mediterranean influence coming from downstream valley of Crna Reka (from the Aegean Sea, through the valley of Vardar River), and temperate continental influence coming from upstream valley of Crna Reka (from Pelagonian Basin). Of the climate parameters only temperature and precipitation will be presented.

According to the thermal regime (and the climate in general) the area has three different parts (Stankoski 1984): the narrow belt along the valley of Crna Reka, starting from Tikveš and up to around 600 m elevation (Manastir Village), has modified Mediterranean thermal regime with mean annual temperature of 12.4 °C and maximal rainfall in May (68.1 mm); the areas of the valley of Crna Reka above 600 up to 900 m, with the hilly terrains in Mariovo and Tikveš have almost same thermal regime as in the Pelagonian Basin, with mean annual temperature 11.3 °C. Summers are warm, and winters cold with more rainfall in autumn, giving temperate continental characteristics to the thermal regime; mountain areas of Kožuf, Kozjak and Dren mountains have mountain climate with mean annual temperatures from 6 °C at the summits and ridges to 8–10 °C on the slopes. Absolute temperatures in the area are maximum of 40.1 °C in July and minimum of −19.8 °C in December.

Annual distribution of precipitation in the area is very irregular as a result of the complexity of the relief, winds, and the position regarding the Aegean Sea. The area has modified Mediterranean pluvimetric regime with maximum in spring (May) and second maximum in autumn (November) and minimum in August and July. The precipitation is mainly influenced by the relief, resulting in precipitation of up to 500 mm in the valley of Crna Reka, to 600–700 mm on the hilly terrains of Mariovo and Tikveš, and 800–1000 mm on the mountain areas. Most of the precipitation comes in spring (32 %), autumn has 28 %, winter 22 % and summer 18 %. Average precipitation is 570 mm with maximum in May (102.9 mm) and minimum in August (30.5 mm). Of the overall annual precipitation, snow takes from 9 % in the valley of Crna Reka up to 30–40 % above 1500 m. In average snow starts in the middle of December (14.XII) and lasts until middle of March (10.III) Special characteristic of the pluviometric regime in the area are the continuous no-rain days—draughts. They are most common in summer, when continuous no-rain days reach up to 58 days in some years, and every year there is period of almost one month with drought (Stankoski 1984).

If we summarize, the area has three climate zones: modified Mediterranean climate along the valley of Crna Reka (in narrow belt along the valley downstream to Tikveš) with maximum precipitation in spring (May) and autumn (November), and minimum in summer; temperate continental climate occupying the hilly and plateau parts of the area, with maximum precipitation in November and secondary in May, and minimum in July and August; mountain climate in the area of Kozjak, Dren and Kožuf mountains.

Overall the area has average annual precipitation of 570 mm, most of it precipitated in spring and autumn, except the mountain parts that have higher precipitation up to 1000 mm and more even annual distribution. The average annual temperatures range from 6 to 10 °C in the mountains to 12.4 °C in the lower parts in valley of Crna Reka, with maximum of 40.1 °C and minimum of −19.8 °C (Stankoski 1984).

2.6 Hydrography

The area occupies the lower part of the drainage basin of Crna Reka, starting from the confluence of its right tributary Satoka River, to the confluence of its biggest tributary, Raec River. In this area Crna Reka has number of tributaries of which the right tributaries are characteristically bigger and with bigger discharge, draining the mountainous areas of Nidže, Kozjak and Kožuf mountains. Main tributaries in the area are: Buturica, Blašnica and Kamenica to the right, and Gališka and Drenovica to the left.

Crna Reka is the second longest tributary to Vardar River, the biggest river and main drainage system in Macedonia. It starts in Demir Hisar area, to the west of Pelagonian Basin, with the Železnec springs considered as the source. From the source to the confluence with Vardar River it has a length of 207 km, with vertical difference of 631 m between the source and the confluence elevation, and average slope of the longitudinal profile of 3 ‰, which in Mariovo is higher at 5.9 ‰, and at some sections even 11 ‰. Average annual discharge, measured at the measurement station in Skočivir at the entrance to Mariovo area (prior to the research area, so without the water coming from the later described tributaries), is 19.3 m^3/s, with the highest discharge in March (71 m^3), and lowest in September with 0.10 m^3 (Gaševski 1984).

Buturica River, in the upper part called Vitoliška Reka, emerges on Kozjak Mountain at 1600 m in the area called Vlaški Kolibi. It has a number of smaller right tributaries which come from east from a more forested part of its basin. Before Vitolište Village, Buturica flows in NE direction where receives a right tributary coming from the area of Živovo Village. After this confluence, Buturica has W direction down to Melnica, where it receives its biggest tributary Polčiška Reka. Downstream from here, Buturica takes NW direction and before the confluence to Crna Reka turns to N direction. Buturica River is 20 km long and has basin of 102 km^2. Its valley is mostly gorge like (Gaševski 1984).

Blašnica River is the biggest tributary to Crna Reka in the research area. Begins on Kozjak at 1700 m close to the river head of Buturica and confluences to Crna Reka near Tumba (384 m), having length of 28 km, drainage area of 210 km^2 and average drainage elevation of 980 m. It has more developed drainage than the other tributaries in the area. Bigger tributaries are Krusta, Kozarik, Dabov Dol, Topli Dol, and Mrežička Reka. Blašnica has gorge like valley, with some smaller parts where its profile has smaller gradient, mostly due to the different lithology (Gaševski 1984).

Kamenica River is 14 km long, starting from its head near Bojančište village at about 940 m until its confluence to Tikveš Lake. It has several tributaries, of which Dragoželska Reka is the biggest (Manakovik 1971).

There are two bigger left tributaries of Crna Reka in the area. One is Gališka Reka that emerges at 1110 m below Kjave (1557 m) on Dren Mountain, with length of 9 km and SE direction connecting with Crna Reka on the beginning of the Tikveš Lake. The other is Drenovica, also 9 km long, and emerging below Kjave (1557 m) at 1100 m on the eastern slopes of Dren Mountain, flowing in NE direction to the Tikveš Lake near the dam.

2.7 Karst Extension

In the before defined general borders of the research area, karst rocks cover 187.67 km^2, which is 22.36 % of the area (total area of 839.42 km^2). Karst rocks are represented with carbonate rocks with various degrees of diagenesis and metamorphosis, with marbles, limestones, dolomites and travertines, having ages from Precambrian, Cambrian, and Cretaceous to Pleistocene time. Important characteristic of the Precambrian formation is that most of the marbles are dolomitic marbles (Table 2.2).

Table 2.2 Surface area of karst rock outcrops in the research area

Age	Rock type	Surface area (km^2)	Percentage of karst rocks
Precambrian	Dolomitic marble	8.53	4.55
Precambrian	Calcitic marble	2.08	1.11
Cambrian	Calcitic marble	6.62	3.53
Triassic	Metamorphosed limestone and dolomite	97.93	52.18
Turonian	Limestone	23.90	12.74
Senonian	Limestone	32.46	17.30
Pleistocene	Travertine/tufa	16.15	8.61
Total		187.67	100

The Upper Triassic carbonate formation has the largest extent, with little more than half of the karst rock surface area, having both dolomites and limestone, partly metamorphosed. The calcitic Precambrian marbles have the smallest surface area, together with the Precambrian dolomitic marbles and Cambrian calcitic marbles, although their thickness is quite significant, with most of these rocks covered by younger sediments (Fig. 2.4).

Spatially carbonate rocks here are generally located in three NNW–SSE oriented stripes, with tectonic or sedimentary borders to the west and east, transversely cut in segments separated by river valleys or Neogene-Quaternary deposits.

The western stripe is located along the eastern edge of the Pelagonian Massif, composed of Precambrian and Cambrian marbles, separated by a thin clastic section from the overlying thick Senonian limestones. The western border is sedimentary with the underlying Precambrian gneiss formation, while the eastern border is represented by an overthrust fault along which Turonian clastic formation is overthursted onto the Senonian limestones.

The middle stripe is mostly composed of Upper Triassic limestones and dolomites, with tectonic borders to the west and east; with small Senonian limestone stripe to the west, and Turonian limestones to the east. The eastern stripe is composed of Turonian limestones which continue from the Turonian limestone in the central stripe, with western border defined by contact with the underlying clastic formation or by faults, while to the east they are buried by the Neogene-Quaternary Tikveš Basin deposits. To the north and south these carbonate rocks are generally buried by Neogene-Quaternary lacustrine, fluvial and pyroclastic deposits. Travertine rocks represent generally the topmost formation of Mariovo Basin deposits.

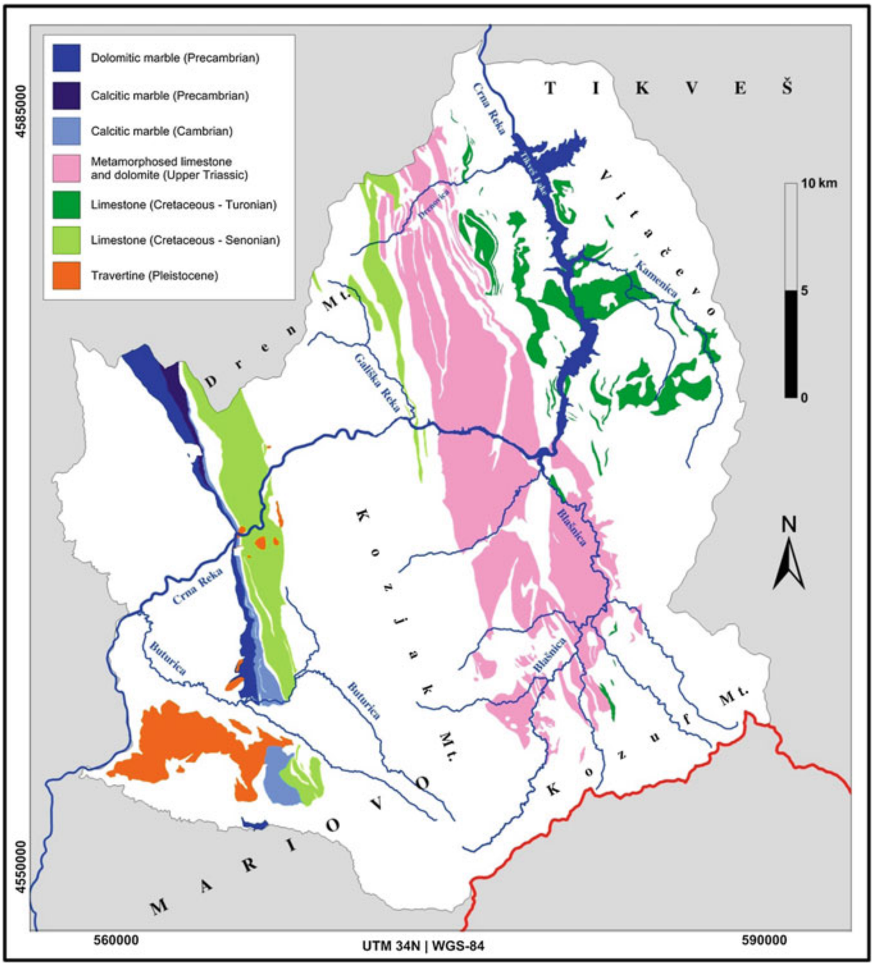

Fig. 2.4 Extension of karst rock outcrops in the research area

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Chapter 3
Methodology

Since the approach to understanding the evolution of the karst in the research area will be mostly through speleological research, an overview will be given of the main concepts regarding speleogenesis.

3.1 Concepts

3.1.1 Karst Evolution and Speleogenesis

Karst is a terrain formed on especially soluble and fractured (carbonate) rocks resulting in the development of special karst landforms (depressions, caves, sinkholes, etc.) and extensive subterranean water drainage (Gams 1973; Ford and Williams 2007). It is an evolving system due to progressive dissolution, with caves being both product and agent of this evolution. Most of the karst systems receive their inputs from recharge sites at the surface, which also evolve over time as a consequence of dissolution. Karst can also operate only in the subsurface, without any apparent relationship to the surface (Ford and Williams 2007).

Temporal and spatial karst evolution therefore operates as a combined system between the karst surface supplying recharge and karst underground as an evolving transmitter of karst waters.

Karst underground can also operate as isolated system from the surface recharge. This is the characteristic for the hypogenic karst development (Klimchouk 2007).

Continuous downward development of karst, and surface lowering, can completely destroy (dissolve) previously formed underground karst features. Clear example of the effect of continuous development of karst can be seen in the Classical Karst of Slovenia, where surface karst denudation has reached caves formed at more than 100 m below the former surface, exposing relicts as unroofed caves, filled with clastic sediments and flowstone, often with some preserved cave passages leading to them (Mihevc et al. 1998; Mihevc 2001, 2007).

Fluviokarst development combines both the development of karst and fluvial features. While karst underground is functioning as normal karst system, karst surface can have fluvial morphology. Active fluviokarst can form when karst

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development is young and/or hydraulic gradient is very low. In dry areas with seasonal torrential rains, a regular dendritic valley patterns can develop having heads in the karst rocks. They are formed by channeled runoff during storms, while between storms, epikarst is able to sufficiently drain any surface water. Such terrains can have significant caves developing below. Where high discharge allogenic waters are crossing through karst terrains, a through valley or gorge can develop, acting as a regional base level (Gunn 2004; Ford and Williams 2007).

Temporal evolution of karst can be continuous or can be interrupted by transgression or burial and later exposure, exhibiting several phases of karst development (Klimchouk and Ford 2000).

Cave development is connected to three broadly recognized speleogenetic settings (Klimchouk 2007; Ford and Williams 2007): (1) syngenetic/eogenetic (coastal and oceanic), generally in young rocks of high matrix porosity and permeability, connected to mixing of waters of contrasting chemistry at the halocline; (2) hypogenic, predominantly confined, by water that recharges the cavernous zone from below, independent of recharge from the overlying or immediately adjacent surface; and (3) epigenic (hypergenic), unconfined, where water is recharged from the overlying surface.

This research is based on the concepts of epigenic and hypogenic speleogenesis.

3.1.2 Epigenic Speleogenesis

Epigenic caves have been defined as caves formed by waters in which solutional capacity is due to carbon dioxide acquired from the atmosphere and/or (most importantly) from the soil (Palmer 1991, 2007; Audra and Palmer 2013).

Caves formed by epigenic waters received far more attention throughout the history of cave study. Most of the known caves have been considered epigenic by its origin (80–85 % according to Palmer 2007), and therefore, epigenic caves have been usually considered as “normal” caves.

Epigenic caves can form in three hydrologic settings: in the vadose zone where conduits with free-surface streams develop; phreatic zone with closed conduit flow along gentle gradients; and epiphreatic zone which is flooded during high water and drained during low water, thus containing both types of flow (Palmer 2007; Ford and Williams 2007). Their identification is generally based on the analysis of typical cave patterns in both horizontal and vertical dimension, passage morphology, micro-morphology, and sediments (Palmer 2007; Ford and Williams 2007) (Fig. 3.1).

3.1.2.1 Vertical Cave Patterns

Vertical development of cave passages is generally connected to the geomorphic evolution of the surrounding landscape. The Four State Model by Ford and Ewers (1978) states that the vertical cave patterns of cave passages depend on fissure

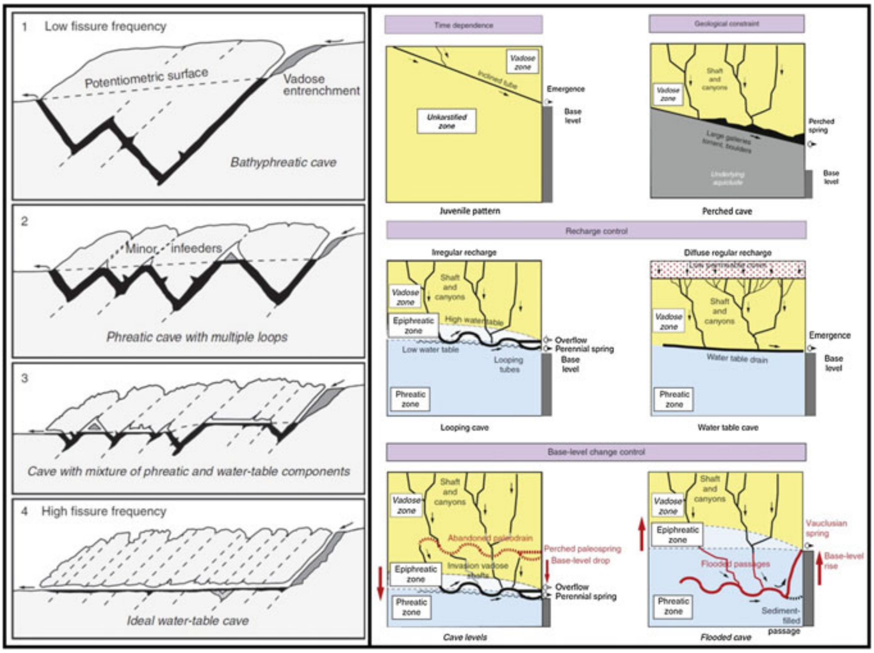

Fig. 3.1 Concepts of vertical cave development: *Left* The Four State Model by Ford and Ewers (1978); *Right* Vertical cave patterns by Audra and Palmer (2013)

frequency. The initial fissure frequency is low, but increases with time and fractures become wider due to stress release as a result of erosional unloading and cave development. In state 1 due to low fissure frequency, a bathyphreatic cave is developed with few phreatic loops that extend deep below the water table. With the increase of fissure frequency, a multi-loop phreatic cave develops (state 2) with shallower loops and water table drops with increase of permeability. In state 3, a mixture of shorter and shallower loops and water table segments develop. With very high fissure frequency (state 4), there is a low resistance and phreatic loops cannot form so cave passages develop almost entirely along the water table.

Audra (1994) emphasized the importance of epiphreatic zone for the development of high-amplitude apparent phreatic loops on studies of caves in the Alps, stressing that high-level passages with large vertical loops are not necessarily the oldest. Audra and Palmer (2013) questioned the idea of diminishing of phreatic loops in progressively lower and younger passage levels. Palmer and Audra (2004), and Audra and Palmer (2013) thus proposed vertical cave pattern development due to control by time (juvenile pattern), by the position of the aquifer (perched vs. dammed), by recharge type (regular vs. irregular), and by base-level changes (lowering vs. rising).

The juvenile pattern is a time-controlled pattern that prevails where soluble rocks are exposed by uplift and by removal of any impermeable cover. The water table is steep and high above the fluvial base level due to sparse fracturing. Initial phreatic passages are later entrenched with lowering of water table and shifting to vadose setting. This pattern often corresponds to the initial phase for most vertical passages and is common in young rapidly developing karst (Palmer and Audra 2004; Audra and Palmer 2013).

Perched caves develop where the aquifer is perched above base level on an underlying aquiclude. There is no significant phreatic cave development, so shafts and canyons converge to form conduits at the aquiclude top draining to springs along hillslopes. *Dammed* karst is characterized with karst aquifer extending below the spring outlet which location is determined by fluvial or structural base level. The main drain is along the water table with major passages either following the water table or having shallow phreatic loops (Palmer and Audra 2004; Audra and Palmer 2013).

Looping caves develop in the epiphreatic zone as a result of an irregular recharge. During high flow, water rises in phreatic lift tubes emerging at overflow springs. During low flow, water follows lesser openings at lower elevations. This creates looping passages in the epiphreatic zone which are enlarged by aggressive high flows. Amplitude of the loops depends on vertical amplitude of the epiphreatic zone and with that on the height and velocity of flooding. The irregular recharge can be due to storms or from glacial or snow melt, or as the result of concentrated surface runoff into dolines. Water table caves can develop as a result of regular recharge, which can be due to semipermeable cover that filters the recharge, leading to uniform transfer and mainly water table flow, or in mature through caves with passages large enough to allow transfer of all stages of flow fed by extensive impermeable catchment (Palmer and Audra 2004; Audra and Palmer 2013).

Base-level changes can have profound effects on vertical cave patterns. *Lowering* of *base level* can lead to reorganization of drainage in dammed karst settings where patterns depend on base-level position. With lowering of water table, successively lower phreatic passages will develop, and new invasion vadose shafts and canyons will extend the vadose zone to the new water table. Former conduits and springs are abandoned and partly filled with floodwater sediments and secondary minerals. Pause in base-level lowering can produce cave levels that correlate with river terraces (Palmer 1987). *Base-level rises* on the other hand cause flooding of conduits resulting with per ascensum speleogenesis (PAMS). Although some of them can become sediments filled, the main flow lines remain active, creating ascending routes which result with phreatic lifts, chimney-shafts, and vauclusian springs. Base-level rise influencing PAMS can be due to various reasons such as river aggradation, tectonics, glacial dam, sea level rise, etc. (Audra et al. 2009a; Palmer and Audra 2004; Audra and Palmer 2013).

An expressive example of the PAMS is seen in the southern France, where deep phreatic cave systems are connected to the Messinian Salinity Crisis (MSC). Fast entrenchment of canyons was initiated as a result of the desiccation of the Mediterranean Sea during the MSC (5.96–5.32 Ma), which reflected in vertical development of karst following the abrupt base-level drop. Pliocene transgression then flooded the karst systems forcing upward cave development, with cave levels

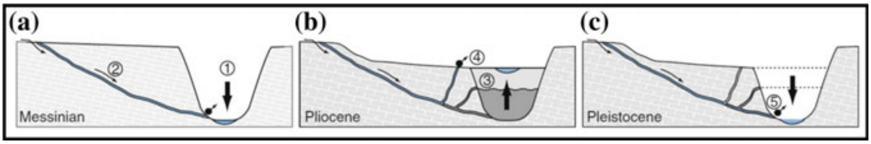

Fig. 3.2 Per ascensum model of speleogenesis connected to the Messinian–Pliocene cycle (Audra et al. 2009a): **a** Deepening of karst drainage due to Messinian canyon entrenchment; **b** deep drainage uses phreatic lifts to emerge as vauclusian springs, recording successive positions of the base level. If the Messinian canyon is located below the current base level, it remains fossil. The karst remains flooded and discharges by a vauclusian spring; **c** if the Messinian canyon is located above the current base level, the canyon is exhumed and the karst is drained. The current drainage uses the deep Messinian drain; The Pliocene phreatic lifts are abandoned as fossil "chimney-shafts"

correlating to successive positions of the base level due to sediment filling of the Messinian canyons, and later fluvial aggradation. Pleistocene re-entrenchment partly or entirely drained some cave systems, while others remain flooded (Audra et al. 2004, 2009a; Mocochain et al. 2009) (Fig. 3.2).

3.1.2.2 Plan-View Cave Patterns

Palmer (1991, 2007) identified several plan-view cave patterns: branchwork, maze (network, anastomosis, spongework), and ramiform. The most common (epigenic) cave pattern is branchwork (at least 60 % of all caves according to Palmer 2007). They contain passages that join as tributaries. Each first-order branch starts from a discrete recharge source and converges into higher order passages that become fewer and larger in the downstream end (Palmer 1975). Maze caves can be formed in both epigenic and hypogenic settings (Palmer 2011), with ramiform caves typically being hypogenic formed by sulfuric acid or less commonly by mixing processes (Palmer 2007).

Network caves consist of angular grid of interconnecting fissures formed by widening of nearly all major fractures. Closed loops are common feature. In epigenic settings, they are produced by uniform seepage through overlying insoluble rock or by periodic floodwater. Anastomotic caves have curvilinear tubes which intersect in a braided pattern with many closed loops, usually as a two-dimensional array along a favorable parting or low-angle fracture. They are formed by floodwaters and usually are superimposed on branchwork caves. Spongework caves consist of interconnected solution cavities of varied size in a random three-dimensional pattern like pores in a sponge. Most appear to have formed by coalescing of intergranular pores. Ramiform caves have irregular rooms and galleries that wander in three dimensions with branches extending outward from the main areas of development. They are characteristic of hypogenic caves (Palmer 1991, 2007, 2011) (Fig. 3.3).

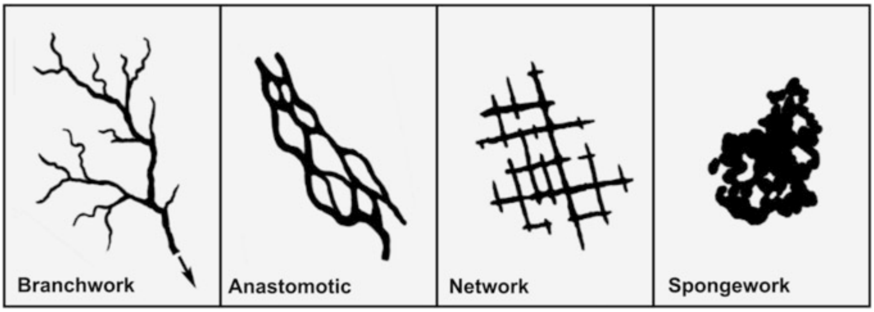

Fig. 3.3 Common epigenic cave patterns (Palmer 1991)

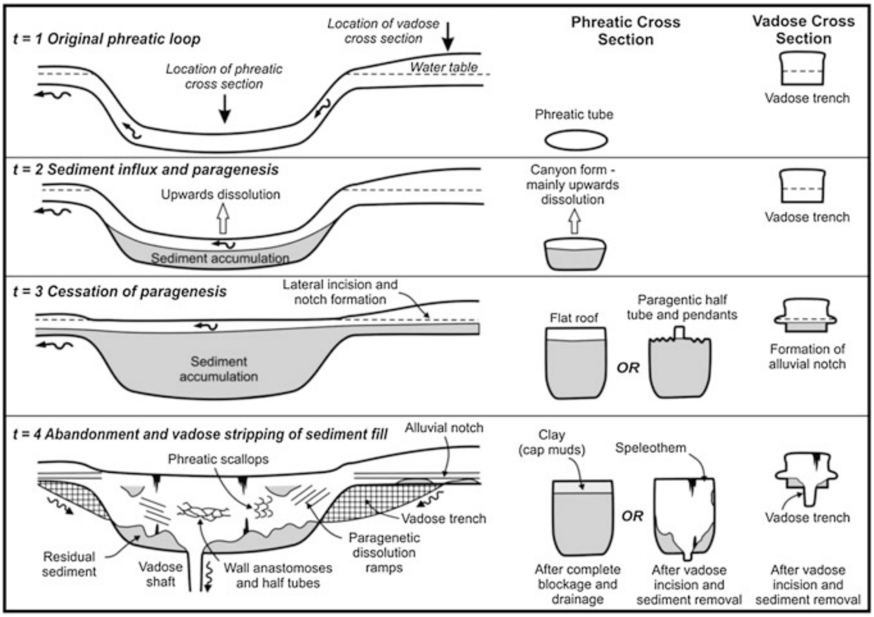

Fig. 3.4 Paragenetic evolution in phreatic and vadose settings, after Farrant and Smart (2011)

Caves consisting of single passages are generally considered as rudimentary forms of any of the before mentioned types (Palmer 1991, 2007) (Fig. 3.4).

3.1.2.3 Meso- and Micro-Morphology

Meso-morphology of caves can be observed at passage level in cave cross section. There is a clear distinction between passages formed in free-surface flow or in closed conduit flow (Lauritzen and Lundberg 2000; Palmer 2007; Ford and Williams 2007).

The most common vadose passage types include shafts and canyons. In phreatic setting, dissolution is symmetric and directed radially out from the passage axis, which enlarges the passage along the entire perimeter producing tubular passage. Tubular passages develop also in the epiphreatic setting, where passages can be dry for a long period, but during floods, they are completely water filled and act as phreatic tubes. Their main difference is the small-scale scallops that reflect the high velocity flow in the epiphreatic zone. Some passages have composite character, most common of which is the keyhole passage which is a tube with canyon incised in the floor.

Smaller scale forms in caves (microforms) are features much smaller than the passage diameter (Lauritzen and Lundberg 2000). They can develop in various settings with most typical representatives in various types of pockets, cupolas, scallops, notches, potholes, anastomoses, spongework, ceiling channels, pendants, grooves, ramps, flutes, and rills (Slabe 1995; Lauritzen and Lundberg 2000; Palmer 2007).

3.1.2.4 Paragenesis

In epigenic caves, especially in caves with allogenic input where big amounts of sediments can be transported within the cave system, as well as in caves affected by regional base-level rise, sediment deposition can have major influence on cave passage development. In phreatic passages, accumulation of sediment on the floor can force upward dissolution of the ceiling, due to shielding of the floor which leaves only the upper surfaces of the tube to be dissolved by the aggressive water. With upward retreat of the ceiling, more sediment accumulates to maintain the equilibrium between erosion, deposition, and water velocity. The upward migration will stop when the tube reaches the water table. This mechanism is known as paragenesis (Renault 1968; Farrant and Smart 2011). Passages formed by paragenesis can be easily mistaken for vadose or phreatic passages. They can be distinguished from vadose passages by phreatic wall morphology (scallops, pendants, grooves). In meandering paragenetic passages, meander migration axis propagates upward in the direction of flow, as opposed to vadose meanders where the axis propagates downward (Lauritzen and Lundberg 2000). Keyhole passages can also develop in paragenetic setting. Along with the passage form, typical solution features that can identify paragenetic development include pendants and half tubes, drainage grooves, bedrock fins, and paragenetic solution ramps (Farrant and Smart 2011).

3.1.2.5 Condensation Corrosion (in Epigenic Caves)

Condensation corrosion can also influence passage morphology and evolution, although in epigenic caves it is not considered as a cave-forming process (Ford and Williams 2007; Palmer 2007). Condensation occurs where warm moist air rises from the lower regions and reaches cooler surfaces. In caves with rising moist air, condensation can form irregular tubes, domes, and cupolas that extend upward from the original passage, and also, it can etch speleothems (Palmer 2007). It can be significant process in cave entrances or through caves with strong draft, having high-temperature and relative humidity gradients. It is more significant process for hypogenic caves.

3.1.3 Hypogenic Speleogenesis

Hypogenic speleogenesis historically has received far less research attention than epigenic speleogenesis, but lately, there has been an increase in research focus on hypogenic cave development (Klimchouk 2007, 2009, 2013; Palmer 2011).

Hypogenic speleogenesis or hypogenic caves have been defined by Palmer (1991) as caves formed by acids of deep-seated origin, or epigenic acids rejuvenated by deep-seated processes, and have no relation to recharge through the overlying surface. Klimchouk (2007, 2009) later adopted a hydrological approach to hypogenic speleogenesis, defining it as the formation of solution-enlarged permeability structures by water that recharges the cavernous zone from below, independent of recharge from the overlying or immediately adjacent surface. In the general context of groundwater flow system (Toth 1963), Klimchouk (2007) associates the development of hypogenic karst to discharge regimes of regional or intermediate flow systems, with epigenic speleogenesis predominantly associated with local flow system.

There is still an ongoing debate between defining hypogenic speleogenesis using hydrological or geochemical approach (Palmer 2011; Bella and Bosak 2012; Klimchouk 2013).

Several dissolution mechanisms are operating under hypogenic settings (Palmer 1991, 2007; Klimchouk 2007), such as mixing corrosion, cooling of thermal waters, H_2S oxidation, and condensation corrosion. Some of them (CO_2, mixing corrosion) are also important in epigenic settings (Palmer 2007; Ford and Williams 2007).

The recognition and interpretation of hypogenic caves, especially inactive ones, are based on lack of genetic relationship to recharge from overlying or immediately adjacent surfaces, characteristic morphology, and certain diagnostic speleothems and minerals (Audra et al. 2009b, c, d; Palmer 2007).

Palmer (1991, 2007) describes ramiform and maze patterns (spongework, network, anastomoses) as most common hypogenic cave patterns. Audra (2007) and Audra et al. (2009c) based on the analysis of more than 350 hypogenic caves give a conceptual model of a cave pattern, integrating all kinds of hypogenic caves. They subdivide them into two main types: deep phreatic systems with *isolated geodes*, *3D and 2D maze caves,* and *deep phreatic shafts* are the typical representatives; and *upwardly dendritic caves*, *isolated chamber*, *water table sulfuric caves, and smoking shafts* as cave systems developed above the water table.

Two major classes of hypogenic caves develop due to dissolution of carbonate rocks by CO_2- and H_2S-rich thermal waters (Palmer 1991; Dublyansky 2000). A brief overview of the concepts will be given below.

Rising thermal carbonic waters cool down along their flow path, increasing their aggressiveness due to the inverse relationship between solubility and temperature, which leads to a progressive increase in $CaCO_3$ solubility and also a drastic drop of solubility near the water table due to the loss of CO_2. As a result, a geochemical zone of carbonate dissolution and zone of carbonate precipitation appear within the aquifer (Dublyansky 2000). While degassing produces oversaturated water and deposition near the water table, above the water table there is a concentration of gas, which produces dissolution (Audra et al. 2002). Where H_2S-rich waters mix with shallower oxygen-rich waters, sulfuric acid forms at or near water table, which rapidly dissolves the carbonate rocks (Egemeier 1981). This process is known as sulfuric acid speleogenesis and has been recognized as a significant cave-forming process in many caves around the world, such as Carlsbad and Lechuguilla Caves in New Mexico (Hill 2000), Frasassi Caves in Italy (Galdenzi and Menichetti 1995), Cueva de Villa Luz in Mexico (Hose and Pisarowicz 1999), Chat Cave in France (Audra 2007), and Kraushöhle in Austria (Plan et al. 2012). Above the water table, H_2S escapes in the cave air and redissolves in water condensation droplets on cave walls. There it oxidizes to sulfuric acid which attacks the carbonate rock and converts it to gypsum by forming replacement gypsum crusts on cave walls and ceiling (Fig. 3.5).

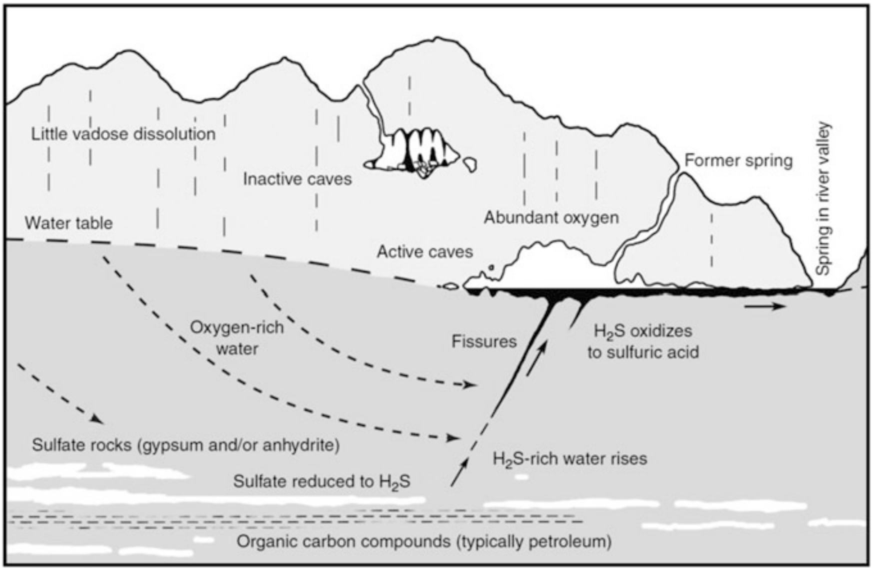

Fig. 3.5 Sulfuric acid speleogenesis concept (Palmer 1991, 2013)

Considering that condensation corrosion can be significant in thermal caves (Audra et al. 2007), rising CO_2- or H_2S-rich thermal waters can form cave passages and smaller morphologies in both phreatic and vadose environments.

Phreatic speleogenesis includes cave patters such as isolated geodes, 2D and 3D maze caves, and deep phreatic shafts (Audra et al. 2009c), with morphologies that include more common hypogenic morphologies such as feeders leading to rising wall and ceiling channels and cupolas, described as the "morphological suit of rising flow" (Klimchouk 2007), as well as phreatic chimneys, bubble trails, thermosulfuric discharge slots (Audra et al. 2009d). In vadose settings, due to condensation-corrosion, isolated chambers, upwardly dendritic caves and smoking shafts can develop, with smaller morphologies including wall niches, ceiling cupolas, condensation-corrosion channels, megascallops, condensation domes, and vents. Some morphologies are typical of sulfuric acid caves, such as features produced by replacement of carbonate rock with gypsum (replacement pockets), dripping tubes, sulfuric karrens, and cups, as well as water table features such as corrosion tables and flat roof notches (Audra et al. 2009c, d) (Fig. 3.6).

Identification of hypogenic caves based only on morphology can be sometimes ambiguous. Therefore, the presence of some characteristic deposits associated with

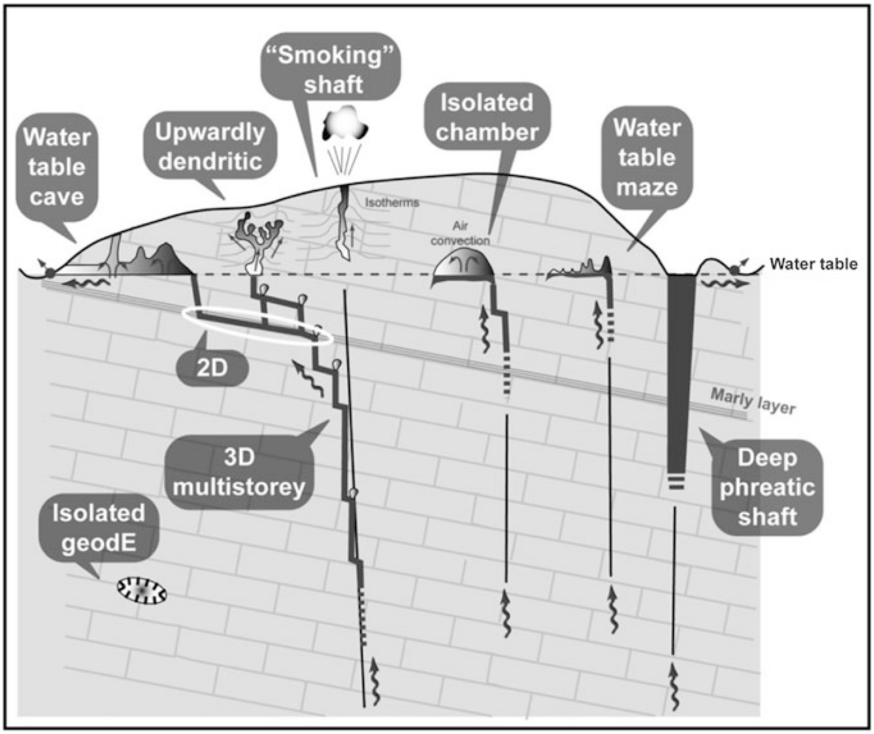

Fig. 3.6 Conceptual model of the hypogenic cave patterns (Audra et al. 2009c)

sulfuric acid speleogenesis, or thermal carbonic speleogenesis, can help in interpreting hypogenic origin. Many known hydrothermal caves are lined with scalenohedral (dogtooth spar) calcite crystals (Dublyansky 2013). Gypsum deposits, found as replacement crusts, are indicative of sulfuric acid speleogenesis. Replacement gypsum crusts may detach and form mounds or blocks of massive gypsum on the floor (Egemeier 1981; Galdenzi and Maruoka 2003). Massive gypsum can also form below water table as a result of sulfate supersaturation of the groundwater, as documented in the caves of the Guadalupe Mountains in USA where the rising water contained much sulfate that escaped reduction, which gave the water a head start in depositing subaqueous gypsum (Palmer and Palmer 2000). In contact with aluminosilicates, sulfuric acid produces a characteristic suit of minerals such as alunite, jarosite, natroalunite, and hydrated halloysite. They are of high importance since dating of these K-rich sulfate minerals that formed during the speleogenesis have potential to yield the age of the cave-forming process (Polyak and Provencio 2001).

3.1.4 Karst and Caves in Conglomerates

Carbonate conglomerates present important part of the younger carbonate deposits in the research area and have some karstic features; therefore, an overview of the recent research on conglomerate karst and caves will be given, with main focus to speleogenesis.

Conglomerate rocks with carbonate fragments are common deposit in various environments. Their carbonate matrix material combined with mostly carbonate fragment makes them act as a compact carbonate rock.

Karst in conglomerates has been studied in Udin Boršt, Slovenia (Kranjc 2005); Montello, Italy (Castiglioni 2005); Molasse Basin, northern margin of the Alps (Goeppert et al. 2011); and Catalonia, Spain (Bergadà et al. 1997). Some notable caves in conglomerates are also the Oreshnaya Cave in Russia (Klimchouk 2004) and Pozodel Portillo System in Honduras (Finch and Pistole 2011). Beside these examples, there is still lack of knowledge regarding karst in conglomerates (Gabrovšek 2005; Goeppert et al. 2011) (Fig. 3.7).

The conglomerates in the reported cases consist mostly of carbonate fragments cemented by calcite matrix with smaller part of the fragments consisting of non-carbonate rocks. In all of these areas, karst has most of the normal features with dolines and smaller scale forms on surface, and caves underground. Goeppert et al. (2011) report even uvalas and small-scale poljes in the Molasse Basin conglomerates in the Alps. Most of the caves have water table or vadose passages with branchwork pattern and are developed at or close to the contact with an underlying impermeable unit. Gabrovšek (2005) points that the settings of high primary porosity and permeability of the Udin Boršt conglomerates with autogenic recharge would exhibit a curvilinear branchwork geometry.

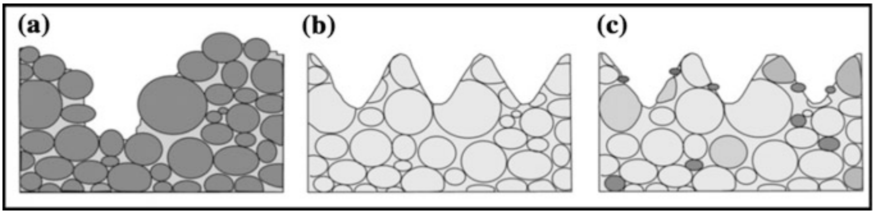

Fig. 3.7 Schematic illustration of weathering processes in conglomerates at the Hochgrat site in the Molasse Basin (northern margin of Alps), after Goeppert et al. (2011): **a** Mechanical weathering resulting in erosional channels; **b** chemical dissolution of well-cemented carbonate conglomerates with karren (true karstification); **c** karren with the non-soluble components that protrude during karstification

Goeppert et al. (2011) describe the combined action of mechanical weathering and chemical dissolution of carbonate rocks, with the later mostly prevailing, as the mechanism responsible for karstification of the Hochgrat site in the Molasse Basin. This was noted in the development of surface features such as karren as well as on cave walls.

3.2 Research Methods

As the approach to understand the evolution of karst in the researched area is through speleogenesis, this thesis is based on research made mostly in caves.

This generally includes morphological analyses based on cave maps and field observations, combined with sediment analyses and in some cases dating of cave sediments.

3.2.1 Morphological Analyses

Cave morphology was used for interpretation of environment in which caves were formed. Analyses were made of macro- (cave patterns), meso- (passage morphology), and microforms imprinted on walls of cave passages.

Cave passage patterns were analyzed in both horizontal and vertical dimension, using detailed cave maps.

Morphology at cave passage scale was analyzed to interpret development in phreatic, epiphreatic, or vadose settings, as well as development in hypogenic settings. Special care was taken to differentiate morphologies and passages formed by paragenesis.

Typical small-scale morphology was taken in consideration in interpretation of cave passages.

3.2.1.1 Cave survey

Most of the caves studied were previously not known, or not published. Only some of them (Kolčakovski et al. 2004; Manakovik 1971; PSD Orle, not published) were surveyed, but most of the cave maps were found lacking in detail and/or precision, with even big directional errors in some of them. Therefore, they were not useful for analyses, and new cave maps were produced not only for the newly discovered caves, but also for most of the known caves.

Cave surveying was done with a detailed in-scale field mapping in 1:100 scale using Leica laser distance meter (Disto D3) and Suunto compass (Suunto KB-20). Field data (sketches, measurements) were later processed in Therion cave mapping software (Budaj and Mudrak 2008), to produce cave maps in plan, profile, and 3D view.

3.2.2 Sediment Analyses

Distribution and stratigraphy of cave sediments and deposits were described for every cave. Samples from characteristic sediments and deposits were collected for X-ray analysis. Alunite and jarosite from Provalata Cave were dated by ^{40}Ar/^{39}Ar method, and sediments from Budimirica Cave were dated by paleomagnetism.

3.2.2.1 X-ray analyses

X-ray analyses were carried out at the CEREGE—CNRS, France. X-ray powder diffraction (XRD) patterns were recorded on a Philips diffractometer using Cobalt radiation (λ = 1.79 Å) with a secondary graphite monochromator. The diffractometer optic used to record all samples was a front fixed slit of 1°, a scattered radiation slit of 1° after the sample, and a 0.2-mm detector slit. The X-ray tube operating conditions were 40 kV and 40 mA, and the step-scan data were continuously collected over the range 3.5–78° 2θ using a step interval of 0.05° 2θ and a counting time of 2.5 s/interval.

3.2.2.2 Stable isotope analyses (δ^{13}C, δ^{18}O and δ^{34}S)

Calcite crust from Provalata Cave, with a presumed thermal origin, was sampled for stable isotope δ^{13}C and δ^{18}O analyses. The sample was collected from the ceiling of a small channel emerging from the north part of the First Room. The δ^{13}C and δ^{18}O stable isotope ratios were measured at the Stable Isotope Laboratory at Saint Louis University (Department of Earth and Atmospheric Sciences), Missouri, USA. The isotopic ratio is given in per mil (‰), according to VPDB international standard, with analytical error of 0.03 and 0.06 ‰ for δ^{13}C and δ^{18}O, respectively.

The sulfur isotope ratio of cave gypsum was analyzed at the Institute of Mineralogy and Geochemistry of the University of Lausanne using a Carlo Erba 1108 elemental analyzer (EA) connected to a Thermo Fisher (Bremen, Germany) Delta V isotope ratio mass spectrometer (IRMS) that was operated in the continuous helium flow mode via a Conflo III split interface (EA-IRMS). The stable isotope composition of sulfur is reported in the delta (δ) notation as the per mil (‰) deviation of the isotope ratio relative to known standards: δ = [(Rsample − Rstandard)/Rstandard] × 1000, where R is the ratio of the heavy to light isotopes ($^{34}S/^{32}S$). The sulfur standard is the Vienna Cañon Diablo Troilite (VCDT). The reference SO_2 gas was calibrated against the IAEA-S-1 sulfur isotope reference standard (Ag_2S) with a $\delta^{34}S$ value of −0.3 ‰. The overall analytical reproducibility of the EA-IRMS analyses assessed by replicate analyses of three laboratory standards (barium sulfate, with a working $\delta^{34}S$ value of +12.5 ‰; pyrite Ch, +6.1 ‰; pyrite E, −7.0 ‰) is better than ± 0.2 ‰ (1 SD). The accuracy of the $\delta^{34}S$ analyses was checked periodically by analyses of the international reference materials IAEA-S-1 and IAEA-S-2 silver sulfides (0.3 ‰ and +22.7 ± 0.2 ‰, respectively, values from IAEA-Catalogue and Documents) and NBS-123 sphalerite (+17.09 ± 0.31 ‰, value from NIST-Catalogue and Documents).

3.2.2.3 Fluid inclusion analysis (δD and $\delta^{18}O$)

Sample of the calcite crust covering the wall in northern part of First Room in Provalata Cave was analyzed also for fluid inclusions by Yuri Dublyansky at the Institute of Geology, University of Innsbruck in Austria. Double-polished sections for fluid inclusion petrography observations were prepared employing low-speed precision sawing and polishing, which minimize thermal and mechanical stresses on the samples.

To analyze the isotopic composition of water trapped in fluid inclusions (δD and $\delta^{18}O$), samples were crushed in a heated crushing cell (Dublyansky 2012). After cryogenic focusing, the water was transported by He flow into the high-temperature reactor of the TC/EA unit (Thermo Fisher) and pyrolized into H_2 and CO at 1400 °C. The evolved gases were separated in a chromatographic column and analyzed using a Thermo Fisher Delta V Advantage isotope ratio mass spectrometer. Analytical precision was better than 1.5 ‰ for δD and ca. 0.5 ‰ for $\delta^{18}O$ (1 σ). For a detailed description of the method, see Dublyansky and Spötl (2009).

3.2.2.4 $^{40}Ar/^{39}Ar$ Dating

Samples of alunite and jarosite (pale yellow sand) from Provalata Cave were dated by the $^{40}Ar/^{39}Ar$ method at the New Mexico Geochronology Research Laboratory in Socorro, New Mexico, USA. Two aliquots of each sample were analyzed, one unwrapped and one wrapped in Ag with a platinum crimp. The second analysis was not a complete degassing. Results were similar for both the alunite and jarosite, but some higher step ages were apparent at the end of degassing, indicating minor to trace amounts of contamination from another older phase. Because of this, the results are considered maximum ages. Actual crystallization ages could be slightly younger.

3.2.2.5 Paleomagnetic dating

56 samples from a profile of cave sediments in Budimirica Cave were collected for paleomagnetic dating using sampling methodology described by Zupan Hajna et al. (2008).

Samples were analyzed at the Institute of Geology, Academy of Sciences of the Czech Republic (Bosak et al. 2013). Oriented hand samples were collected from individual horizons. Sediments were sampled to small plastic cubes 20 × 20 × 20 mm. In the laboratory, they were measured on the JR-6A spinner magnetometers (Jelínek 1966). Totally, 56 specimens were demagnetized by the alternating field procedures, up to the field of 100 mT in 10–13 steps. The LDA apparatus (AGICO, Ltd.) was employed for AF demagnetization. The remanent magnetization (RM) of specimens in their natural state (NRM) is identified by the symbol M. Graphs of normalized values of $M/M_o = F(H)$ were constructed for each analyzed specimen (Fig. 5.34). Volume magnetic susceptibility (MS) was measured on a KLY-4 kappa-bridge (Jelínek 1973). The separation of the respective remanent magnetization components was carried out by multi-component Kirschvink analysis (Kirschvink 1980). The statistics of Fisher (1953) was employed for the calculation of mean directions of the pertinent remanence components derived by the multi-component analysis.

3.2.3 *Water Analyses*

Water from springs Gugjakovski Izvori, Karsi Podot, and Melnica was sampled and analyzed for basic physical and chemical parameters at the Center for Public Health in Prilep, Macedonia.

Field measurements of pH, EC, and temperature of some springs and cave streams were later done with a HI 98129 (Hanna Instruments) multi-parameter tester.

3.2.4 *Cartographic Methods*

Karst rock outcrops, together with other geological data, were digitized from basic geological maps in 1:100,000 scale, sheets Vitolište, Kavadarci, Kožuf, and Prilep (Dumurdžanov et al. 1976; Hristov et al. 1965; Rakićević et al. 1965; Rakićević and

Pendžerkovski 1970), as well as unpublished geological maps in 1:25,000 scale (Geological survey Skopje) using Global Mapper software. Aster GDEM data, version 2 (Meyer et al. 2012), was used for terrain analysis and representation in maps.

Digitized data was used to produce geological, karst, and general geographical maps of the research area. Data from geological maps were also used to interpret extension of paleovalleys in Vitačevo plateau.

Digitalization was done in Global Mapper, and final maps were produced in Esri ArcGIS Map 10 and Golden Software Surfer 11.

Morphometric analysis of karst surface (slope and elevation distribution) was done using the Spatial analyst tool in ArcGIS Map 10.

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Chapter 4
Hypogenic Cave Development

Hypogenic karstification has been registered in three localities in the researched area: *Melnica*—in the NE part of Mariovo Basin, west foothill of Kozjak Mt, the northern margin of the small Vitolište graben; *Podot*—north from Melnica, in Crna Reka Valley; and *Kožuf*—between the southeast foothill of Kozjak Mt, and northwest foothill of Kožuf Mt (Fig. 4.1).

Caves have been found in Melnica and Podot localities, with cave development attributed to thermal waters and sulfuric acid speleogenesis. In Kožuf locality, hypogenic caves were not found, but several thermal springs emerging from carbonate rocks indicate that karstification is ongoing in deeper parts of the karst system.

4.1 Melnica and Podot Thermal Caves

Melnica Karst area is located in the eastern part of Mariovo Basin, on the west foothill of Mt. Kozjak. Melnica karst encompasses the area between Pantelejmon (1344 m) and Gola Skrka (1187 m) mountain peaks, including the plateau area between Manastir, Bešište, and Polčište villages. In the middle part, this area is cut by the superimposed valley of Buturica River, with its tributary Polčiška Reka (Figs. 4.2 and 4.3).

This area belongs to the Pelagonian Massif, with mountain parts developed in pre-Cenozoic rocks with Neogene and Quaternary deposits filling the Mariovo graben. The pre-Cenozoic rock formations are part of the Veprčani Monocline, starting with Precambrian gneiss rocks to the west, with some Paleozoic granitoid intrusions, overlain by Precambrian dolomitic marbles. To the east, the Precambrian formation is overlain by Cambrian rocks, starting with phyllito-micaschists in the southern parts covered by calcitic marbles, while in the northern parts (north of Buturica Valley) the calcitic marbles lie directly on the Precambrian dolomitic marbles, with some schist lenses found close to the contact with them. To the east, they are covered by Cretaceous (Senonian) rocks, starting with clastic rocks, followed by a thick limestone formation. This whole complex (Veprčani Monocline) has NNW–SSE direction and dips to the ENE by 25–50° (Dumurdžanov et al. 1976).

M. Temovski, *Evolution of Karst in the Lower Part of Crna Reka River Basin*,
Springer Theses, DOI 10.1007/978-3-319-24547-8_4

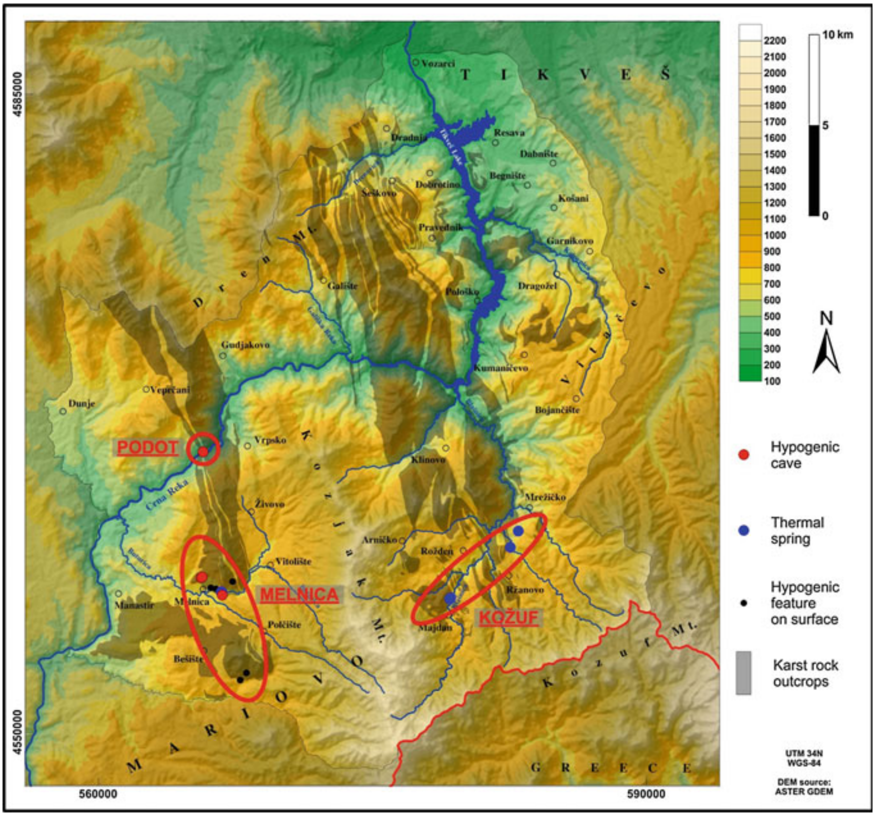


Fig. 4.1 Karst areas with hypogenic speleogenesis

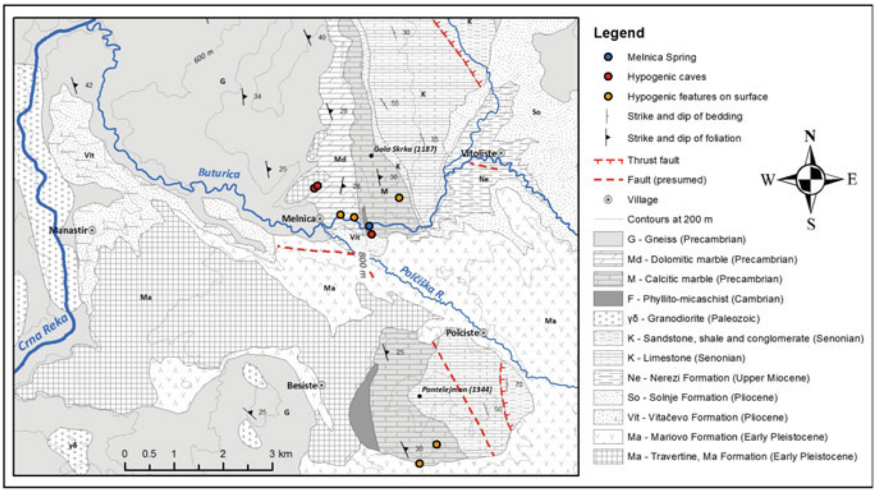


Fig. 4.2 Geological setting of Melnica karst area. Geological data after Dumurdžanov et al. (1976), Geološki Zavod—Skopje, unpublished

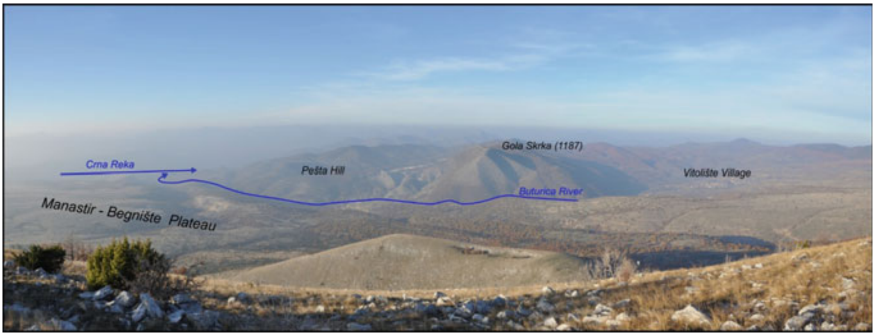


Fig. 4.3 Panoramic view from Pantelejmon (1344 m) to the north, with a look of Manastir–Bešište plateau, Buturica Valley, Pešta Hill, and Skrka (1187 m), photograph by M. Temovski

Overprinted on the pre-Cenozoic formation, between Pantelejmon and Gola Skrka, lays the Mariovo graben. It yields deposits of Miocene, Pliocene, and Early Pleistocene age, deposited in a lacustrine to fluvial environment. Four sedimentary formations are recognized in Mariovo Basin (Dumurdžanov et al. 2004):

- Nerezi Formation (Upper Miocene)—gravel and sandstone; siltstone and silty claystone that grades upward into claystone and coal; and siltstone and sandstone followed by a hiatus.
- Solnje Formation (Pliocene)—poorly stratified gravel and sandstone, continuing to:
- Vitačevo Formation (Pliocene)—stratified tuff overlaid by sandstone and gravel interbedded with beds of diatomite, tuff, and sandy claystone; travertine deposits, tuff-agglomerate, and sandstone.
- Mariovo Formation (Pleistocene)—pyroclastic rocks with nine travertine layers and a 20-m-thick travertine deposit on top.

In Pleistocene, the area was affected by the general uplift of central Balkan Peninsula, as well as the subsidence and shaping of the present Aegean Sea, which influenced draining of the Mariovo Lake (as late as Middle Pleistocene; Dumurdžanov et al. 2005), with Crna Reka and its tributaries establishing its fluvial basin. Buturica River then incised its valley first in the Mariovo Basin deposits, then forming the superimposed valley in the pre-Cenozoic rocks of Veprčani Monocline. The plateau area between Manastir and Bešište villages is of sedimentary origin, covered by travertine deposits, and is largely preserved, affected by fluvial erosion only in the northern and southern parts (by Crna Reka, Buturica, and Satoka river valleys).

Three caves are found in Melnica karst area, two of which are developed in Pleistocene carbonate conglomerates (Melnička Peštera 1 and Melnička Peštera 2) and Provalata Cave is developed in Cambrian calcitic marbles. Beside them, remnants of thermal karstification can be seen on surface: below Provalata Cave, along the valley of Buturica River; at Gumnište and Crveno Gumnište localities between Provalata Cave and Melnička Peštera 1 and 2; at Čavkarnik locality, on the southern foothill of Pantelejmon Mt; as well as the thermal vents Uškova koliba and Skrka located on the southern slopes of Pantelejmon (1344 m) and Skrka (1187 m).

Podot area is located to the north of Melnica area, in Crna Reka Valley, in the same Veprčani Monocline. It is developed in Quaternary travertine deposits, covering the pre-Cenozoic rock formations (Figs. 4.4 and 4.5). The pre-Cenozoic formation is quite thinned here, changing from Precambrian gneiss, through dolomitic marbles, Cambrian calcitic marbles, to Cretaceous (Senonian) clastic rocks and limestones in only 300 m distance. As in Melnica, the pre-Cenozoic formation is dipping to the ENE by 30–50°. Both the travertine deposits and the older rocks are cut by Crna Reka Valley.

Between Podot locality and the confluence of Gugjakovska Reka with Crna Reka 4 km downstream (Figs. 4.6 and 5.50), there are remnants of terraces as well as clastic and travertine deposits mainly located on the right side of the valley. The clastic deposits (sand, silt, and gravel) are considered as Pliocene (Solnje Formation), and the travertine deposits are as Pleistocene (Mariovo Formation) by correlation with similar deposits in Mariovo Basin (Dumurdžanov et al. 1976, 2003). The clastic deposits are found above 400 m up to 600 m a.s.l. (Gramos, Ramnište, Volčja Jama) with the travertine deposits overlain onto them, ranging from 500 m up to 650 m elevation (Gramos, Milevi Nivi, Ramnište), and carbonate conglomerates with tufa also found above them at Peštera (700–750 m) and Vrlalnikot (700–800 m) localities. The travertine deposits in Mariovo Basin, which are found from 550 to 1000 m elevation, are considered as the topmost formation of the lake system, deposited in shallow lacustrine environment (Dumurdžanov et al. 2003), before draining of the lake and onset of fluvial drainage.

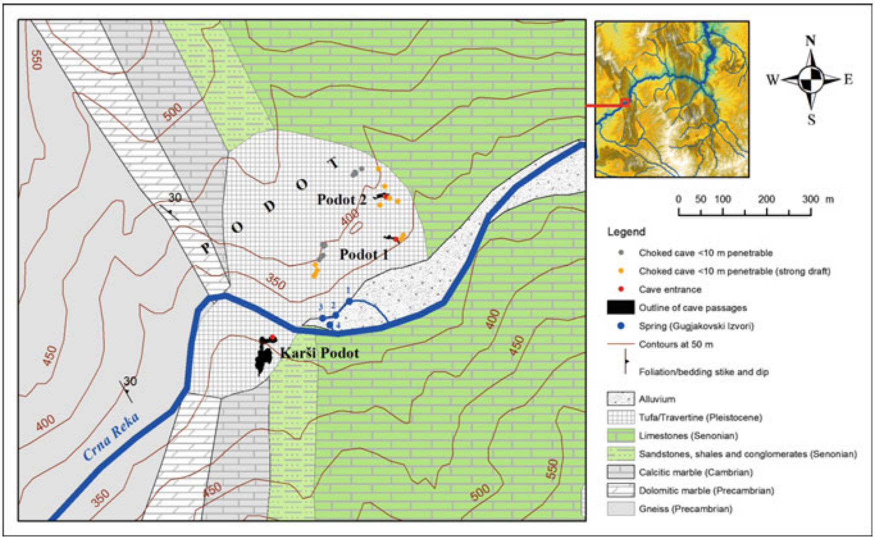


Fig. 4.4 Geological characteristic and location of caves and springs in Podot locality. Geological data modified after Dumurdžanov et al. (1976), Geološki Zavod—Skopje (unpublished)

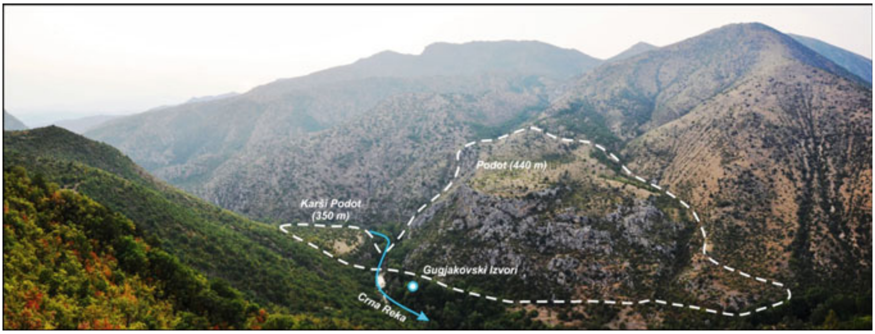


Fig. 4.5 View from the east to Podot locality in Crna Reka Valley. Travertine deposits are outlined by dashed line. Photograph by M. Temovski

These travertine deposits are micritic, as in Mariovo Basin, sub-horizontal, except at Milevi Nivi, where they are dipping to the south by 30°. Here it looks that the travertine deposits are cut by WSW–ENE fault, with the southern block uplifted. This fault is not clearly expressed, but small karst depression is formed along this fault in the travertines, and fragments of travertine deposits are found in the southern block up to 800 m elevation, along the steeply sloping valley side.

The sub-horizontal surfaces at Milevi Nivi (620 m) and Gramos (570–590 m) are likely depositional. At Milevi Nivi, smaller remnants of a terrace cut the travertine deposits at 565 m, and in clastic deposits at Ramnici below Gramos (515 m), with remnant of terrace (540 m) also cutting travertine and clastic deposits at Ramnište locality.

Travertine deposits are also found at lower elevation in Podot locality, although they are quite different from the micritic travertine deposits at higher elevation in a

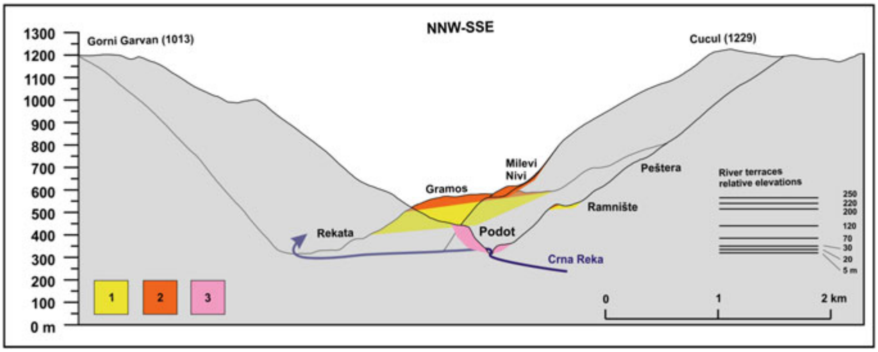


Fig. 4.6 Cross section of Crna Reka Valley at Podot locality and downstream areas with Pliocene–Pleistocene deposits and river terraces: *1* sand, silt, and gravel of Pliocene Solnje Formation; *2* travertines of Pleistocene Mariovo Formation; *3* Younger Pleistocene travertines: tufaceous limestones, tufa, and carbonate conglomerates

way that they are mostly bioconstructed with various encrusted plants. They are composed of tufaceous limestones and tufa, with some carbonate breccia–conglomerates in them composed of marble and limestone fragments. Two terraces are found in these deposits, one at 440 m (Podot) and the other at 350 m (Karši Podot).

Downstream from Podot locality there are travertine deposits all along the 350-m terrace. Podot travertines are likely of younger Pleistocene age than the higher travertines, being deposited in a paludal environment in a stable period after aggradation in Crna Reka Valley. The travertines at the 350-m Karši Podot terrace are covering alluvial deposits, later cut by Karši Podot Cave. The high discharge Gugjakovo karst springs and the thermal spring in Karši Podot Cave, which are located in the travertine deposits close to the riverbed of Crna Reka, may have facilitated rapid deposition of calcium carbonate, building the thick travertine sequences. Beside the two terraces (at 440 and 350 m), conglomerate layers in the travertines indicate that their deposition may have occurred in several phases, connected to the evolution of the Crna Reka Pleistocene valley.

Based on the distribution of the Pliocene clastic deposits covered by Pleistocene micritic travertine deposits, as well as terraces cut in these deposits and the lower Podot travertine deposits and terraces, we can assume that the sub-horizontal areas (terraces) at Gramos and Milevi Nivi at 570–590 m and 620 m, respectively, represent lacustrine depositional surfaces, with terraces at 565 m (Milevi Nivi), 515 m (Gramos), and 540 m (Ramniste) cut later by Crna Reka in the travertines and clastic deposits after draining of the lake (Pleistocene). The Podot terraces at 440 m and 350 m are fill terraces, formed after change of incision and aggradation in Crna Reka Valley. Remnants of terraces are also found cut in limestone at elevation of 385 and 335 m opposite Dupkite caves, with the lowest terrace at 5 m above present Crna Reka riverbed, having Gugjakovo karst springs perched on it. The relative elevations of the preserved remnants of river terraces in and below the Pliocene–Pleistocene deposits therefore are at 250 m (Milevi Nivi), 220 m (Ramnište), 200 m (Gramos), 120 m (Podot), 70 m (Rekata), 30 m (Karši Podot), 20 m (Rekata), and 5 m (Podot and Rekata).

Caves are found in travertines on both terraces at Podot locality, with numerous cave entrances on Podot terrace, of which two were penetrable (Podot caves 1 and 2), while thermal Karši Podot Cave is located in Karši Podot terrace, developed in travertines, alluvial deposits, and dolomitic marbles.

4.1.1 Provalata Cave

Provalata Cave is located at the top of the southern slope of the superimposed valley of the Buturica River, with entrance at 823 m on the bottom of a collapse doline (Fig. 4.7). The cave is mostly formed in Cambrian marbles, with some (mostly upper) parts formed in marble breccia, which together with the underlying Precambrian dolomitic marbles and overlying Cretaceous rocks are dipping to the ENE by 25–50°, as part of the NNW- to SSE-oriented Veprčani Monocline.

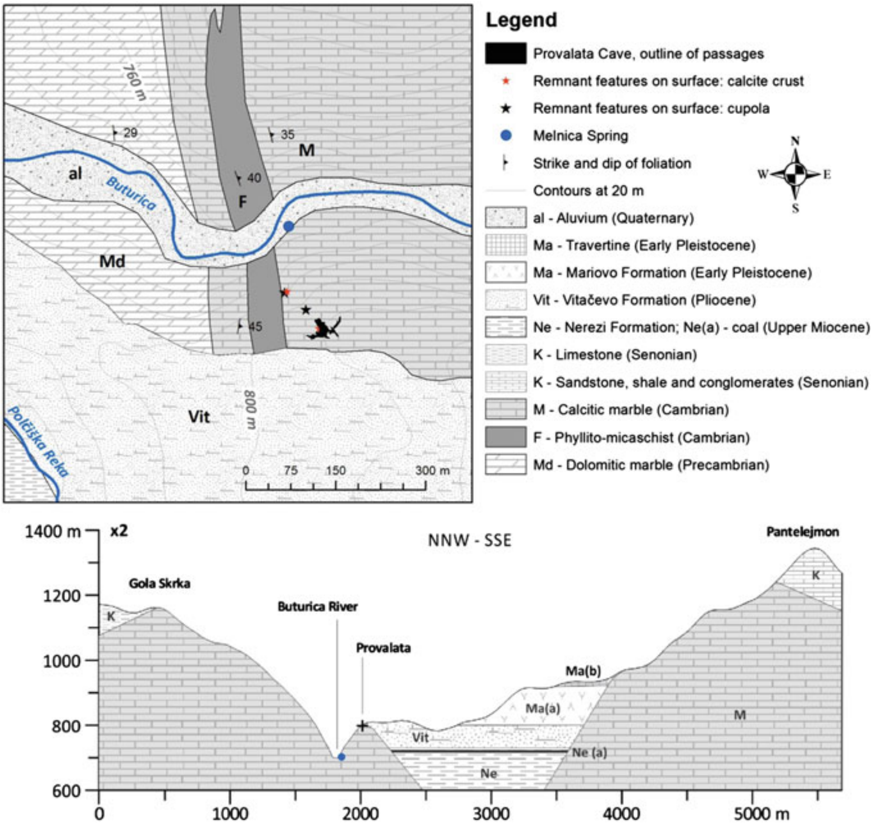


Fig. 4.7 Geological setting of Provalata Cave with surface features and Melnica spring

In the northern parts (north of Melnica area), these Cambrian marbles have lenses of phyllito-micaschists, and to the south they lie directly over Cambrian phyllito-micaschists (Dumurdžanov et al. 1976). One such lens is located just west of the cave (the cave is formed near the contact of marbles and phyllito-micaschists).

The cave was first explored by caving clubs Peoni and Ursus Speleos from Skopje, and first published in the scientific literature (as Cave Gulabinka) by Kolčakovski et al. (2004). They noted the presence of gypsum in the cave and suggested that the origin of the cave is connected with dissolution of marble by hydrothermal waters enriched with H_2S, although concluded that the cave is a fossil ponor cave.

4.1.1.1 Cave Morphology

Provalata is a ramiform cave with a total length of about 230 m and total depth of 24 m. There are two major rooms (First and Second) with more or less vague (due to collapse) outlines, and two main passages (Lower and Upper) with more distinct (fracture guided) morphology (Fig. 4.8).

The most representative and common morphological features of the cave are cupolas and solution pockets (Fig. 4.9a, d). Cupolas vary in form and size, often

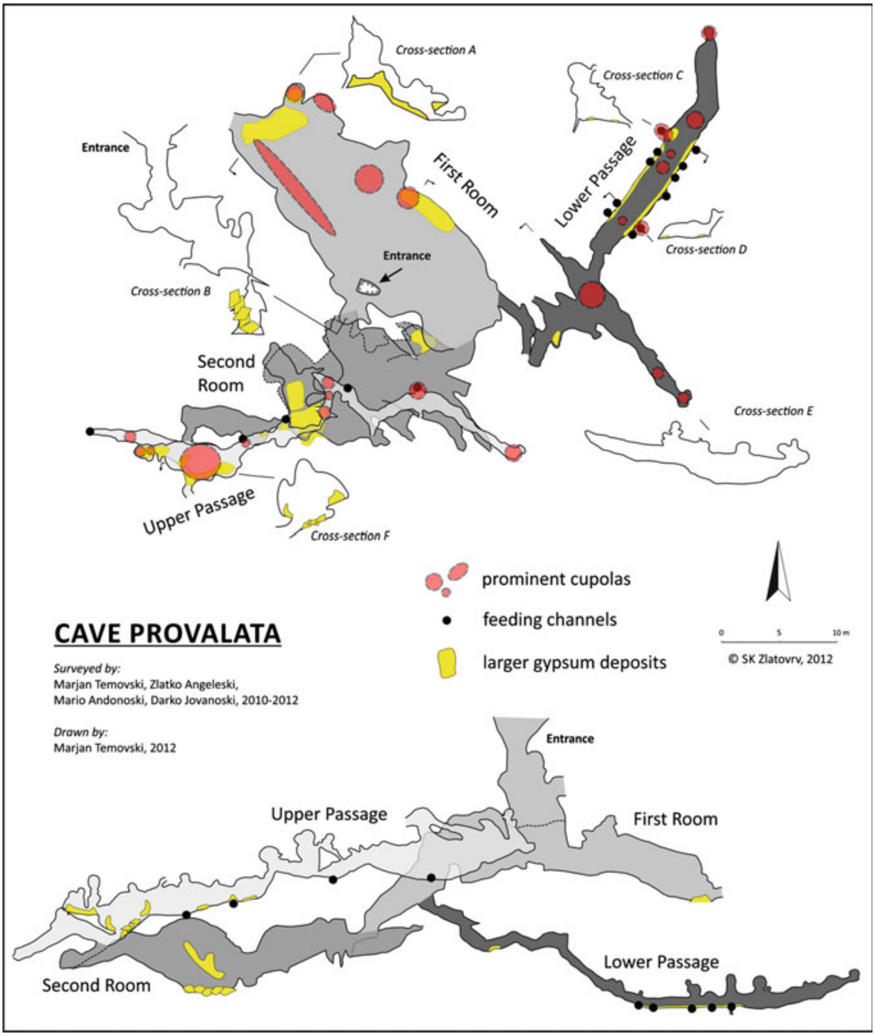


Fig. 4.8 Map of Provalata Cave with distribution of prominent cupolas, feeders, and larger gypsum deposits

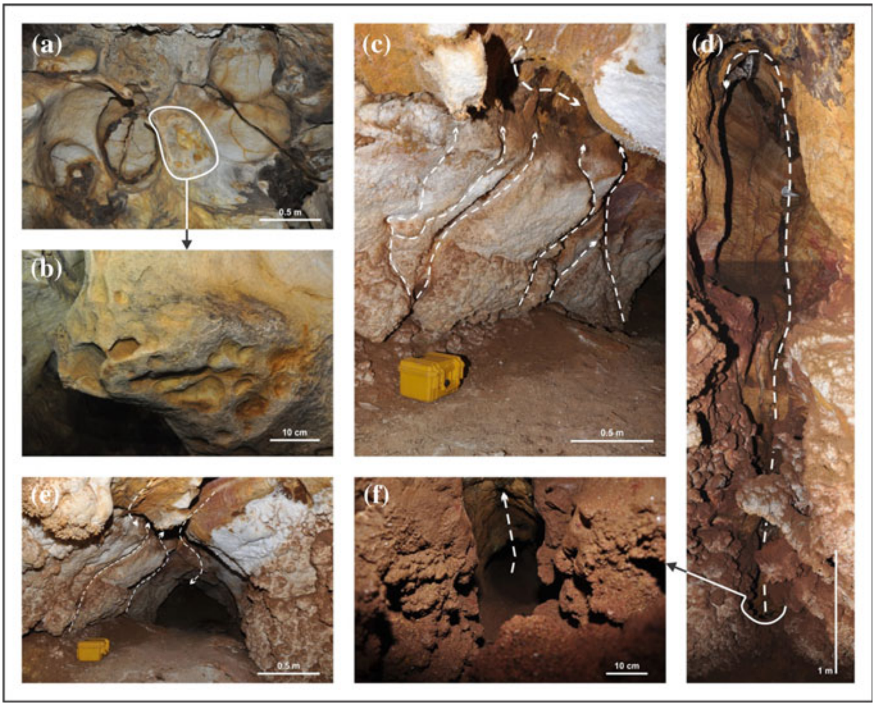


Fig. 4.9 Morphological features of Provalata Cave. **a** Cupolas, with some replacement pockets in between. **b** Replacement pockets on a pendant between cupolas. **c** Small half tube wall channels rising from feeders to a ceiling channel. **d** A suite of feeder leading to wall channel, rising to cupola at the top. Lower parts are covered with calcite popcorns (the *horizontal line* is due to photograph merging). **e** Continuation of the ceiling channel shown in C, with some wall channels joining it. **f** The feeder at the bottom of the rising suite at D. Photographs by M. Temovski

combining several cupolas overlain on another. They are most abundant in the Lower Passage as well as in the Upper Passage, but the highest ones (up to 7 m) are in the First Room, in marble breccia, as well as the entrance shaft which is a cupola formed in marble breccia opened to the surface by collapse. Two generations of cupolas and solution pockets can be clearly detected in the cave: one formed in marbles (or marble breccia) and covered with calcite crust, and the other formed in the calcite crust covering the first cupolas, or completely cutting through the calcite crust to the first generation cupola, and creating a secondary cupola or solution pocket.

Half tube wall channels are found in the Lower Passage, starting from feeders and leading to ceiling channels and cupolas (Fig. 4.9c, d, e, f); they are 10–15 cm wide, mostly vertical and sometimes bifurcating. They rise from discrete small feeding channels along the floor sides and lead to a central ceiling channel.

The ceiling channel is curvilinear in plan view, 30–40 cm in diameter, and continues to SW to the neighbor passage rising in a big cupola. The small feeding channels have similar dimensions as the wall channels they lead to. The passage wall between rising wall channels is covered with white calcite popcorn speleothems. The popcorn distribution starts from the central ceiling channel downwards, with popcorn speleothems covering some of the half tube passages as well (Fig. 4.9c). Small gypsum crusts are also covering lower parts of passage walls with detached crust covering the floor near the walls. Along some prominent fractures, the half tube wall channels lead to cupolas.

The genesis of this set of small feeding channels rising to half tube channels which converge in a central ceiling channel is attributed to condensation corrosion, with the feeding channels representing vents supplying the rising moist air. Rising vapor from the vents cools and condenses at the contact with wall in upper parts producing film runoff due to accumulation of condensation. Cooler air that sinks warms up and produces evaporation. This leads to condensation corrosion in the upper part, and evaporation–deposition in the lower part (Audra et al. 2007). The condensation corrosion is largest at the ceiling producing the central ceiling channel, with popcorns and replacement gypsum deposited below the ceiling channel along the passage walls due to evaporation. The ceiling channel then continues to SW to the neighbor passage rising to a big cupola developed in calcite crust.

Gypsum replacement pockets (cf. Galdenzi and Marouka 2003) can be found at several places with gypsum deposits already removed. In the Upper Passage, they are developed in marble between two cupolas (Fig. 4.9a, b), but replacement pockets formed in calcite crust can be also seen in the First Room. Their size ranges from few centimeters up to few decimeters in diameter.

On the basis of distribution and association with deposits, two sets of morphologies were identified and attributed to two separate speleogenetic phases: phreatic morphologies (cupolas) formed by cooling of rising carbonated thermal waters, covered with mammillary calcite crust (first phase); vadose morphologies (replacement pockets, second-generation cupolas and pockets, vents, half tube wall, and ceiling channels), formed by condensation corrosion by sulfuric vapors (second phase), with second-phase morphologies partly or completely imprinted onto the first phase morphologies.

4.1.1.2 Cave Deposits

A calcite crust (sample PR09), black to transparent, up to 0.5 m thick and highly corroded (Fig. 4.10e), is covering the walls and ceiling throughout the cave. In places it is completely corroded.

It covers various channel features with phreatic morphologies, such as cupolas, and solution pockets. The crust has mammillary morphology with mostly acicular calcite crystals. The morphology and thickness suggest formation by carbonic degassing in shallow thermal waters (Palmer 1991; Dublyansky 2000b; Audra 2009) preceding the clay infilling and sulfuric acid phase.

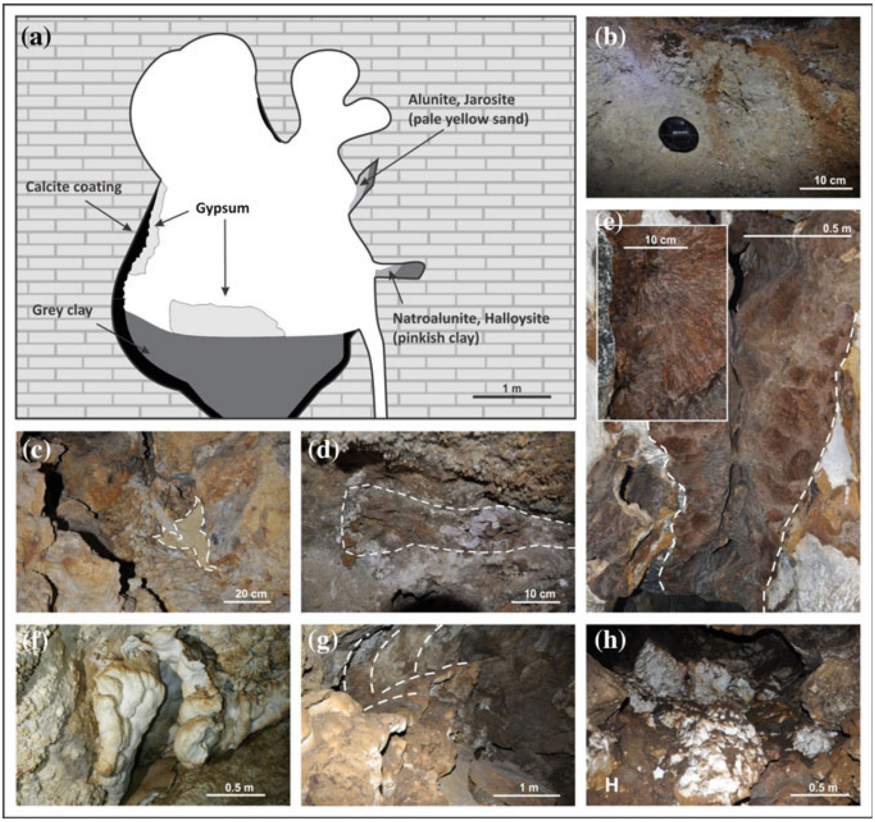


Fig. 4.10 Cave deposits in Provalata Cave. **a** Schematic cross section of sediments, showing stratigraphic relationships. **b** Gray clay (montmorillonite, kaolinite, sanidine, albite, muscovite, and quartz). **c** *Pale yellow* sand (alunite, jarosite, muscovite, and quartz). **d** *Pink clay* (halloysite-7Ä, natroalunite, muscovite, and quartz). **e** Corroded calcite crust. **f** Replacement gypsum crust. **g** Gypsum crust, detached from the wall. **h** Detached gypsum crust piled as gypsum blocks. Photographs by M. Temovski

Five samples from a ~20 cm cut through the calcite crust and marble host rock (Fig. 4.11) were collected for δ^{13}C and δ^{18}O analyses, two of which were from the weathered marble host rock (C1, C2) and three from the calcite crust (C3, C4, C5). All of the five samples have light δ^{18}O ratios (−12.7 to −10.4 ‰), but quite heavy δ^{13}C ratio (2.8–7.2 ‰). The values of δ^{18}O are within the typical range for thermal calcite (Dublyansky 2000b), but the values for δ^{13}C are quite high for the calcite (Table 4.3).

Fluid inclusion analyses of a sample from corroded calcite crust from the northern part of the First Room indicate deposition at moderate depth, and at temperatures lower than 50° (Dublyansky 2013, pers. comm.). The calcite is not a typical mammillary calcite, growing from many centers of nucleation, forming

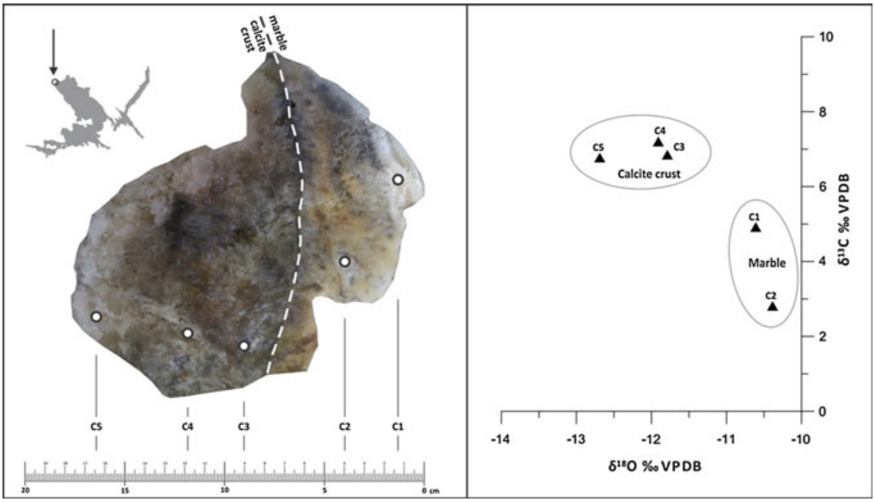


Fig. 4.11 Sample location and δ^{18}O and δ^{13}C values from calcite coatings and marble host rock

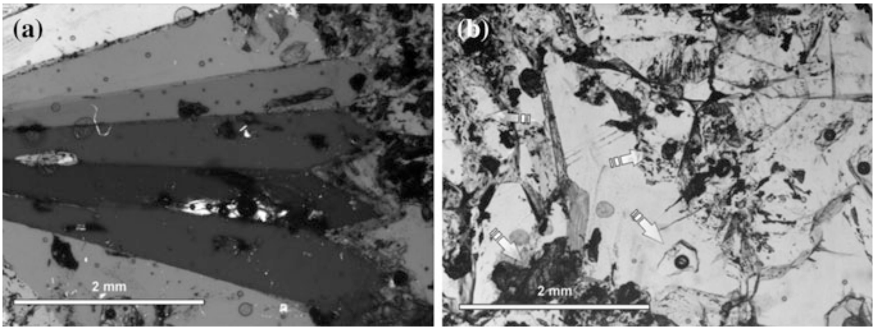


Fig. 4.12 Calcite fabrics from the calcite crust in Provalata Cave: **a** Palisade aggregates of crystals (crystal growth started at nearly the same nucleation point). **b** Aggregates of erratically oriented crystals (*arrow mark* intra-granular inclusions). (Dublyansky 2013, pers. comm.)

either palisade aggregates of crystals with high aspect ratios (length to width), or aggregates of rather erratically oriented crystals with smaller aspect ratios (Fig. 4.12). The character of the crystalline aggregate suggests growth in conditions of supersaturation and, possibly, of non-quiet hydrodynamics, which is not typical of a deposition in conditions of a lake (e.g., cave clouds), rather more consistent with conditions of a feeder of a karstic spring, discharging supersaturated water.

Stable isotope composition of water from fluid inclusions (Table 4.1) suggests meteoric character of the mineral-forming water (Dyblyansky 2013, pers. comm.).

Table 4.1 Results of measurements of stable isotopic compositions of fluid inclusion water from two replicates of the calcite crust from Provalata Cave. (Y. Dublyansky 2013, pers. comm.)

Sample ID	$\delta^{18}O$ (‰ SMOW)	$\delta^{2}H$ (‰ SMOW)	Sample weight (g)	Water content (μL/g)	Water amount (μL)
Prov_a	−12.0	−81.0	0.20	0.94	0.19
Prov_b	−11.9	−83.6	0.25	0.48	0.12

Gray clays (Fig. 4.10b) cover the lower parts of cave passages, but small patches of gray clay can be found filling parts of cupolas in the Upper Passage, suggesting a complete infilling of the cave at some time, and later removal. X-ray analyses (sample PR04) confirmed composition of sanidine, kaolinite, montmorillonite, albite, muscovite, and quartz. Considering the composition, its origin is likely related to the overlaying pyroclastic sediments (tuff) of the Mariovo Formation. X-ray analysis of a tuff sample from Sadevite locality (sample T01) nearby Provalata Cave showed composition of sanidine, kaolinite, montmorillonite, albite, biotite, and goethite. This is also suggested by results of X-ray analyses of clays from caves on the Vitačevo Plateau, formed in limestones covered by similar pyroclastic sediments (Sect. 5.1: Vitačevo Karst).

Fine-grained pale yellow sands can be found in the First Room, covering the walls and ceiling, and filling fractures (Fig. 4.10c). X-ray analyses of sample PR10 from the wall in the SE end of the First Room confirmed the presence of alunite, jarosite, quartz, and muscovite. $^{40}Ar/^{39}Ar$ dating of alunite and jarosite gave maximum ages of 1.6 and 1.46 Ma, respectively (Table 4.2).

Pink clay was found on the wall at the entrance part of the Lower Passage (Fig. 4.10d). X-ray (sample PR08) confirmed a composition of halloysite-7Ä, natroalunite, muscovite, and quartz. It has a white to pale pink color and it is dehydrated, with a waxy texture.

Gypsum deposits (sample PR05) are the most characteristic cave deposits. They are found in every part of the cave, except some places which have periodic vadose percolation, where gypsum most likely was dissolved.

Gypsum deposits are present as replacement crusts up to 40 cm thick (Fig. 4.10f), or detached replacement gypsum crusts (Fig. 4.10g) that accumulated in gypsum blocks (Fig. 4.10h). Preliminary stable isotope analyses (Table 4.3) of sulfur from cave gypsum (2 samples) gave $\delta^{34}S$ values of −2.3 to −1.9 ‰.

The origin of H_2S involved in the sulfuric acid speleogenesis of Provalata Cave might be attributed to the coal deposits, if we consider the proximity of the coal deposits in Mariovo Basin to Provalata Cave, and the fact that no sulfate rocks have been found in the stratigraphy in this part of Macedonia.

Sulfur in the coals from Mariovo Basin is found as organic sulfur, pyrite, and gypsum (Lerouge et al. 2007). Gypsum in coals can be a weathering product of pyrite when occurring closely connected with pyrite, while gypsum in fine layers associated with calcite is considered to be formed by crystallization of calcium and sulfate ions dissolved in the pore water during the sedimentation (Lerouge et al. 2007). Total sulfur content in the coals is low, 1.18–1.3 % (Raleva et al. 2012),

Table 4.2 Summary of $^{40}Ar/^{39}Ar$ results from Provalata Cave

Sample	Lab #	Irradiation	Mineral	Age analysis	Steps/analyses	Age (Ma)	**±2σ**	MSWD	Comment
Provalata-a	60, 983	247	Alunite	Laser step-heat	3	1.60	0.05	1.03	Maximum age
Provalata-j	60, 984	247	Jarosite	Laser step-heat	3	1.46	0.03	1.19	Maximum age

Table 4.3 Stable isotope properties of marble, calcite crust ($\delta^{18}O$, $\delta^{13}C$), gypsum, and vitrinite ($\delta^{34}S$) from Provalata Cave and nearby coals

Location	Sample	$\delta^{34}S$ (‰)	$\delta^{18}O$ (‰)	$\delta^{13}C$ (‰)
Coal seams nearby Vitolište village (Lerouge et al. 2007)	Gypsum (7 K)	17.2		
	$MgSO_4$ (7 K)	14.9		
	Gypsum (8L)	17.3		
	Gypsum (8R)	8.5		
	Vitrinite (8R)	13.2		
	Vitrinite (8 M)	5.4		
Provalata Cave	Cave gypsum (P4)	−2.1		
	Cave gypsum (P5)	−2.2		
	Marble (C1)		−10.6	4.9
	Marble (C2)		−10.4	2.9
	Calcite crust (C3)		−11.8	6.8
	Calcite crust (C4)		−11.9	7.2
	Calcite crust (C5)		−12.7	6.7

with high sulfur content in macerals (1.2–2.3 %), showing that measured sulfur can be attributed to organic matter (Lerouge et al. 2007). $\delta^{34}S$ values are ranging from +8.5 to +17.3 ‰ for gypsum in coal seams and from +5.4 to +13.2 ‰ for vitrinite (Table 4.3).

Considering the complexity of sulfur isotopic evolution that can derive from generation of H_2S by bacterial sulfate reduction or thermochemical sulfate reduction, depending on paucity and/or supply of hydrocarbon electron donors and sulfate (Wynn et al. 2010), as well as modification due to contribution of secondary source of S (ex. pyrite, Onac et al. 2011), further stable isotope analyses of cave gypsum, coal, and sulfate of Melnica spring are necessary to determine the origin and evolution of sulfur participating in the sulfuric speleogenesis of Provalata Cave.

Calcite popcorns are covering the corroded calcite crust at various places. Also small flowstone deposits are developing in a few places in the cave as a result of late vadose percolation.

4.1.1.3 Remnant Features on the Surface

Remnants of cupolas and solution pockets are also found on the surface, exposed by denudation, in the small gully in the gorge following the contact of marbles and the phyllito-micaschist lens. Remnants of a similar calcite crust can be found on the surface, near the entrance of the cave (Figs. 4.7 and 4.13).

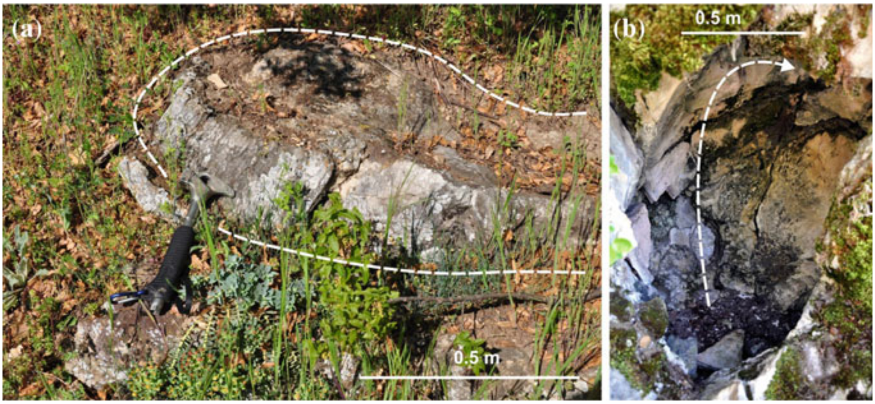


Fig. 4.13 Remnant cave features on surface near Provalata Cave: **a** Calcite crust close to the entrance of Provalata Cave. **b** Cupola exposed on Buturica Valley slope, close to the contact of marbles with phyllito-micaschist. Photographs by M. Temovski

4.1.1.4 Melnica Spring

In 2010, a small spring in the riverbed of the Buturica River (Fig. 4.7), just below Provalata Cave (at 715 m), reemerged after (according to the local population) ~40 years of inactivity. The spring is discharging at several locations along the left bank of Buturica River, near the contact of Cambrian marbles with a lens of phyllito-micaschists. Considering that both Provalata Cave and the spring are located along the contact of marbles with phyllito-micaschist lens, and remnants of cupolas with calcite are found in between, along the same contact, the spring might be the present discharge point of the same system that formed Provalata Cave.

Preliminary analysis of some physical and chemical parameters shows slightly thermal waters (20–22 °C), with a high amount of dissolved solids, EC values from 891–972 μs/cm, and slightly acidic pH ranging from 6.62 to 6.9 (Table 4.4).

If Melnica spring is considered as a late stage phase of Provalata Cave evolution due to incision of Buturica River, then the question of cease of sulfuric acid dissolution remains. If origin of H_2S for Provalata Cave sulfuric acid speleogenesis is attributed to the nearby coal deposits, then the sulfuric phase can be a temporal manifestation, which ceased after lowering of water table below the elevation of the coal field. Further analysis of Melnica spring chemistry, cave gypsum, and Mariovo coal deposits is needed for this hypothesis to be tested.

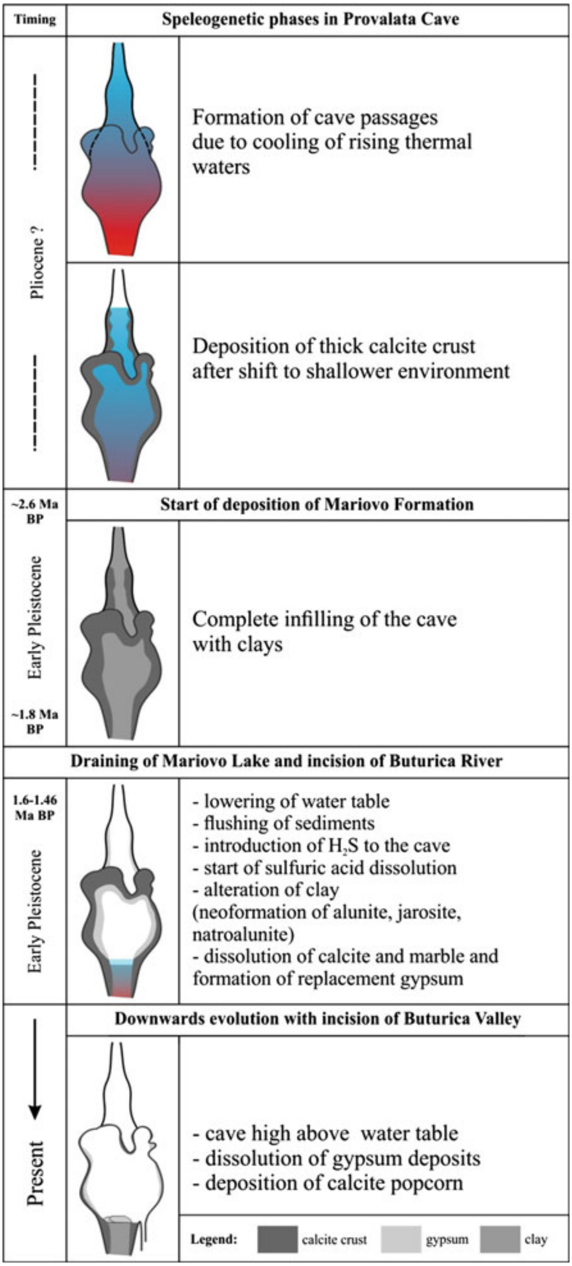
4.1.1.5 Speleogenesis

The thick mammillary calcite crust was deposited in shallow phreatic environment by thermal waters, filling previously formed passages and convectional features (cupolas, pockets) formed in a previous phase in deeper parts of the thermal system due to cooling effect of rising carbonated thermal waters.

Table 4.4 Some basic physical and chemical parameters of the Melnica thermal spring: temperature (T) in °C, ion concentrations in mg/l, specific electric conductivity (EC) in μS/cm, and total hardness (TH) in dH

Date	T	pH	EC	TH	HCO_3	Ca	Mg	NO_3	Cl	Fe	SO_4	Measured in
21/07 2012	22	6.9	891	18.6	634.4	105.7	34.64	3.18	8	0	14.7	Lab
24/11 2012	21.5	6.64	945	/	/	/	/	/	/	/	/	Field
27/01 2013	21	6.74	892	/	/	/	/	/	/	/	/	Field
09/02 2013	20.6	6.62	914	/	/	/	/	/	/	/	/	Field
24/02 2013	21.1	6.7	972	/	/	/	/	/	/	/	/	Field

The cave was later completely filled with clay deposits (Fig. 4.14), originating from weathering of pyroclastic sediments most likely from Mariovo Formation, which were deposited in a lacustrine environment in Early Pleistocene (Dumurdžanov et al. 2004).



Timing

Speleogenetic phases in Provalata Cave

Pliocene ?

Formation of cave passages due to cooling of rising thermal waters

Deposition of thick calcite crust after shift to shallower environment

~2.6 Ma BP

Start of deposition of Mariovo Formation

Early Pleistocene

Complete infilling of the cave with clays

~1.8 Ma BP

Draining of Mariovo Lake and incision of Buturica River

1.6-1.46 Ma BP

Early Pleistocene

- lowering of water table
- flushing of sediments
- introduction of H_2S to the cave
- start of sulfuric acid dissolution
- alteration of clay (neoformation of alunite, jarosite, natroalunite)
- dissolution of calcite and marble and formation of replacement gypsum

Downwards evolution with incision of Buturica Valley

Present

- cave high above water table
- dissolution of gypsum deposits
- deposition of calcite popcorn

Fig. 4.14 Schematic representation of the evolution of Provalata Cave

Presence of alunite, jarosite, natroalunite in altered clay deposits, combined with large deposits of gypsum found as replacement crusts or gypsum blocks, and morphological features such as gypsum replacement pockets point toward dissolution by sulfuric acid.

Gypsum replacement crusts in sulfuric caves are considered to be of subaerial origin by condensation of H_2S-rich vapors on carbonate rock (Galdenzi and Marouka 2003; Palmer 2007, 2013). In Provalata Cave, they are found covering walls in several locations, with best examples found in the Second Room and Upper Passage, where detached crust is found piled below still standing wall crusts.

Morphological features such as pockets and cupolas developed in calcite crust, as well as through the calcite crust in the marble host rock suggest second phase of dissolution after the deposition of the calcite crust. Based on their association with gypsum deposits (gypsum replacement crusts and replacement pockets found on calcite crust), their origin is attributed to dissolution by sulfuric acid. At places, these second-generation cupolas are also connected to feeders and wall and ceiling half tube channels. Such features are often indicative of convective cells in phreatic conditions (the "morphological suite of rising flow," Klimchouk 2007), but can be also formed by condensation corrosion above the water table, by highly corrosive vapors (Audra 2007; Audra et al. 2007, 2009d; Palmer 2013). The rising suite in the Lower Passage was produced by condensation corrosion with the small feeding channels representing vents supplying rising moist air, with condensation corrosion producing half tube wall and ceiling channels and popcorn speleothems and gypsum crust depositing in the lower parts due to evaporation.

The sulfate minerals (alunite, natroalunite and jarosite) are clear evidence of alteration of clay by sulfuric acid (Polyak and Provencio 2001). As pointed by Palmer (2007, 2013), alunite is formed by alteration of clay by low-pH (less than 4) sulfuric acid. Sulfuric acid is most likely to reach such low pH needed to produce the alunite only in vadose moist droplets on clay (Palmer 2007, 2013). The distribution of deposits and morphology connected with the sulfuric acid speleogenesis indicates that most of the dissolution in the sulfuric phase was above the water table by condensation corrosion. Typical water table morphology such as corrosion tables, flat roof notches (Audra 2007; Audra et al. 2009d) should be expected to develop in such environment. This was not evident in Provalata Cave and the absence of such morphology might be due to the presence of the formerly deposited gray clay. Covering the passages floors, the clay might have shielded the calcite crust or marble host rock from aggressive sulfuric waters or such morphology is located in a lower (presently not accessible) part of the cave.

$^{40}Ar/^{39}Ar$ dating of alunite and jarosite from the First Room gave maximum age of 1.6 and 1.46 Ma. Considering their formation in a vadose environment, such condition could have been achieved only after the draining of Mariovo Lake and incision of the valley of Buturica River.

Since last layers of tephra can be found in the travertine layers deposited in lacustrine environment as end part of Mariovo Formation, with volcanic activity in Kozjak (Kožuf) Mt. active from 4.0 ± 0.2 to 1.8 ± 0.1 Ma (Kolios et al. 1980) and with the oldest maximum age of cave alunite at 1.6 Ma we can place the draining of Mariovo Lake and onset of fluvial drainage somewhere between 1.8 and 1.6 Ma.

With further incision of Buturica River, cave features (cupolas, pockets, calcite crust) were exposed on surface on the valley slope, due to slope retreat. The low thermal Melnica Spring found below the cave in the riverbed is likely the present discharge point of the system.

Considering this, the calcite crust and the cave features covered by it, which represent the first thermal carbonic phase, formed before deposition of Mariovo Formation and are probably from Late Pliocene–Early Pleistocene age.

4.1.2 Melnička Peštera 1 and 2

Melnička Peštera 1 and 2 are located in a small flat hill called Pešta (meaning cave, or with caves), 1.5 km NW of Provalata (Fig. 4.15). The entrance of Melnička Peštera 1 is located in a cliff on the SE side of Pešta hill at 871 m, and the entrance of Melnička Peštera 2 is located 80 m to the SW at 868 m. Melnička Peštera 1 is more than 600 m long, with depth of 17 m, and Melnička Peštera 2 has total length of passages of 97 m with depth of 8 m. They both have SW–NE general direction. The caves were first explored in 2007 by caving clubs Zlatovrv—Prilep and Ursus Speleos—Skopje, exploring and mapping 170 m in Melnička Peštera 1, and only registering Melnička Peštera 2. In 2012, new passages were discovered in Melnička Peštera 1, of which 600 m were mapped with explored passages approx. close to 700 m.

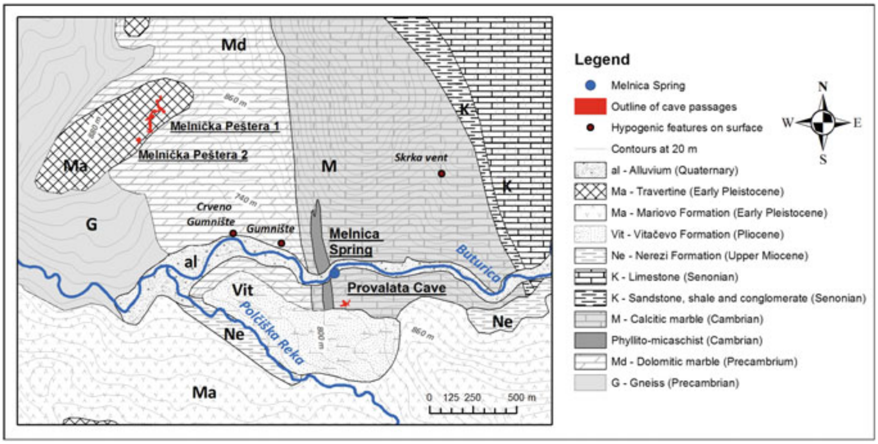


Fig. 4.15 Local geological setting of Melnica, with Provalata Cave, Melnica spring, Melnička Peštera 1 and 2, the thermally altered features on surface (Gumnište and Crveno Gumnište), and the inactive Skrka thermal vent

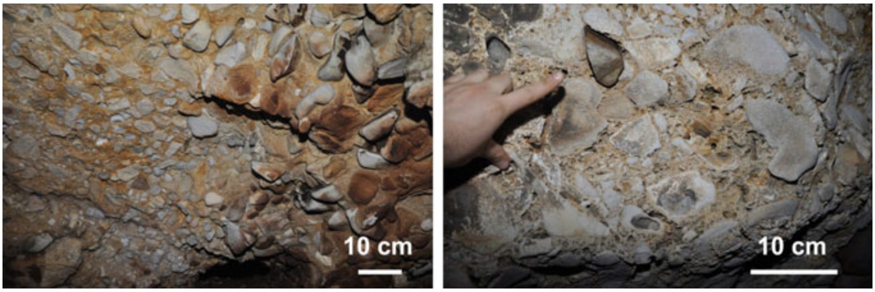


Fig. 4.16 Carbonate conglomerates from Melnička Peštera 1, with some quartz fragments (*right*) protruding from the corroded carbonate surfaces. Photographs by M. Temovski

Both are developed in carbonate conglomerates close to the contact with underlying dolomitic marbles. In Melnička Peštera 1, this contact with underlying dolomitic can be seen at two locations.

In the geologic literature (Dumurdžanov et al. 1976, 2003, 2004; unpublished geological maps in 1:25000 scale, Geological Survey Skopje), the rocks in which these caves are formed are described as lacustrine travertine deposit of Pleistocene age, deposited as topmost part of Mariovo Formation in Mariovo Basin. In fact in Pešta Hill, travertine deposits as described for the big travertine plateau between Manastir and Bešište villages can be seen only in upper part of the formation. Here, this formation is mostly composed of carbonate conglomerates that grade upward into travertine (Fig. 4.16).

These conglomerates can be found all along the Pešta Hill, and also to the north on the small Jančeva Peštera Hill, where a small few meter cave is also found. They covered far bigger area before erosion cut small valleys and dissected the plateau into small hills.

The conglomerates are mostly composed of marble pebbles, cobbles, and boulders with sizes varying from few cm up to 1 m, usually 5–20 cm. Marble fragments are of both dolomitic and calcitic marble. Small percent of non-carbonate rocks such as gneiss, schist, and quartz fragments are also present (Fig. 4.16). They are far less rounded, especially the quartz fragments. Cemented with carbonate matrix, the conglomerates act as a solid carbonate rock, although these have much higher primary porosity. At places, some marly and sandy layers can be found. The thickness of the formation, including the top travertine deposits, is 30–40 m.

Considering the location, deposited above the contact of Precambrian gneiss and marble, and the surrounding, the origin of the conglomerates is rather clear. They were transported from north by a paleostream and deposited in a fluvial to coastal lacustrine environment. The wide valley of Ramnobor, north from Pešta, is a remnant of this paleovalley, with present intermittent Ramnobor stream incising younger valley in it.

The conglomerates are cut by number of fractures in several directions. Some are gravitational and connected to cliff retreat; others are probably connected with the regional tectonic movements at the north margin of Mariovo Basin. The second group is usually with NE and ENE directions, characteristic of tectonics connected to the Kožuf–Kozjak volcanic centers to the south.

4.1.2.1 Melnička Peštera 1

Morphology

In plan view (Fig. 4.17), passages in Melnička Peštera 1 create a branchwork pattern with loops formed mostly because of collapse. Prominent noted fractures have ENE to NE, and NNW direction. Two were clearly seen (NW and NE), others are presumed from breakdown or passage morphology. Passages have irregular wall morphology.

In vertical dimension, passages are mostly horizontal with three notable levels, although the elevation of the upper one is most affected by collapse. The passages are developed slightly above the contact with the underlying dolomitic marbles, at places at contact with overlying marly layers. In the end of Chandelier Room and North Passage, the passages are developed at the contact, finishing with small crevices in dolomitic marbles.

Passages in cross section are mostly elongated in width, with vague morphology due to dense network of solution pockets, cupolas, spongework, and breakdowns (Fig. 4.18). Some have flat roof at contact with overlaying less permeable marly layers (as in Corridor Passage). At the end of Corridor Passage, as well as in Big Cupolas Room and on the east wall of Big Room, water level notches can be seen. They are best preserved on the SE wall of Corridor Passage, right before "The Door." Water level at same elevation can be determined by a shelfstone deposits in

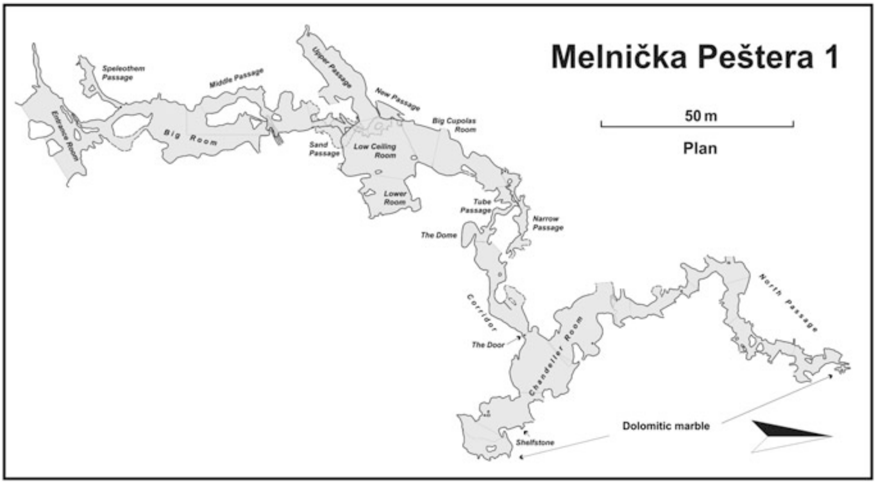


Fig. 4.17 Simplified map of Melnička Peštera 1. For more detailed cave map, see Appendix

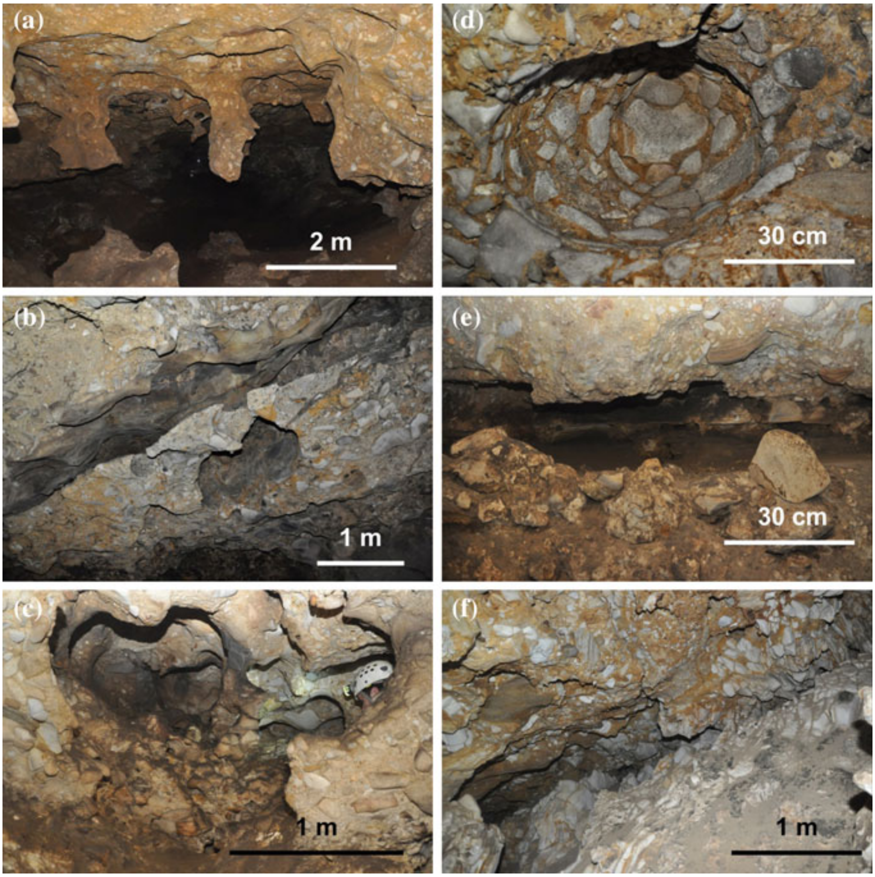


Fig. 4.18 Morphological features of Melnička Peštera 1: **a** Chandelier Room with pendants and cupolas. **b** Cupolas and pockets developed in conglomerates and calcite vein in the Big Room. **c** Spongework morphology at the beginning of Narrow Passage. **d** Cupola on the ceiling of Big Room. **e** Water table notch on the wall of Corridor Passage. **f** Southern end of Chandelier Room at the contact of conglomerates with underlying dolomitic marbles. Photographs by M. Temovski

a small niche on the NE wall of Chandelier Room. At the contact of passages, some wider rooms are located, such as the Chandelier Room, Low Ceiling Room, and Big Room.

On passage walls and ceilings, numerous solution pockets in various sizes can be seen. They are carved in carbonate fragments and matrix material with less soluble non-carbonate fragments pointing outward. They are best expressed in parts with larger carbonate fragments, more in calcitic marble than dolomitic marble. Some pockets are also developed in monocrystalline calcite veins as well in conglomerates. Some of these veins seem connected to fractures; others just fill out space between pebbles and are older than the cave, probably deposited at same time or soon after deposition of the conglomerates. In number of places, pockets are so dense and interconnected that create spongework morphology. Cupolas are found at several places and some have both solutional and breakdown morphology. They were probably formed by solution and later altered by breakdown (e.g., Big Cupolas Room). Some parts (e.g., The Dome) have circular form in plan and have dome-shaped ceiling with conical floor. Their origin is likely due to collapse, but some pockets and calcite coatings indicate also solutional origin. Pendants are found at number of places as remnant features between former solutional pockets and cupolas. Best examples are the so-called Chandeliers in the Chandeliers Room with stacked concave wall morphology.

Cave Sediments

There is not much cave sediments present in the cave. Close to the contact with dolomitic marble, dolomitic sand is found due to weathering of the marble. At most places, thin matrix residue clay is covering passages. Some pebbles, found in passage floors, are likely from collapsed conglomerate blocks. Breakdown blocks and debris are widespread throughout the cave, especially in the first part of the cave.

Secondary deposits found in the cave are shelfstone crust and calcite coatings (Fig. 4.19). Calcite coatings are the most intriguing ones. They completely cover the walls and ceiling in the Narrow Passage with needle-like calcite (or maybe aragonite), and are found covering fragments of walls in other locations, where they were either dissolved or removed by collapse. In the Big Cupolas Room, calcite coatings of orange color can be found covering the lower to middle parts of walls. At some places, small cups or pockets can be seen carved in them. In the small “Dome” passage, there are two calcite coatings, lower (older) yellowish, covered by white rhomohedral calcite coating. In the middle part of the North Passage, right after it bends to the east, on the ceiling there is a thick deposit of coating, composed of converging fans of needle-like carbonate mineral (calcite or aragonite), quite corroded with a spongework morphology.

The floor in the entrance part of the cave is covered with fine-grained sand and dust of eolian origin, mostly composed of weathered tuff cover, at places with sheep defecation deposits. Its thickness as registered in two pits dug by treasure hunters is more than 1 m.

Fragments of ceramic pottery are also seen at several places in the cave, mostly toward the entrance.

Typical vadose cave speleothems can be only seen in parts near the entrance, typically in the Speleothem Passage, covered with stalactites, stalagmites, and flowstone. In other parts of the cave, such speleothems are absent.

4.1.2.2 Melnička Peštera 2

Melnička Peštera 2 is smaller in size, but quite similar in morphology to Melnička Peštera 1. The cave has triangular form in plan, with steep entrance passage leading

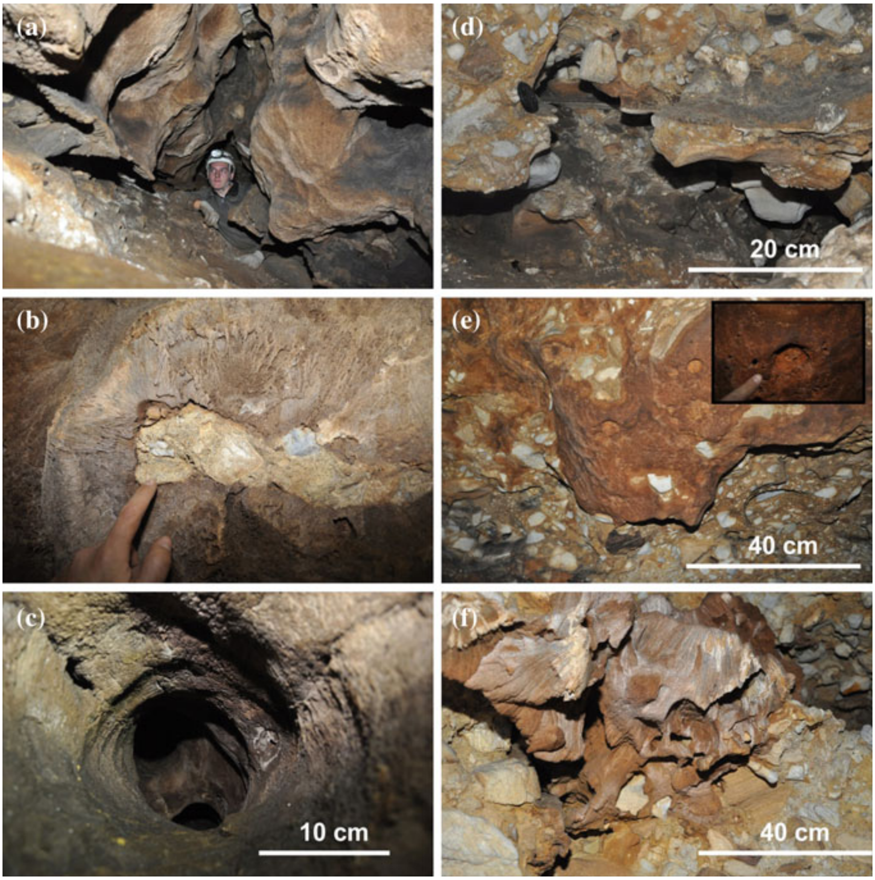


Fig. 4.19 Cave deposits in Melnička Peštera 1: **a** Mammillary calcite crust in the Narrow Passage. **b** Close-up view of the calcite crust from a broken wall (Narrow Passage). **c** Tube-like small conduit developed in the calcite crust (Narrow Passage); **d** Shelfstone in Chandelier Room; **e** Small pockets (cups) developed in breakdown affected calcite crust covering walls in Big Cupolas Room; **f** Corroded acicular calcite (or aragonite) crust in the North Passage. Photographs by M. Temovski

to a "Ring Road Passage," with collapse in center, under which lies the Lower Passage. There are two continuations, one smaller to the west and bigger one to the south. On the northern wall in the Lower Passage, there is a small passage with vertical development "Raft Passage." Typical small-scale morphology as in Melnička Peštera 1 is found in the Lower Passage with nice cupolas and pockets developed in calcitic marble conglomerates with quartz fragments protruding outward.

As it is closer to the surface, vadose speleothems are more common in this cave, with nice stalactites and curtains emerging from a cupolas in the NW part of the cave, under which flowstone is deposited. In the Raft Passage, cave raft deposits were found pilled up on floor and covering walls (Fig. 4.20). This passage is

Fig. 4.20 Cave rafts in Raft Passage of Melnička Peštera 2. Photographs by M. Temovski

severely affected by collapse so the original depositional environment of the cave rafts is difficult to reconstruct.

On surface, between Melnička Peštera 1 and 2, there is a small hole opened on the ceiling of a cupola, suggesting connection of passages between the caves.

4.1.2.3 Speleogenesis of Melnička Peštera 1 and 2

On the Possibility of Thermal Origin

Consideration of thermal origin of Melnička Peštera 1 and 2 is due to the registered thermal activity in the area: Provalata Cave, Melnica spring; traces of thermal alteration of dolomitic marble 500 m SE from Pešta Hill in Gumnište locality (Figs. 4.15 and 4.27); as well as the small-scale morphology in the caves, the lack of fluvial sediments, and the ambiguous origin of calcite and/or aragonite coatings in the cave. The model of origin could have been similar to the thermal carbonic phase in Provalata Cave.

Cave passages may have formed by rising thermal waters with elevation of passages connected to the elevation of the spring determined by the valley of Buturica River. Calcite (or aragonite) coatings were deposited after shifting in shallower settings. Above water table, due to condensation corrosion small-scale solutional forms developed (pockets, cupolas), some as daughter pockets on earlier phreatic pockets. At water level corrosion notches developed and shelfstone and cave rafts deposited in small isolated niches. With lowering of water table, calcite (or aragonite) was also corroded by condensation corrosion, with some small pockets and cups carved in coatings. Thermal waters may have been discharging along the contact of less permeable dolomitic marbles and more permeable carbonate conglomerates. With incision of Buturica River, thermal waters started discharging at lower levels, with thermally altered dolomitic marbles suggesting thermal activity in Gumnište locality (500 m SE from Melnička Peštera 1 and 2). Collapse in the cave happened as a result to instability of the host rock, due to dense clusters of pockets, cupolas and spongework, and the structure of conglomerate host rock.

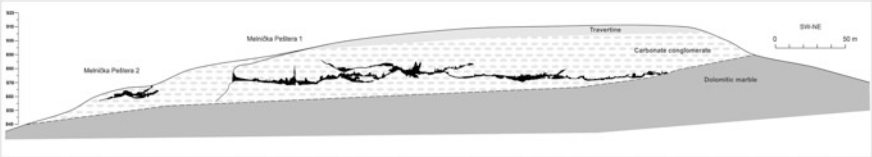


Fig. 4.21 Cross-section of Pešta Hill with Melnička Peštera 1 and 2

Lack of vadose speleothem deposits in cave passages indicates poor connection with the epikarst zone, which could be partly due to some impermeable marly layers (Fig. 4.21).

Possible Epigenic Origin of the Small-Scale Morphology

Small-scale features such as pockets, cupolas, and spongework can also develop in an epiphreatic environment, due to fast flowing, aggressive flood waters. Such origin of Melnička Peštera 1 and 2 is possible considering the geological and geomorphological location. Water coming from the Pleistocene Ramnobor valleys to the north of the caves was sinking at the contact of gneiss and dolomitic marbles with the overlying carbonate conglomerates, emerging to the south in the valley of Buturica River, creating a pirate connection. The high matrix porosity of the carbonate conglomerates influenced the irregular passage morphology, with small-scale morphology imprinted on the walls.

The problematic part in this model is the explanation of the calcite crust covering wall passages as well as small-scale features, found up to the highest levels, with secondary small-scale features imprinted on the crust deposits, and also absence of fluvial sediments. Their mammillary morphology and acicular crystals of calcite (or aragonite) are unlikely to be possible in an epiphreatic environment, as the water from which they were deposited must have been oversaturated with calcium carbonate. Their deposition in isolated oversaturated pools is also questionable, especially regarding the supply of calcium carbonate to the pools, with no vadose speleothems found in the cave. Also the secondary small-scale features (pockets, cups) carved in the calcite crust hardly can be explained with epiphreatic dissolution.

The development of the caves was surely governed by water table position as a result of base level position of Buturica Valley, and further analysis of the crust deposits will allow more plausible discrimination between the possibility of epiphreatic and the thermal hypogenic origin of the caves.

4.1.3 Karši Podot Cave

Karši Podot Cave is located in Karši Podot travertine terrace (350 m), with the entrance at 335 m, located on the NE edge of the terrace, 15 m above the Crna Reka riverbed (Fig. 4.4). The entrance part is in tufaceous limestone, where due to

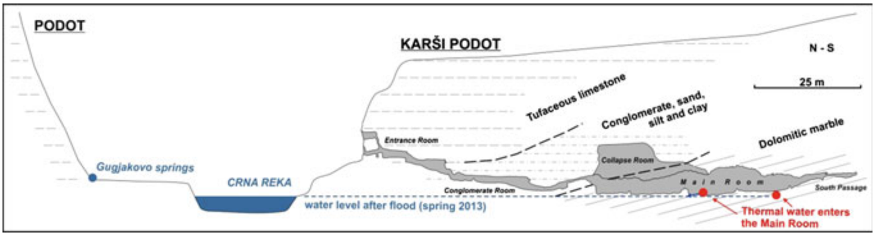


Fig. 4.22 Extended profile of Karši Podot Cave with geological and hydrological characteristics

collapse of a big block, the cave can be entered from two points, above and below the collapsed block. The cave can be entered also by a narrow channel from a lower point on the slope, which joins with the Conglomerate Room (Fig. 4.22).

4.1.3.1 Morphology

Karši Podot Cave has 200-m-long passages, with three separate segments based on lithology in which cave passages are developed. The Entrance Room is formed in tufaceous limestones; Conglomerate Room, Middle Passage, and Collapse Room are formed in clastic sediments; and the Main Room and Southern Passage are formed in dolomitic marble (Fig. 4.23).

Entrance Room and Conglomerate Room have E–W orientation. The Conglomerate Room is circular in plan view with nearly flat ceiling. It is mostly

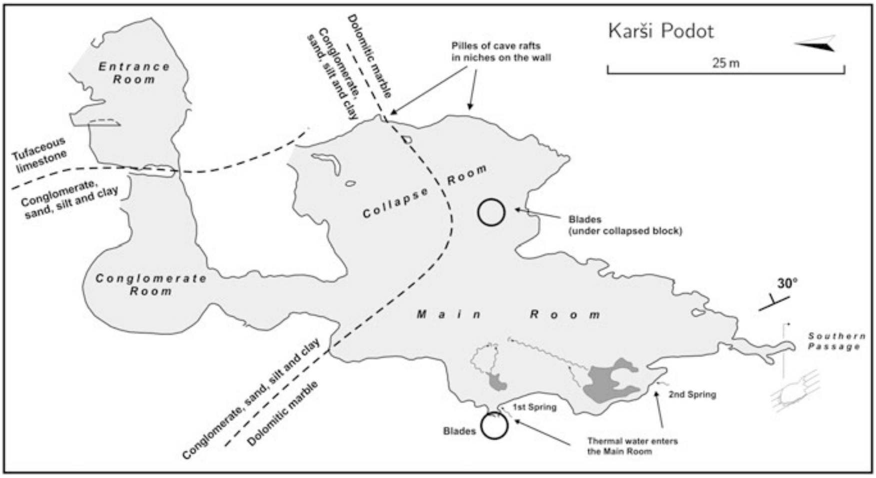


Fig. 4.23 Plan view of Karši Podot Cave with lithology and location of characteristic hydrological and morphological features. For more detailed cave map, see Appendix

developed in conglomerates that grade upward into silt and clay. The Middle Passage is developed mostly in silt and clay and leads to the Main Room.

The Main Room is the most important part of the cave, and it is completely developed in dolomitic marbles, which are covered by clastic sediments to the N–NE. It is 50 m long, 10–20 m wide, with 3–6 m high ceiling, completely developed in dolomitic marbles. The floor is covered with breakdown material, clay, and large guano deposits due to the large bat colony present.

There is a small passage (Southern Passage) continuing to the south from the Main Room. The Southern Passage is a 10-m-long passage, with dolomitic sand covering floor and half of the east wall. At the end of the passage, there is a profile of the dolomitic sand with visible bedding that continues in the host dolomitic marble rock. The same bedding can be clearly seen across the eastern wall of the Main Room. Such features are typical of karstification by ghost-weathering (Bruxelles and Wienin 2009; Quinif 1999).

Collapse Room is located to the NE from the Main Room, and it is mostly developed in clay and silt, with large collapsed blocks mostly along or close to the contact with underlying dolomitic marbles. To the north, a small passage continues, developed in tufaceous limestones.

Micro-morphology of the Main Room and Southern Passage

In the dolomitic marbles in the Main Room and the Southern Passage, characteristic pendant-like and spongework small-scale morphological features are widespread (Fig. 4.24). They can be well-rounded when developed along the foliation, or sharper when developed at cross-points of fractures and foliation. Their size varies from few centimeters up to 20–30 cm in length. In Southern Passage, they are also seen below the dolomitic sand. Removal of softer parts of weathered walls in the Southern Passage reveals such pendant-like morphologies in dolomitic marble.

4.1.3.2 Cave Sediments

Red-brown clay deposits are covering floor, roof, and walls in the Main Room. At some places, these clays have been eroded and only yellow stains on the dolomitic marble are left to testify of their former distribution. X-ray analysis of sample (KP02) above first spring determined quartz, goethite, kaolinite, muscovite, talc, vermiculite, and dolomite (Table 4.5).

X-ray analysis of ***brown silt*** sample (KP03) from the same location as KP02 determined magnesiohornblende-ferroan, lizardite, goethite, albite, kaolinite, talc, dolomite, muscovite, quartz, and vermiculite.

A sediment profile in the southern part of the Main Room reveals cross-bedded pattern with white to yellow dolomitic sand and brown sand and silt, deposited on top of a white dolomitic sand alterite. X-ray analysis of ***brown sand*** sample (KP06) from this profile determined fluorapatite, vermiculite, kaolinite, dolomite, magnesiohornblende, talc, muscovite, clinochlore, sepiolite, albite, and quartz.

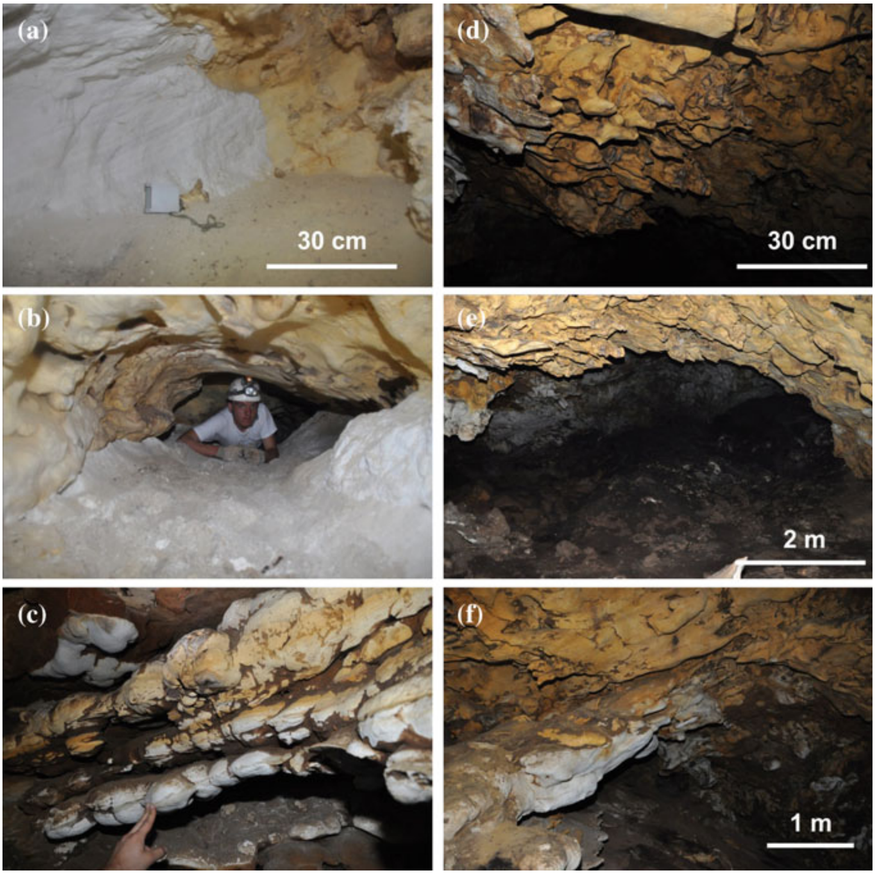


Fig. 4.24 Morphological features in Karsi Podot Cave: **a** Dolomitic alterite sand with preserved foliation structure (Southern Passage). **b** Dolomitic alterite sand on the floor and partly on the wall with pendants on the ceiling and wall revealed after removal of alterite (Southern Passage). **c** Well-rounded pendants (Main Room). **d** Pendants on the ceiling in the southern part of the Main Room. **e** Ceiling pendants and collapsed blocks covered with thick guano deposits in the Main Room. **f** Pendants developed along the bedding (Main Room). Photographs by M. Temovski

Table 4.5 Mineral composition of clay and sand from Karši Podot Cave

Sediment (sample)	Mineral composition
Red-brown clay (KP02)	Quartz, goethite, kaolinite, muscovite, talc, vermiculite, dolomite
Brown silt (KP03)	Magnesiohornblende-ferroan, lizardite, goethite, albite, kaolinite, talc, dolomite, muscovite, quartz, vermiculite
Brown sand (KP06)	Fluorapatite, vermiculite, kaolinite, dolomite, Magnesiohornblende, talc, muscovite, clinochlore, sepiolite, albite, quartz

Quartz, muscovite, albite, and magnesiohornblende are most likely detrital minerals, coming either from the Precambrian metamorphic and magmatic rocks (gneiss, granodiorite, micashist, amphibolite) brought by Crna Reka with backflooding, or from the local terrace clastic deposits that where previously deposited by Crna Reka. Dolomite is found in all samples and is most likely coming from dolomitic sand residue. In sample KP06, it is from redeposition of the dolomitic sand, and in samples KP02 and KP03, it is probably from local dolomitic sand residue at the contact with altered bedrock. Clinochlore can also be a detrital mineral as it is found in the Precambrian gneiss and micashists.

Goethite and kaolinite are most likely local weathering products. Vermiculite, talc, sepiolite, lizardite, and clinochlore can be local hydrothermal weathering products of mica and amphibole minerals. Fluorapatite found in the sediment profile in the Main Room is likely connected to the thick bat guano deposits.

Breakdown material is widespread in the cave, with different lithology depending on the lithology in which the passage is formed. In the Main Room, the breakdown material has the same pendant-like morphology.

Most of the floor in the Main Room and partly in the Collapse Room is covered by thick ***guano deposits***, due to the large bat colony living in the cave.

Stacked piles of ***cave rafts*** (Fig. 4.25) are found in the Collapse Room (Fig. 4.23) in small niches in dolomitic marble or at the contact with clays. Their thickness is from less than mm and up to cm size, with voids between rafts at places filled with silt and clay deposit.

Unusual elongated ***carbonate blades*** are found in a small side passage (Blade Passage) behind the first spring in the Main Room, and also below a collapsed block in the Collapse Room (Figs. 4.23 and 4.25). Their contact with the bedrock suggests that they are of depositional origin, and not a speleogen. They are curvilinear in long direction and platy to round in cross section.

In the end of the Blade Passage, they are sub-horizontal and emerging from what it seems like a deposit of stacked blades below and on the ceiling with intercalations of silt and clay between stacked blades; while closer to the connection with the Main Room, they are intersecting each other and are inclined at different angles in an organized fashion, with intersecting blades inclined at similar angles but in opposite direction (60° and 45°; 30° and 15°).

The blades are mostly covered with gray to brown silt. At places, thin layers of flowstone are deposited on them, covering the silt deposit, while small popcorn speleothems are also found growing on the tips of the blades.

The blades resemble the stacked rafts, with different inclination of blades comparing to differently inclined rafts (intersecting and inclined at high angles filling vertical voids, while sub-horizontally aligned rafts are covering vertical voids previously filled with rafts or deposited on horizontal surfaces at first). While their organizational structure is similar to the relationship of rafts, they have more irregular form and are elongated and curvilinear. This can be due to later widening after sinking below water surface (post-depositional). The sediment (mostly silt) between blades, as well as cave rafts, is not indurated and it seems it filled voids after deposition of rafts.

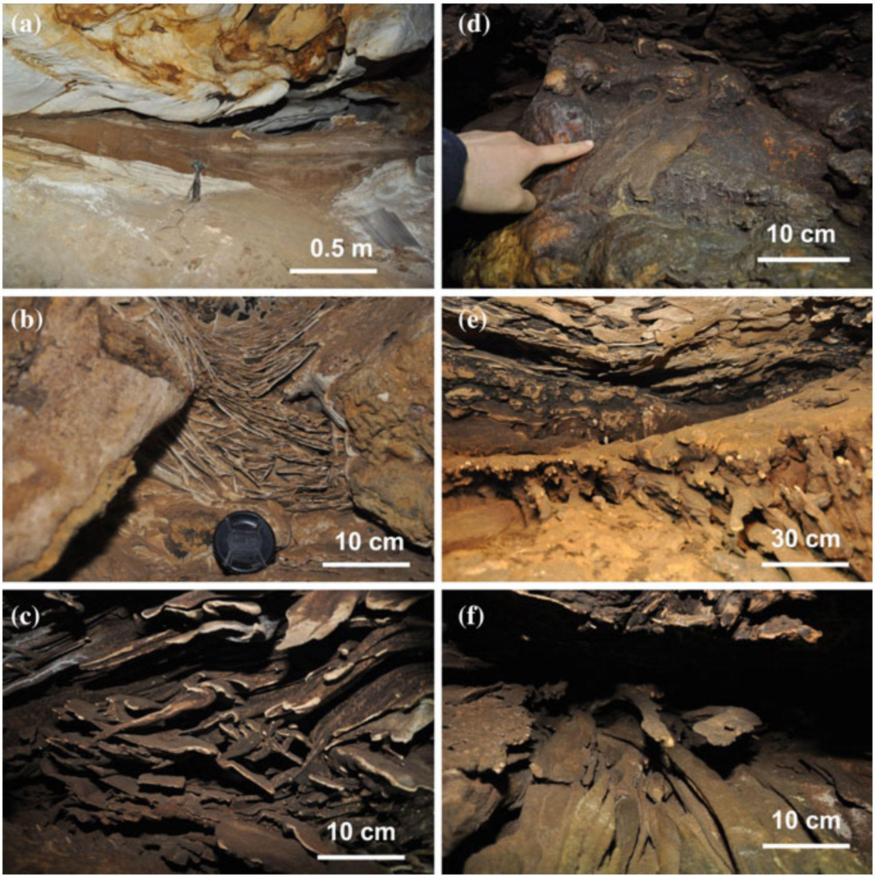


Fig. 4.25 Cave deposits in Karši Podot Cave: **a** Sediment profile with cross-bedded pattern of brown sand and silt with dolomitic sand, deposited on top of white dolomitic sand alterite (southern part of Main Room). **b** Cave rafts in a niche in the Collapse Room. **c** Carbonate blades crossing each other (Blade Passage). **d** Partly exposed carbonate blade (Blade Passage). **e** Carbonate blades with the ones at the ceiling having more flat morphology (Blade Passage). **f** Elongated curvilinear carbonate blades exposed above stacked carbonate blades (Blade Passage), note popcorn speleothems on the tip of the blade. Photographs by M. Temovski

Based on the observation of morphology and relationship of deposits, it is possible that the blades originate from previously deposited piles of cave rafts, overgrown after sinking in saturated waters, with voids between rafts filled with silt and clay deposits. After lowering of water level, and removal of clastic sediments, the elongated and curvilinear blades were exposed with intersecting blades formed from rafts deposited in vertical voids (larger inclination angle), while sub-horizontal, more platy, blades formed from rafts deposited on horizontal surfaces.

4.1.3.3 Hydrological Characteristics

Two springs emerge from the west wall in Main Room (first spring—the one to the north, and second spring—the one to the south), leading to small streams that join below the breakdown pile in the center of the room. Although not accessible, the stream continues to the north toward Crna Reka.

On the right bank of Crna Reka, there is no visible discharge spring. In spring season after rising of water level in Crna Reka riverbed, there is a rise in water level in the cave, causing backflooding, with a small shallow lake forming at the second spring. The water of the spring is mildly thermal, with constant temperature of 23 °C.

The thermal waters discharging in the cave have neutral to slightly acidic pH and have high dissolved carbonate content, with Ca and Mg concentration reflecting dissolution of dolomitic marbles (Table 4.6).

4.1.3.4 Speleogenesis

The Southern Passage with in situ dolomitic sand alterite residue preserving original rock structure indicates ghost-rock weathering in the dolomitic marbles. The development of cave passages in the dolomitic marbles is a result of ghost-rock isovolumetric dissolution of calcite minerals in the dolomitic marble, leaving in situ dolomitic sand alterite residue.

This process has been carried out by slowly moving thermal waters, with insufficient energy to carry the remaining dolomite sand. The removal of the alterite and exposing (development) of phantom passages have been by backflooding of Crna Reka, which eroded the dolomitic sand, depositing elsewhere cross-bedded sediments of dolomitic sand and non-carbonate silt and clay brought by Crna Reka or eroded from the clay-silt sediments in the northern parts of the cave (Fig. 4.26). Downward evolution of the cave due to incision of Crna Reka created spongework cave passages with large void volume that became unstable after the removal of alterite, which resulted with collapse and led to development of a large room—the Main Room.

4.1.4 Indicators of Thermal Speleogenesis Found on Surface

4.1.4.1 Gumnište

Gumnište is an area in Buturica Valley between Provalata Cave and Melnička Peštera 1 and 2 (Figs. 4.15 and 4.27), developed in Precambrian dolomitic marbles. Along this area, there are several localities where the dolomitic marbles are altered, and highly weathered. The alteration is the same as in Karši Podot Cave, with

Table 4.6 Some physical and chemical parameters of thermal waters in the first spring (Karši Podot Cave): temperature (T) in °C, ion concentrations in mg/l, specific electric conductivity (EC) in µS/cm, and total hardness (TH) in dH

Date	T	pH	EC	TH	HCO_3	Ca	Mg	NO_3	Cl	Fe	SO_4	Measured in
18/09 2011	23	7.6	820	29.45	/	160.16	30.344	6	12	0	/	Lab
23/07 2012	23	6.91	881	25	634.4	126.5	53.28	3.1	7	0.027	0.4	Lab
21/04 2013	23	6.69	934	/	/	/	/	/	/	/	/	Field

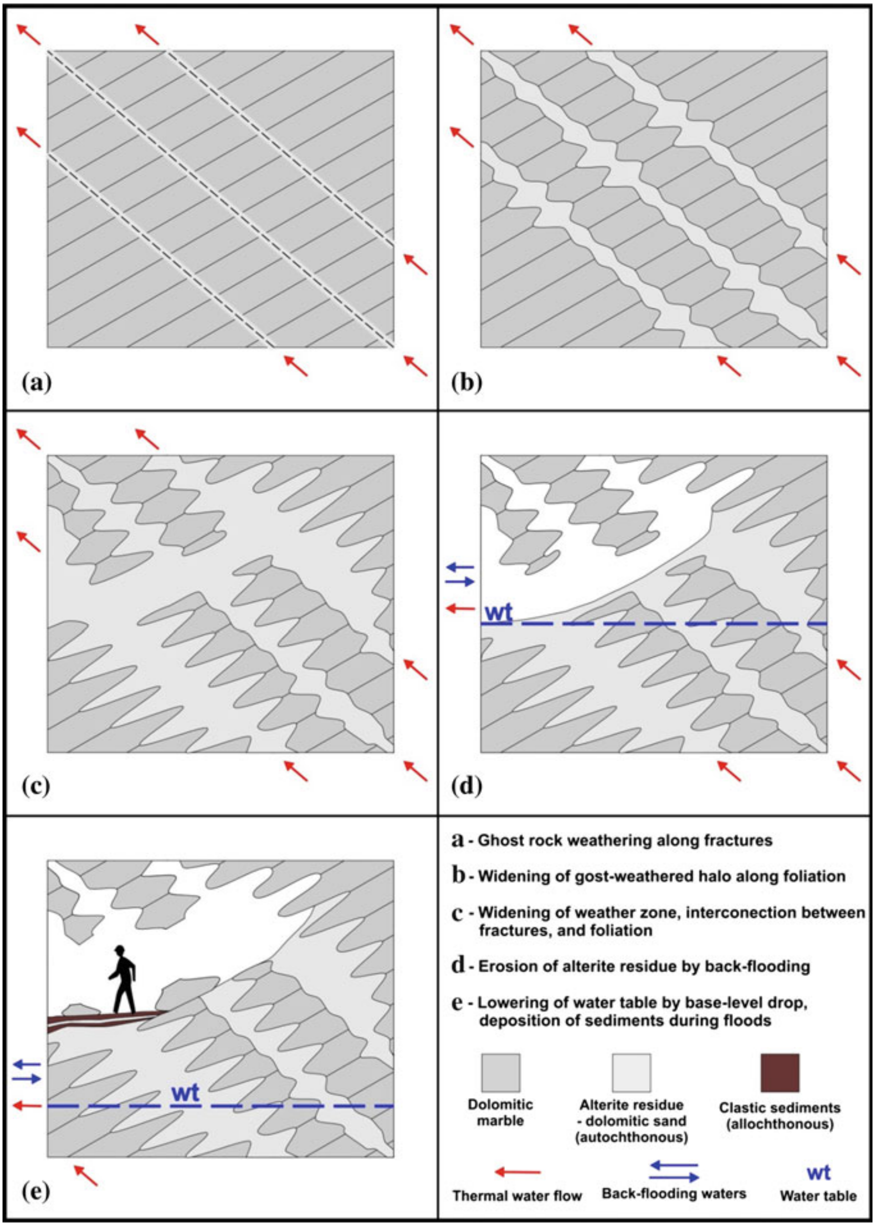


Fig. 4.26 Schematic model of ghost-rock weathering and phantom cave development in Karši Podot Cave

dolomitic sand residue formed as a result of incomplete dissolution (ghost-rock weathering). This sand is later easily removed by the meteoric water, leaving protruding remnant features of dolomitic marble. Artificial carving in patches of in situ dolomitic sand reveals the protruding remnants of dolomitic marble, indicating the in situ development of the dolomitic sand. Same features (dolomitic sand and remnants of dolomitic marble) are seen also in the Ramnobor query, north of Pešta Hill, but unfortunately documenting them was not allowed by the owner.

Fig. 4.27 Ghost-rock weathering and thermally altered dolomitic marble at Gumnište locality: **a** View of western part of Gumnište locality (Crveno Gumnište—CGUM) with Pešta Hill in the background. **b** Protruding remnants of altered dolomitic marble, exposed after erosion of alterite residue produced by ghost-rock weathering (CGUM). **c** Iron mineralization at CGUM. **d** View of eastern part of Gumnište locality (GUM). **e** Protruding remnants of altered dolomitic marbles (GUM). **f** Protruding remnants of altered dolomitic marbles revealed after digging of yellowish dolomitic sand (GUM). Photographs by M. Temovski

In the western part of this area, near the road cut, there is a gradual change of alteration from white dolomitic marble, to grayish and reddish altered dolomitic marble. Some black mineralization is visible in the reddish dolomitic marble. X-ray from a sample (CGUM04) showed composition of calcite, dolomite, and goethite.

Comparing this locality with similar features seen in Karši Podot Cave where the ghost-rock weathering is due to dissolution by thermal waters, and also considering the proximity of this area to the Melnica spring, Provalata Cave, and Melnička Peštera 1 and 2, where thermal speleogenesis is also considered, the alteration found in Gumnište area is likely connected to thermal waters.

4.1.4.2 Thermal Vents

It was reported from the local population that on the slopes of Pantelejmon (1344) and Gola Skrka (1187), there are small holes from which quite hot air is blowing. Two such vents were located, one on the southern slope of Pantelejmon (1344)—Uškova Koliba vent—and one on the southern slope of Gola Skrka (1187)—Skrka vent—both in Cambrian marbles (Fig. 4.2). Both are not penetrable with similar diameter sizes of ~20 cm (Fig. 4.28).

The Skrka vent is located 900 m NE from Provalata Cave at 930-m elevation, 210 m above Buturica River. Although this vent was reported to be active in the late eighties (Micko Derivolski pers. comm.), there was no hot air blowing noted. The temperature measured in February was 12 °C.

Uškova Koliba vent is located on the southern slope of Pantelejmon (1344), at 1040-m elevation, ~200 m above the small Potokot stream, tributary to Satoka River (Fig. 4.2). The vent is located 500 m NE from the Čavkarnik locality. Strong draft was coming from the vent, with measured temperature of 21.2 °C (January).

Skrka vent is probably connected to the thermal karst system in Buturica River, with present thermal spring—Melnica spring located at the riverbed at 715-m elevation.

Fig. 4.28 Thermal vents on surface: **a** Uškova Koliba vent. **b** Skrka vent. Photographs by M. Temovski

Uškova Koliba vent indicates thermal karstification also in Pantelejmon Mt. The geological situation between Skrka and Pantelejmon (depression filled with deposits of Upper Miocene, Pliocene, and Pleistocene age) is replicated between Pantelejmon (1344) and Vrvovite (1403), indicating possible similar situation as in Buturica Valley. Although caves and thermal springs were not found in the vicinity, nearby Čavkarnik locality (Fig. 4.29) has remnant cave features indicating similar cave development as in the first phase of Provalata Cave.

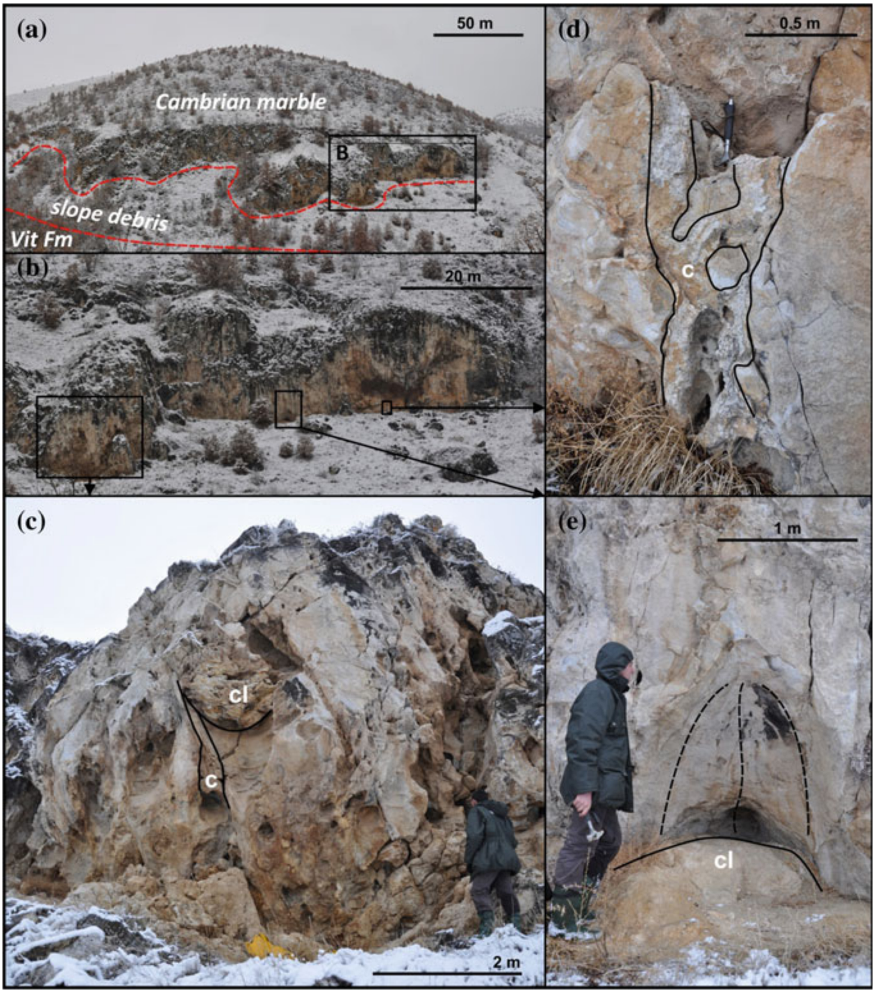


Fig. 4.29 Disolutional features and deposits on Čavkarnik cliff: *cl* clay, *c* calcite crust. Photographs by M. Temovski

4.1.4.3 Čavkarnik

Čavkarnik is a cliff in Cambrian marbles on the SW foothill of Pantelejmon (1344), 500 m SW from Uškova Koliba vent, and 60 m above the small stream Potokot (Fig. 4.2). It is a 250-m-long erosional cliff developed on the left side of the small stream Čavkarnikot. Remnants of cave features are exposed along the cliff due to slope retreat (Fig. 4.29). These features include various convective disolutional features such as pockets and cupolas (Fig. 4.29c, e), and some of them filled with calcite crust and clays. Calcite crust is generally covering vertical dissolution features, as well as lining pockets and cupolas (Fig. 4.29c, d). The thickness of the crust is from several cm up to 0.5 m, with secondary pockets developed in the crust. The clay deposits are mostly filling cupolas and pockets at the foothill of the cliff (Fig. 4.29e), with clay from upper parts mostly removed, but still some remnants of clay deposits can be found filling cupolas and pockets in the upper parts (Fig. 4.29c).

4.2 Kožuf Hydrothermal Karst

4.2.1 Hydrothermal Alteration of Carbonate Rocks in Allchar Ore Deposit

Allchar (Alšar) is a complex, polychrono-polygenetic volcano-hydrothermal Sb–As–Tl–Au deposit, located between the eastern foothill of Mt. Kozjak and western foothill of Mt. Kožuf (Figs. 4.30, 4.31 and 4.32). The name Allchar derives from the names of the mine concessioners (English–French Company) at the end of nineteenth century—Allatini-banker, owner of the concession and Charteau,mining engineer who worked in the mine.

The mine has a long history of exploration dating back to the antiquity. It was mostly explored for arsenic production, especially in the nineteenth century, when also first Tl minerals were found. It received extensive geological investigations after the Second World War, with discovery of 300 000 tons of antimony, arsenic, and thallium ore deposits. From the 1980s, thallium minerals from Allchar, especially lorandite, received special research interest as a possible solar neutrino detectors (Boev et al. 2012).

The deposit is situated in the volcanic complex of Mt. Kožuf, an E–W-oriented complex formed at the on the cross section between the transversal Kožuf–Kilikis structure (E–W) and the Vardar zone (NW–SE to N–S) structures (Boev et al. 2012).

The local geology is represented with Upper Triassic bedded and massive carbonate rocks (dolomite, marble) underlain by Middle Triassic sandstone and claystone. They are unconformably overlain by Pliocene dolomites and tufaceous dolomites grading to ash, crystal tuffs, tuff breccia, and lacustrine tuffaceous

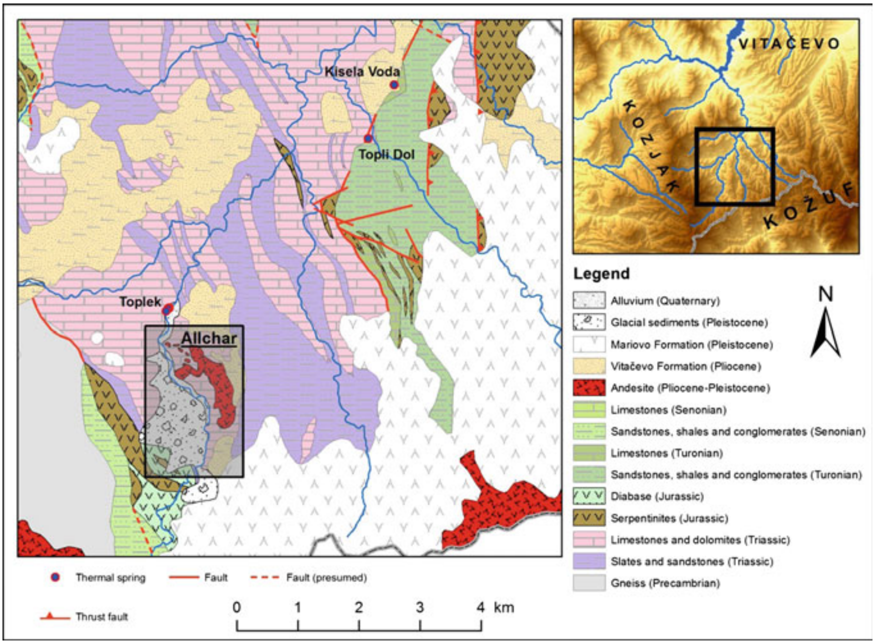


Fig. 4.30 Geological setting of the Kožuf thermal karst. The close-up of Allchar locality is given in Fig. 4.31. Geological data modified after Dumurdžanov et al. (1976), Rakićević and Pendžerkovski (1970), Geološki Zavod—Skopje (unpublished)

sediments. They are covered by Quaternary glacial till (Percival and Radtke 1994; Boev and Serafimovski 1996; Boev et al. 2012).

The ore deposits are hosted in both Triassic and Tertiary rocks and closely connected to the Kožuf volcanism, with two principal volcano-intrusive phases identified (Boev et al. 2012; Boev and Jelenković 2012): Miocene phase (14.3–8.2 Ma); and the most significant Pliocene phase (5.1–3.9 Ma).

While the origin of the ore deposit and its evolution connected to the Kožuf volcanism are of complex nature and it was extensively geologically studied during the last 50 years, the main interest from karst point of view lies in the carbonate host rocks and their susceptibility to karstification. Their characteristic of increasing porosity and permeability as a result of solubility was favorable for the circulation of hydrothermal waters from which the ore minerals were deposited.

Percival and Radtke (1994) described hydrothermal alteration in each of the rocks throughout the Allchar district, with different intensity varying locally, determining six types of alteration: decalcification, silicification, argillization, veining, dolomitization, and supergene alteration.

Decalcification and dolomitization are the two types of hydrothermal alteration that can be attributed to increasing porosity of carbonate rocks at bigger depths, and therefore corresponding to hypogenic speleogenesis, while later supergene

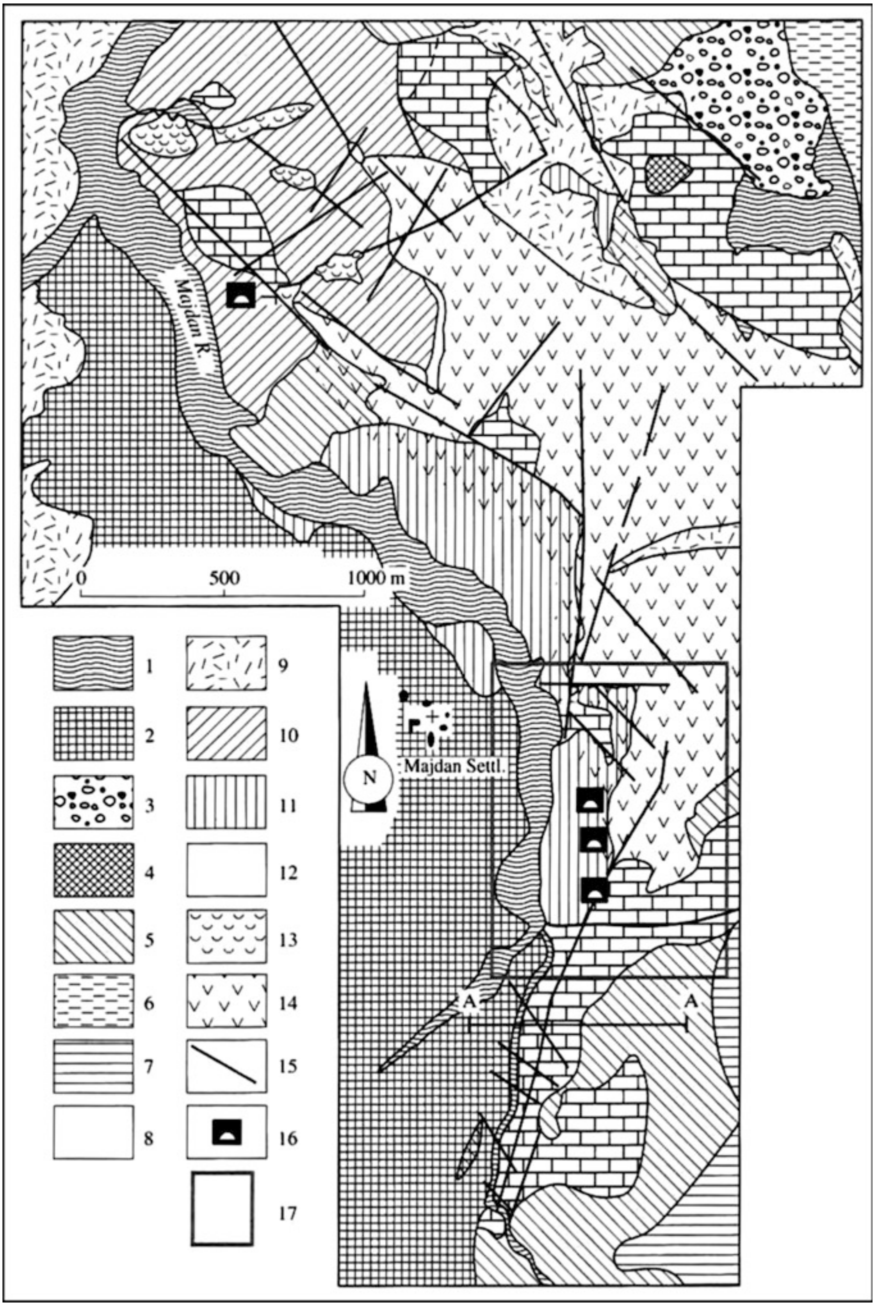


Fig. 4.31 Geological map of Allchar locality, after Volkov et al. (2006). *1* Quaternary alluvial sediments; *2* quaternary moraine sediments; *3* limonitized breccia; *4* tuff; *5* pyroclastic rocks; *6* sericite–chlorite schist; *7* shale; *8* marbleized limestoned; *9* dolomite; *10* hydrothermally altered dolomite; *11* siliceous dolomite; *12* oxidation zone; *13* andesitic subvolcanic bodies and lavas; *14* andesite; *15* fault; *16* adit mouth; *17* central area of the deposit

alteration due to oxidation can also have impact on the speleogenetic evolution in shallow depths, or close to the surface.

Decalcification is described as a process of removal of calcite and dolomite from the sedimentary host rocks by weakly acidic solutions (in a pyrite-stable field) resulting in increased porosity and permeability (Percival and Radtke 1994). This is followed by deposition of replacement silica (silicification) and later argillic alteration. The most complete silicification resulted in the formation of jasperoids, but much larger volumes of rocks are only weakly to moderately silicified (Percival and Radtke 1994). Decalcification affected both the Triassic carbonate rocks, and the Pliocene tufaceous dolomites.

Second style of decalcification, “sanding,” was described by Percival and Radtke (1994), where the decalcification is lacking silicification. Here, the intergranular corrosion by hydrothermal fluids removed the fine-grained matrix, leaving predominantly granular dolomite sand, commonly preserving primary textural features. This alteration was attributed as common for the Tertiary dolomite.

Weekly developed dolomitization was described in the Triassic marble, with dolomitized rocks typically lighter colored than the host marble, and locally mottled, fine-grained, non-layered, highly jointed, containing manganese and iron oxides, and grading into undolomitized marble (Percival and Radtke 1994). Hydrothermal origin of the dolomitization is questioned by Percival and Radtke (1994), suggesting also possible origin from removal of calcium carbonate from dolomitic rocks by low-pH hydrothermal fluids.

4.2.1.1 Evolution of the Hydrothermal System and Ore Mineral Deposition

The evolution of this hydrothermal ore body started with hydrothermal karstification at depth by ore mineral bearing fluids. Water was flowing along high angle faults and favorable bedding planes, dissolving carbonate rocks (decalcification after Percival and Radtke 1994) and also producing alteration such as silicification (replacement of carbonate with silica), as well as so-called sanding decalcification of dolomite rocks, where fine-grained carbonate matrix was dissolved, leaving only dolomite grains as dolomitic sand residue (Percival and Radtke 1994). This increased porosity in the carbonate rocks, which served as a host for ore mineral formation in several phases of deposition due to lowering of temperature and pressure (Boev and Serafimovski 1996): In the first phase, high-temperature sulfides were deposited, such as arsenopyrite, pyrite, and marcasite; the second-phase deposition was after drop of temperature and pressure, with formation of stibrite dominated deposits accompanied by falcmanite, phizelite, pyrite, etc.; the third mineralization phase is represented with massive separation of As–Tl minerals such as realgar, auripigmentum, lorandite, vrbaite, and alsharite; hydrothermal phase ends with relatively low temperatures by deposition of barite, calcite, native sulfur, etc. The ore deposition occurred before 4.31 ± 0.02 Ma, at depth of 200 to 430 m and temperatures of 280 to $\sim$120 °C (Jelenković and Boev 2011).

Oxidation processes on surface or due to mixing with shallow oxygen-rich waters influenced supergene alteration of the ore bodies (Percival and Radtke 1994). Oxidation of iron sulfides produced iron oxides and sulfuric acid, which produced various sulfate minerals.

Water in this hydrothermal system is most likely of meteoric origin (Volkov et al. 2006), with possible participation of juvenile and connate waters (Boev and Serafimovski 1996), heated by high geothermal gradient due to proximity of shallow-seated intrusive rocks of Kožuf volcanism, with most of the ore elements originating from the intrusive igneous rocks with smaller contribution from the surrounding sedimentary rocks (Percival and Radtke 1994; Boev and Serafimovski 1996).

Uplift and erosion during Pleistocene have exposed the ore mineral deposits, with present-day low-temperature thermal springs (Toplek Spring) found nearby the northern part, at the riverbed of Majdanska Reka.

4.2.2 *Kožuf Thermal Springs*

Thermal waters in Kožuf vicinity are found discharging at three localities: Kisela Voda, Toplek, and Topli Dol (Fig. 4.30).

4.2.2.1 Topli Dol

Topli Dol thermal spring is located at 620-m elevation, in the lower part of Topli Dol River, 1.5 km upstream from the confluence with Blašnica River, right-hand tributary to Crna Reka and main and largest river draining the area between Kozjak and Kožuf Mt (Fig. 4.30). It was first described by Kekik (1972), giving information about the local geology and structure and chemical characteristics of the water (Table 4.7).

The spring is located at the contact of Upper Triassic carbonate rocks (marbles and dolomites) and Cretaceous (Turonian) clastic formation. The area is highly faulted, especially to the south (Ržanovo), with numerous ophiolitic (Jurassic) rocks displaced along the faults (Fig. 4.32).

The discharge is 2 l/s, and it has the highest temperature of all thermal springs in Kožuf area at 28 °C (Boev and Lepitkova 2003). The chemistry of water reported by Boev and Lepitkova (2003) indicates high total dissolved contents (884 mg/l),

Table 4.7 Geochemical characteristic of Topli Dol thermal waters, after Kekik (1972)

HCO_3	Cl	SO_4	Ca	Mg	Na + K	Tot. mineralization	pH	Total hardness	Carbonate hardness
774	14	36	164	38.4	45.3	1071.7	6.5	38.6	36.3

Ion concentrations are given in mg/l, hardness in german degrees (dH)

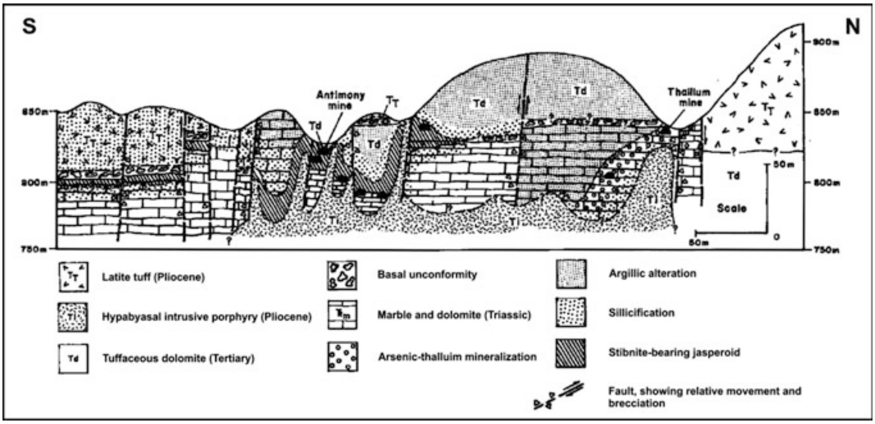


Fig. 4.32 North–south longitudinal profile through Allchar locality with geological, alteration, and mineralization relationship among the northern, central, and southern zone of the area, after Percival and Radtke (1994)

with high carbonate hardness (43.2 dH), with 206.1 mg/l Ca, 62.7 mg/l Mg, and 53.77 mg/l SO_4 (Table 4.8). Water also has acidic taste which is due to presence of free CO_2 (142 mg/l—Kekik 1972; 116 mg/l—Boev and Lepitkova 2003). High Ca and Mg content is due to dissolution of the dolomites and marbles, while the sulfate content might be a result of sulfuric acid dissolution operating at shallow depth. On the base of the situation at Allchar locality where there are sulfate minerals formed as a result of oxidation of iron sulfides, the origin of sulfuric acid can be from oxidation of iron sulfides due to mixing with epigenic oxygenated waters.

4.2.2.2 Kisela Voda

Kisela voda is a thermal spring situated 1.5 km southeast from Mrezicko Village. The spring is located at 690-m elevation, on a NNE-oriented fault, at the contact of Cretaceous (Turonian) clastic sediments with the Upper Triassic carbonate formation, and overlying Vitačevo Formation (Pliocene) deposits.

It has the lowest temperature of the Kožuf thermal springs, 21 °C, with highest dissolved content (900 mg/l). It has acidic taste, with pH at 6.5 and CO_2 content of 96 mg/l, sulfate content is 52.6 mg/l, Ca is 213.8 mg/l while Mg is 76.7 mg/l. The spring has a small discharge of 0.7 l/s (Boev and Lepitkova 2003).

The geochemical characteristics are almost identical as in Topli Dol Spring, with dissolved Ca and Mg carbonate coming from the Upper Triassic marbles and dolomite, while the SO_4 as in Topli Dol and Toplek is probably due to sulfuric acid speleogenesis by oxidation of iron sulfides.

Table 4.8 Geochemical characteristics of the thermomineral waters near Kožuf volcanic complex, after Boev and Lepitkova (2003)

Parameters	Kisela voda	Topli dol	Toplek
Temperature (°C)	21	28	22
Taste	Sour/acidic	Sour/acidic	No
pH	6.5	6.48	8.3
Solids, total (mg/l)	912	868	410
Solids, dissolved (mg/l)	900	884	396
Solids, suspended (mg/l)	12	14	14
$KMnO_4$ demand (mg/l)	3.6	3.3	3.4
Specific electric conductivity (μS/cm)	1112	1108	324.2
M-alcalinity (mg/l)	160	158	30
Total hardness (dH)	46	45	11.1
Carbonate hardness (dH)	44.5	43.2	8.4
CO_2 (mg/l)	98	116	/
H_2S (mg/l)	/	/	/
SiO_2 (mg/l)	10	10	119.3
Discharge (l/s)	0.7	2.0	15
Ca (mg/l)	213.8	206.1	52.3
Mg (mg/l)	76.7	62.7	15.4
Na (mg/l)	17	31.7	16.4
K (mg/l)	8	9.3	10.1
Cl (mg/l)	15.1	15.1	6
SO_4 (mg/l)	52.6	53.77	25.62
Sc (mg/l)	18.3	11	3
As (mg/l)	0.18	0.24	0.38
Pb (mg/l)	0.036	0.040	0.018
Cd (mg/l)	0.001	0.001	0.001
Zn (mg/l)	0.028	0.030	0.007
Cu (mg/l)	0.007	0.007	0.025
Fe (mg/l)	0.025	0.038	0.021
Mn (mg/l)	0.003	0.056	0.002
Co (mg/l)	0.03	0.03	0.002
Ni (mg/l)	0.010	0.006	0.005
Cr (mg/l)	0.004	0.002	0.005
Sr (mg/l)	1.01	1.03	0.032
F (mg/l)	0.10	0.10	0.10
NO_3 (mg/l)	/	/	/
NO_2 (mg/l)	/	/	/
P (mg/l)	/	/	/

4.2.2.3 Toplek

Toplek springs are situated on the northern edge of Allchar locality, on the left bank of Majdanska Reka riverbed (Figs. 4.30 and 4.33). They are located in hydrothermally altered dolomites, with three detectable discharge locations (Toplek 1, 2, 3) along 50-m-long section at elevation of 730 m. Most of the water is discharging at Toplek 2 with 15 l/s discharge (Boev and Lepitkova 2003), making it the biggest thermal spring in Kožuf area. On the cliff behind the spring, there are number of small (few meters long) cavities, which are not penetrable. Downstream 50 m from Toplek 1 spring, there is a cold-water spring, capped for drinking. It is a normal karst water spring, with temperature of water at 6.5 °C (March 2013), with pH of 8.54, and specific electric conductivity of 162 μS/cm (Table 4.9).

Boev and Lepitkova (2003) report temperature of 22 °C for Toplek spring, with pH at 8.3, specific electric conductivity of 324.2 μS/cm, and total dissolved solids of 324 mg/l. It has much less dissolved content comparing to the other thermal springs in Kožuf area with 52 mg/l of Ca, 15.4 mg/l of Mg, and 25.62 mg/l of SO_4, but it has the largest SiO_2 content with 119.3 mg/l, comparing to the 10 mg/l in both Topli Dol and Kisela Voda springs.

Fig. 4.33 Toplek 2 thermal springs, located on the left side of Majdanska Reka riverbed. Photograph by D. Jovanoski

Table 4.9 Some physicochemical parameters of Toplek springs (March 2013)

Spring	pH	Spec. elec. conductivity (μS/cm)	Temperature (°C)
Toplek 1	7.76	355	19
Toplek 2	7.67	370	21
Toplek 3	7.68	390	20.4
Toplek 4 (Češma)	8.54	162	6.5

Considering the nearby cold-water karst spring, which has significantly lower temperature and dissolved content, the reason for the intermediate values in Toplek Spring can be due to mixing with cold epigenic waters, which are draining the upper parts of the Triassic carbonate formation. The high SiO_2 content is in good agreement with the Allchar locality, where hydrothermal waters which produced the ore mineralization had high silica content, which also replaced partly the carbonate rocks.

4.3 Discussion

Hypogenic karst in the researched area is generally connected to thermal waters and found in only three areas (Melnica, Podot, and Kožuf; Fig. 4.1). The thermal waters are most likely of meteoric origin and were heated due to deep circulation in an area of high geothermal gradient. The high geothermal gradient is due to Kožuf–Kozjak volcanism which was active from Upper Miocene to Pleistocene (6–1.8 Ma, Boev et al. 2012), with explosive character which produced large pyroclastic material, filling the neighboring basins.

Present discharge of thermal waters is connected to base level positions, between 620 and 730 m (Melnica and Kožuf localities), with the lowest thermal spring in the riverbed of Crna Reka at 320 m (Podot locality). Caves connected to hypogenic development were only registered in Melnica and Podot localities, while in Kožuf area such caves were not found. Nevertheless, chemical characteristics of thermal waters in Kožuf area suggest that karst is functioning below (Fig. 4.34).

In Melnica and Podot areas, hypogenic karstification is found in dolomitic marbles (Precambrian) and calcitic marbles (Cambrian), and also most likely in Pleistocene carbonate conglomerates. Thermal hypogenic karstification in dolomitic marbles was accompanied by ghost-rock weathering process, which produced incomplete dissolution of the dolomitic marbles, dissolving mostly calcite, and leaving dolomite in situ residue. In Melnica area, such features are found on surface, exposed by erosion due to incision of Buturica Valley, while in Podot area,

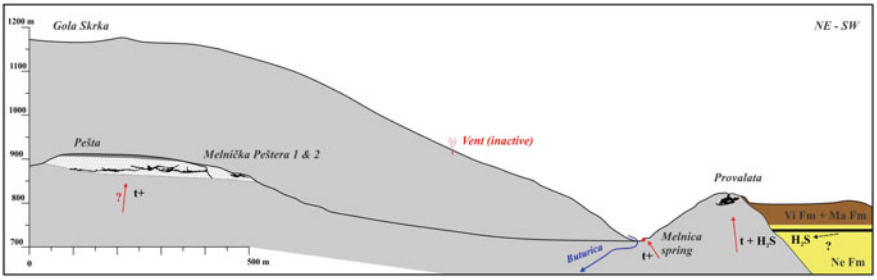


Fig. 4.34 Cross section of Buturica Valley with hypogenic karst features and relationship with Mariovo Basin deposits

ghost-rock weathering is seen in Karši Podot Cave, where removal of dolomitic alterite residue produced phantom cave. Considering that dolomitic marbles are less susceptible to karstification, with no other caves found in them and their general fluvial surface morphology, ghost-rock weathering by slowly moving rising thermal waters and consequently phantom cave development played important role in karstification. To what extent the area between these localities is affected by ghost-rock weathering remains to be seen.

In calcitic marbles, the influence of thermal karstification is more directly expressed. Provalata Cave is a remarkable example of a thermal hypogenic cave, where two distinct speleogenetic phases are recognized. The first phase of cave development is due to dissolution by cooling effect of rising carbonated thermal waters. Meteoric waters were probably circulating deep trough the karst system increasing their temperature due to high geothermal gradient, and rising along fractures and faults on the margin of Mariovo Basin. Phreatic morphology with cupolas and rising channels was formed in deeper parts, on which thick mammillary calcite crust was deposited after shift (most likely due to tectonic movement in Pliocene–Pleistocene) to shallower phreatic environment. Continuous deposition in Mariovo basin in Early Pleistocene covered the whole area with pyroclastic rocks, and pyroclastic rock-derived clays completely filled the cave. The thermal karst system was probably still functioning during this period, contributing calcium carbonate for deposition of travertine deposits in Mariovo Formation. Travertine layers are also found in Vitačevo Formation (Pliocene), with the thermal karst system also contributing to the carbonate content of the lake.

In Kožuf area, thermal karstification can be determined on the base of presence of thermal springs emerging at the contact of carbonate rocks with various schist and clastic rocks, having a high concentration of dissolved calcium carbonate. Kožuf area is more closely related to the source of the geothermal heat, considering the close proximity to intrusions of volcanic rocks (Kožuf volcanic center).

Surface remnants of previous hydrothermal karstification are found at several locations in Melnica area. Ghost-rock alteration is seen in Gumnište locality, and remnants of cupolas and calcite crust are found along the slope of Buturica Valley, just below Provalata Cave (above the Melnica spring). Similar assemblage of phreatic morphology covered by calcite crust and clay deposits, as in the first speleogenetic phase in Provalata Cave, is seen at Čavkarnik erosion exposed cliff. On the southern slopes of both Pantelejmon (1344) and Gola Skrka (1187) at 1040- and 930-m elevations, small thermal vents are found with warm air flow (although the Skrka vent is now inactive).

Geological and Geomorphological Control on Hypogenic Speleogenesis

The hydrothermal karst system is still active in all of the three localities, with low-temperature thermal springs discharging generally small amount of water (up to 15 l/s in Toplek). Water is most likely of meteoric origin, with possible participation of juvenile and connate waters also considered for Kožuf area (Boev and Serafimovski 1996), with deep circulation which resulted in increased temperatures due to the high geothermal gradient as a result of Kožuf (and Kozjak) volcanism.

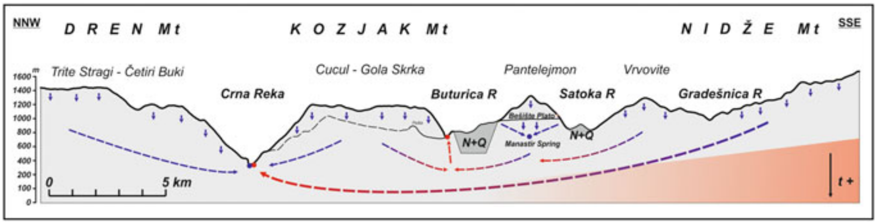


Fig. 4.35 NNW–SSE cross section of trough Podot (Crna Reka) and Melnica (Buturica River) karst areas with schematic representation of the possible hydrogeological relationships

In Melnica and Podot areas, beside the thick marble massif on Gola Skrka—Cucul Mt. segment—deep circulating water contribution maybe coming also from the marble massif south of Satoka River (Vrvovite, Nidže Mt.), with the discharge area in Melnica representing the local to intermediate hydrogeological system, while the regional circulation is directed to the lowest base level position in Crna Reka Valley at Podot locality (Fig. 4.35).

The hydrothermal flow is directed to and along regional or local tectonic structures (Kožuf area), on the margins of Neogene tectonic basin (Mariovo Basin, Melnica area), and also to the base level position (Crna Reka Valley, Podot area).

Hydrothermal karstification was active since Pliocene in Allchar (Kožuf area), Provalata Cave, and Čavkarnik (Melnica area). Late Pliocene and Early Pleistocene deposition in both Mariovo and Tikveš basins filled these areas with sediments (mostly pyroclastic deposits and travertines) and may have partly closed these systems, although travertine deposition (in lacustrine environments) in both Mariovo Basin, Kožuf area and along Crna Reka Valley may indicate that there was still ongoing contribution by the hydrothermal systems.

Pleistocene evolution of the hypogenic karstification was generally connected to the draining of Mariovo Lake and Central Macedonian Lake, and incision of valleys of Crna Reka and its tributaries. ^{40}Ar/^{39}Ar dating of speleogenetic alunite and jarosite (products of above water table sulfuric acid speleogenesis) in Provalata Cave allowed locating the timing of draining of Mariovo Lake, between 1.8 Ma (corresponding to the youngest tephra layers found in the uppermost travertine deposits of Mariovo Lake) and 1.6 Ma (the age of speleogenetic alunite and jarosite formed after Buturica River incised through the travertine and pyroclastic deposits to the underlying Cambrian marbles). Pleistocene valley incision lowered the base level position, which shifted the position of the thermal springs to lower elevations, leaving fossil hypogenic caves at higher elevation (Provalata Cave), and denudation exposed hypogenic karst features on surface (near Provalata Cave, Gumnište, Čavkarnik), as well as allowing phantom cave development (Karši Podot Cave) by removal of ghost-rock weathering produced dolomitic sand alterite.

Recognized Speleogenetic Mechanisms

Main speleogenetic mechanism responsible for hypogenic karstification in these areas is hydrothermal speleogenesis, where carbonate rocks are dissolved by rising thermal waters due to the inverse relationship of carbonate solubility and temperature (Dublyansky 2000a). After shift to a shallower environment, lowering of pressure allowed release of CO_2 from the solution, bringing the waters to supersaturated condition, forcing deposition of calcium carbonate. This is most clearly evident in Provalata Cave, where phreatic morphology is covered by thick mammillary calcite crust. The calcite crust in Melnička Peštera 1 and 2 is likely from the same origin. In Allchar locality, the deposition is much more complex due to the proximity of the volcanic intrusions, with much higher temperatures and high content of dissolved ore elements which formed Sb–As–Tl–Au ore mineral deposits.

In dolomitic rocks, such as the Precambrian dolomitic marbles in Melnica and Podot localities, and the Upper Triassic dolomites in Kožuf locality, a ghost-rock weathering (alteration) process was also operating. By this process, thermal water dissolved the calcite matrix, leaving dolomite crystals as dolomitic sand alterite, which increased the porosity of the rocks, but with the alterite residue remaining in situ, no caves were produced. In Melnica, removal of this alterite exposed remnant non-dissolved pendants on surface, while in Podot locality removal of dolomitic sand by backflooding of Crna Reka formed Karši Podot Cave (phantomization process; Bruxelles and Wienin 2009; Quinif 1999).

Another hypogenic speleogenetic mechanism recognized is sulfuric acid speleogenesis (Egemeier 1981; Palmer 1991, 2007, 2013). Evidence of cave development by sulfuric acid is clearly seen in Provalata Cave. Sulfuric acid phase followed the first thermal carbonic speleogenetic phase, with condensation corrosion dissolving calcite crust and marble host rock, depositing large gypsum deposits as replacement gypsum and forming alunite, natroalunite, and jarosite at the contact with clays. Possible source of H_2S can be the coal deposits of Mariovo Basin, considering the close proximity of the cave to the deposits, although further sulfur isotope analysis of cave gypsum, coal, and sulfate in the Melnica spring is necessary to test this theory. In Kožuf area, sulfuric acid speleogenesis is considered as a possible late operation mechanism due to the sulfate content in the thermal springs, which based on the situation at Allchar hydrothermal ore deposits are likely due to sulfuric acid formed by oxidation of iron sulfide minerals.

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Chapter 5
Epigenic Cave Development

5.1 Vitačevo Karst

Vitačevo karst area is located in the western part of Vitačevo Plateau, where Crna Reka, Kamenica, and Blašnica rivers have eroded the cover of Tikveš Basin deposits, exposing underlying Cretaceous limestones (Fig. 5.1).

There are two karstic areas here, located between the valleys of Crna Reka and Kamenica (Fig. 5.2). One is to the south, mostly presented with more or less continuous plateau-like terrain developed in folded limestones that overlay clastic rocks; and the other is at the confluence of Kamenica and Crna Reka, where a limestone block is delineated by deeply incised valleys of Crna Reka and Kamenica rivers. Beside these larger outcrops, limestone can be found also as lenses in the clastic sediments in Kamenica Valley, but more prominently to the SW, on the right side of Crna Reka Valley.

Geology

Vitačevo Plateau is part of Tikveš Basin and belongs to the Vardar tectonic zone. The area is mostly covered with sediments of Neogene Tikveš Basin, but older Cretaceous and Eocene rocks are exposed by erosion in the western part of the plateau (Fig. 5.3).

Cretaceous rocks are presented with Late Cretaceous (Turonian) clastic sediments in the lower part: conglomerates, sandstones, and shales, with lenses of limestones; and platy-to-massive limestones in the upper parts.

Conglomerates are heterogeneous, composed of well-rounded fragments of quartzite, gneiss, sandstones, and shales, usually found in the lower parts of the formation, slowly grading upward into sandstones. Sandstones are the most widespread member of the clastic formation, mostly composed of quartz and mica minerals, but also contain epidote, zircon, tourmaline, rutile, garnet, pyroxene, and titanite (Dumurdžanov et al. 1976). Platy-to-massive limestones are developed as the topmost part of the Turonian formation. They are micritic, gray to gray white in color with sandy to marly alternations at places, containing numerous fossil

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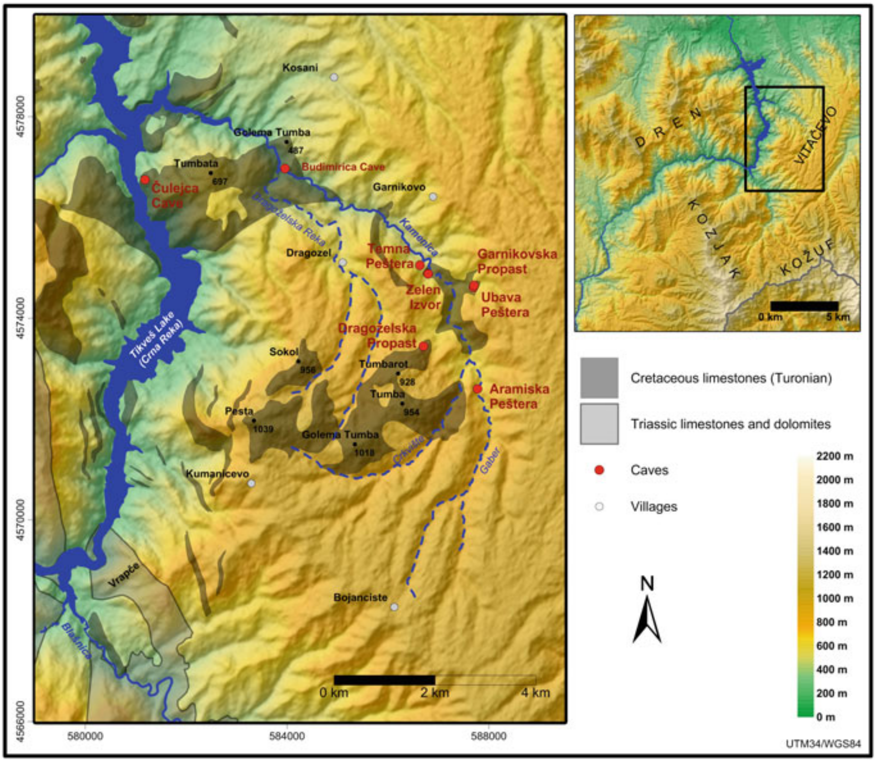


Fig. 5.1 Location of Vitačevo karst area

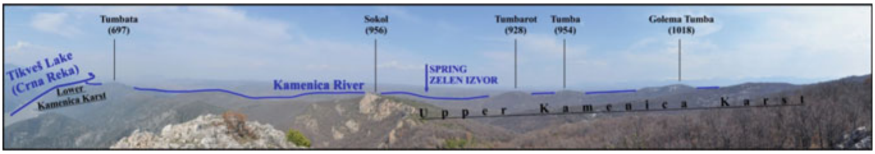


Fig. 5.2 Panoramic view taken from Sokol (956 m) to the NE of Vitačevo Karst

fragments (Rakićević and Pendžerkovski 1970; Dumurdžanov et al. 1976). They are found in two larger outcrops: one in the upper part of Kamenica Valley and the other in the lower part, between the confluence of Kamenica and Crna Reka.

The Turonian rocks were deformed in the latest Cretaceous to Paleocene time (Laramide phase), in number of folds and faults with NNW direction (Dumurdžanov et al. 2005), with Crna Reka and Kamenica anticlines, and Dragožel syncline the most prominent ones, and several secondary folds.

To the northeast, these Cretaceous rocks are covered with Upper Eocene (Priabonian) conglomerates (part of the Paleogene Tikveš Basin), yellow-red in

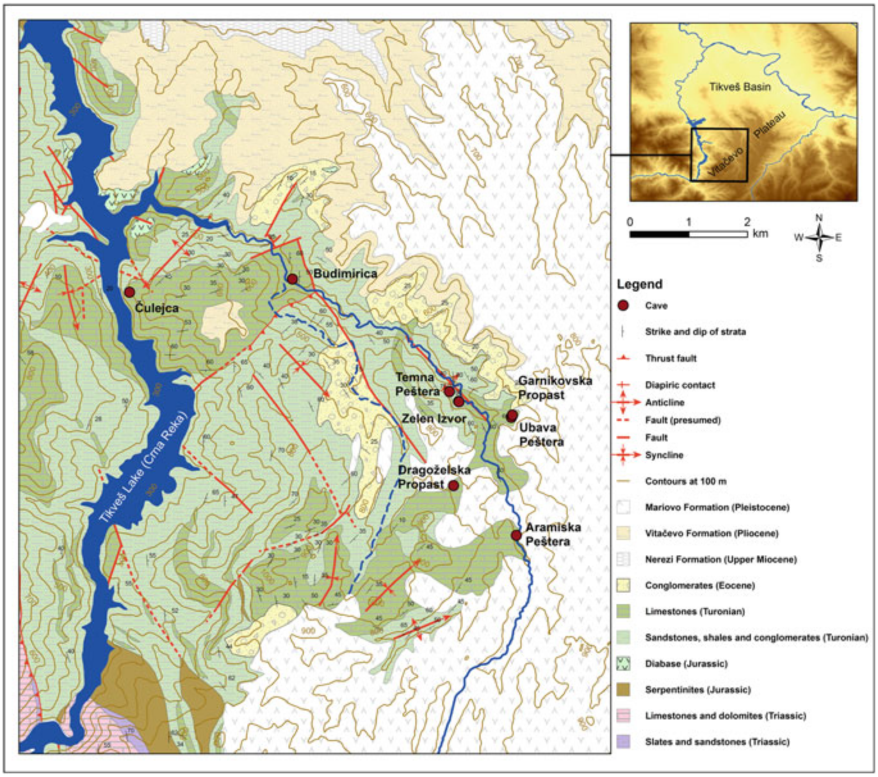


Fig. 5.3 Geological map of western part of Vitačevo Plateau. Geological data modified after Dumurdžanov et al. (1976), Hristov et al. (1965), Rakićević et al. (1965), Rakićević and Pendžerkovski (1970); Geološki Zavod–Skopje (unpublished)

color, with fragment originating from the Turonian sediments (Rakićević and Pendžerkovski 1970). They were deformed during the Pyrenian (Lower Oligocene) and Savian (Oligocene-Miocene) orogeny phase (Petrov et al. 2010).

A NW–SE fault called Dragožel Fault cuts through the eastern limb of Dragožel syncline. This fault is part of a prominent regional fault zone on the western marginal border of the Eocene basin along the Vardar Zone, a system of syn-sedimentary faults, west of which the Eocene deposits have smaller thickness (near Dragožel Village), but to the east (central part of Tikveš Paleogene Basin) they are up to 3000 m thick (Arsovski 1997).

To the NE, east, and SE, these Cretaceous and Eocene rocks are covered with deposits of the Neogene Tikveš Basin (Dumurdžanov et al. 2004): Upper Miocene clays and sandstones (Nerezi Formation), covered by Pliocene tufaceous deposits with sandstones and travertine beds (Vitačevo Formation), with tuff agglomerates as the topmost (Mariovo) formation. The upper (Vitačevo and Mariovo) formations were once covering the whole area and were later eroded after draining of Central

Macedonian Lake and development of fluvial drainage, exposing older rocks in the western part of Vitačevo Plateau.

Two sets of fault structures are recognized in the vicinity of Kožuf area (Kochneva et al. 2006; Boev and Jelenković 2012), also connected to Vitačevo Plateau: older (reactivated) Vardar strike faults with NW–SE (older) to N–S (younger) orientation; and NE–SW to E–W strike, younger than the Vardar system, associated with recent seismic activity.

Geomorphology

Vitačevo Plateau is a sedimentary plateau, composed of pyroclastic rocks deposited in lacustrine to fluvial environments. It is well bounded by the valleys of Blašnica to the south west, Crna Reka to the west and north west, Bošava to the east and Vardar to the north and north east.

In the western part of this plateau, older Paleogene and Cretaceous rocks are exposed by incision of Kamenica and Blašnica rivers as well as by incision of Crna Reka. The area between these three valleys is a plateau terrain formed mostly in Cretaceous rocks, with younger pyroclastic rocks still preserved in the higher southern parts. The elevations are between 800 m and 1000 m a.s.l. in the southern parts, with small hills such as Tumba (954 m), Tumbarot (928 m), Golema Tumba (1018 m), Pešta (1039 m) and Sokol (956 m) separated by small valleys ("tumba" in Macedonian means "small hill"). The elevations are decreasing northward (Plazje, 780 m), down to the larger hill called Tumbata (697 m). Here, the upper part of the hill is covered by sediments of Vitačevo Formation. The highest part of the plateau is developed in limestones folded in several prominent folds with north to NE-oriented axis. Small valleys have developed usually along the top of the anticlines, exposing lower flysch rocks, with low-relief karst morphology developed in the small hills between them.

In the upper part of Kamenica Valley, in its smaller tributary Crkvište, as well as at the confluence of Crkvište and Gaber, where Kamenica actually begins, we can see a peculiar situation where stratified tuff deposits are filling depressions of lower elevation. These depressions are elongated with eastward general direction having a dendritic pattern, representing former valley network (Fig. 5.4). Considering the stratified tuff deposits (Pliocene Vitačevo Formation) filling these paleovalleys, they are older than the latest Quaternary fluvial evolution, either of Pliocene age or even older. They were likely formed by Pre-Pleistocene rivers flowing to the east, later filled with stratified tuff deposits of Tikveš Basin (Vitačevo Pliocene Formation, grading upward to Mariovo Pleistocene Formation). After draining of Central Macedonian Lake in Pleistocene, incision of Kamenica River started in sediments of Mariovo and Vitačevo Formation, continuing to the older Cretaceous (here mostly limestone) rocks below, developing the present superimposed valley.

Determining the location and direction of these paleovalleys is important in understanding possible past karst development phases, and the inheritance component of the karst, especially since downstream and upstream parts from the confluence of Gaber and Crkvište are developed in Cretaceous limestones.

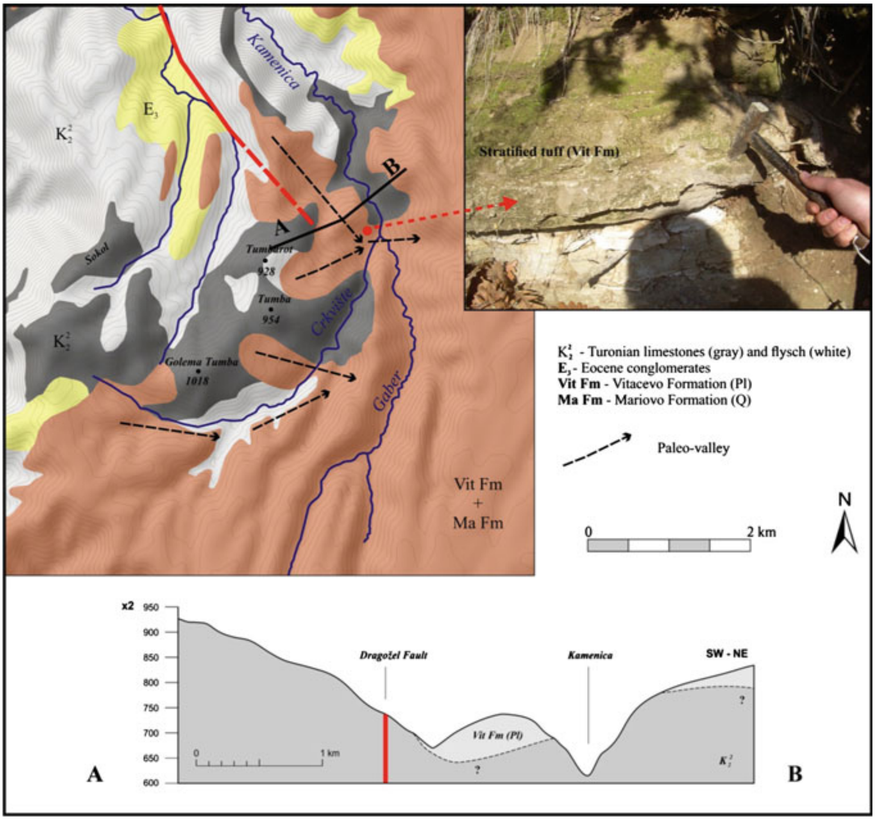


Fig. 5.4 Paleovalleys filled with deposits of Vitačevo Pliocene Formation in the upper part of Kamenica Valley

The river valleys delineating the plateau borders are from Pleistocene developed after draining of Central Macedonian Lake and start of fluvial relief development in the basin. They cut through the Early Pleistocene and Pliocene deposits first and continued downward in older rocks of mostly Cretaceous and Eocene age (superimposition). Considering the karst rock outcrops distribution mostly in the western part of the plateau, incision of Kamenica River has played a major role in shaping the relief of this part of the Vitačevo Plateau. As Kamenica River is a tributary to Crna Reka, its incision is guided by the incision of Crna Reka, representing its local base level. Crna Reka incision also directly influenced erosion and relief formation in the western end of the plateau.

As this area was filled with sediments (Vitačevo Formation, Mariovo Formation) deposited in lacustrine to fluvial environment in Tikveš Basin, part of the Central Macedonian lake system, karst development stopped (was fossilized) during the burial (Pliocene to Early Pleistocene). After the draining of the lake system (as late as Middle Pleistocene; Dumurdžanov et al. 2005) karst development was guided by the removal of overlying Plio-Pleistocene deposits, which in turn was controlled by surface erosion due to incision of Crna Reka and its tributaries.

5.1.1 Aramiska Peštera

Aramiska Peštera is located in the upper part of Kamenica River valley, ~0.5 km south from the confluence of Gaber and Crkvište streams, where Kamenica River actually begins (Fig. 5.5). The entrance is at 660 m, on the left side of the stream 4 m above the riverbed, located between blocks falling along the valley side.

The cave is formed in the Cretaceous Turonian limestones of Kamenica Anticline. The axis of this anticline plunges to the NW, where most likely is cut by the Dragožel fault, now covered with pyroclastic rocks of Vitačevo and Mariovo Formations (Fig. 5.5).

Aramiska Peštera was first described by Manakovik (1971), together with some other caves from Kamenica Valley interpreting their evolution with the successive draining of Central Macedonian Lake and incision of Kamenica River in the

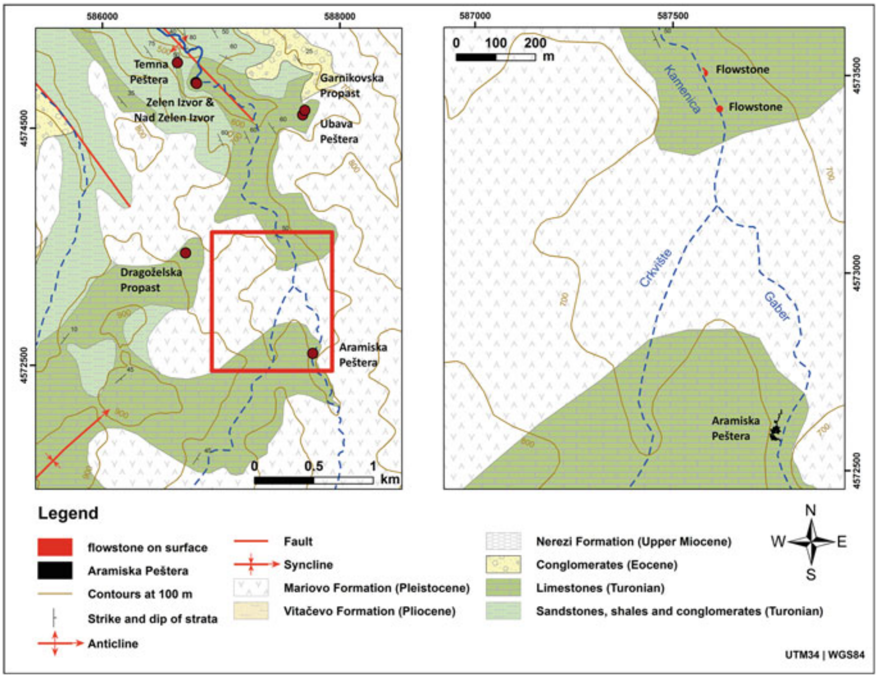


Fig. 5.5 Location of Aramiska Peštera and other caves in the upstream part of Kamenica Valley. Geological data modified after Rakićević and Pendžerkovski (1970), Geološki Zavod–Skopje (unpublished)

limestone rocks, with Aramiska Peštera considered as the oldest, located in the upstream part with highest elevation of the three, and Buturica and Crkviče considered as younger, located at lower elevations downstream along the valley of Kamenica River.

5.1.1.1 Morphology

The entrance to the cave is between collapsed blocks, on the left side of the valley about 5 m above the present riverbed. This side of the valley is vertical and quite unstable, so the former entrance (which was also between collapsed blocks, but a little bit lower) is now choked due to movement of the blocks in recent years.

The cave has northward general direction below Kamenica River valley. Morphologically, we can separate the passages at higher elevations including Entrance Room, Room of Bones, and Pit Passage, from the passages at lower elevations located both in the upper part (Upper Stream Passage) and lower part (Lower Stream Passage, Flowstone Room, and Below Pit Passage).

The passages in the lower elevation have generally smaller dimensions, with vadose canyons leading to sub-horizontal water table (epiphreatic) tube-like passages, which change to phreatic passages to the north. The present active passage is composed of vadose canyon passage emerging from the SE end of the Room of Bones and continuing to the west at the end of Upper Stream Passages. The passage then turns to the north and continues in the Lower Stream Passage, diminishing in vertical gradient changing to sub-horizontal passage leading to the phreatic passages below Orle Lake.

In the vadose section, the passages are roughly following dip of strata (dipping to the SW by 60°), but they are also influenced by former phreatic parts developed along the strike as in Room of Bones (SW to west direction), while in the lower epiphreatic and phreatic section, passages are developed in northern general direction changing between strike direction (NW) and SW–NE-oriented fractures. Change of gradient of passages (steep to sub-horizontal) coincides with the change of vadose to phreatic morphology, which indicates former water table position (Palmer 2007). This organization of passages can be seen in at least four positions in the lower elevations (Fig. 5.6), while in the higher elevations in the cave, passages are greatly modified by paragenesis (Figs. 5.7, 5.8 and 5.9).

The passages at higher elevation have larger dimensions and are highly affected by collapse processes, with paragenetic morphologies above the (clay to sand) sediment-filled floors and walls. The upper parts of Upper Stream Passage have clear paragenetic morphology with paragenetic canyon formed in the ceiling of former tube passage due to sediment (sand) deposition. In plan view, this paragenetic passage continues across the Room of Bones, leading to the small passage in the NW end of the room, choked with sediments. The passage connecting Room of Bones and Entrance Room is also a paragenetic passage with ceiling channels leading to a flat paragenetic ceiling with small ceiling channels in the Entrance Room. Remnants of Paragenetic morphologies are seen also in Pit Passage. The vertical extent of the

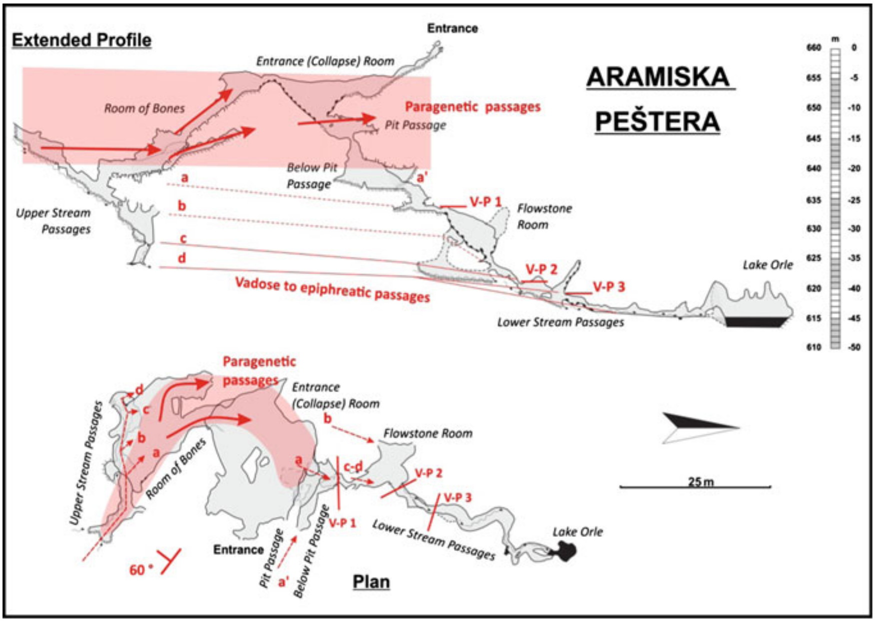


Fig. 5.6 Simplified cave map of Aramiska Peštera with morphological interpretation of passages: paragenetic passages in the higher parts and series of vadose to epiphreatic passages (*a*–*d*) in the lower parts with location of several vadose-phreatic transitions (*V-P*). For more detailed cave map, see Appendix

paragenetic development (Between the tube in Upper Stream Passages and the flat ceiling in the Entrance Room) is 15 m. These passages are likely connected to aggradation and base-level rise in the output part of the karst system (Zelen Izvor locality). The present water table in Aramiska Peštera is at 615 m a.s.l. (Lake Orle), while the location of Zelen Izvor spring is at 510 m a.s.l. If we apply the same gradient between the Entrance Room (655 m) and the spring area, it corresponds to the terrace at 550 m and Temna Peštera–Dragožel Cave, which also has abundant clastic deposits and paragenetic morphologies (see, Sect. 5.1.5).

Small alluvial paragenetic notches can be seen in the lower epiphreatic passages, which have only widened the passages due to lateral dissolution along the sediment covering floor, but ceiling has retained phreatic morphology with pockets and small cupolas indicative of floodwater dissolution in epiphreatic settings.

5.1.1.2 Cave Sediments

Clay sediments are covering room and passage floors mostly in the Room of Bones, Entrance Room, and the Below Pit Passage. They are usually covered with breakdown material. The X-ray analysis of a sample (AR01) from the western wall

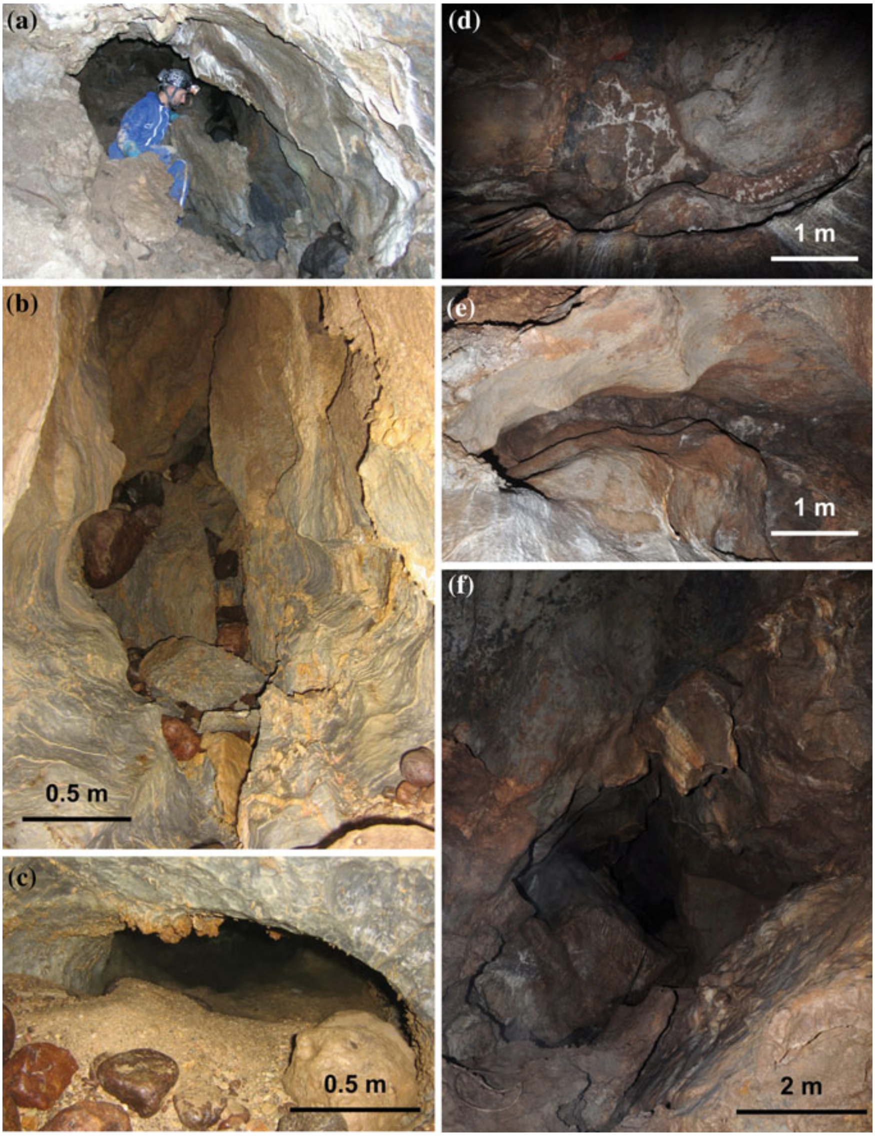


Fig. 5.7 Morphological features (1) in Aramiska Peštera: **a** Vadose entrenchment in paragenetic passage in the Upper Stream Passages (USP); **b** Vadose passage in the USP; **c** Phreatic passage (upper sump) in the lower end of USP; **d** Paragenetic ceiling channel and pendants in the Room of Bones (ROB); **e** Paragenetic ceiling channel in the ROB; **f** View of the passage leading from the ROB to the Entrance Room. Photographs by J.-Y. Bigot (**a**) and M. Temovski (**b**–**f**)

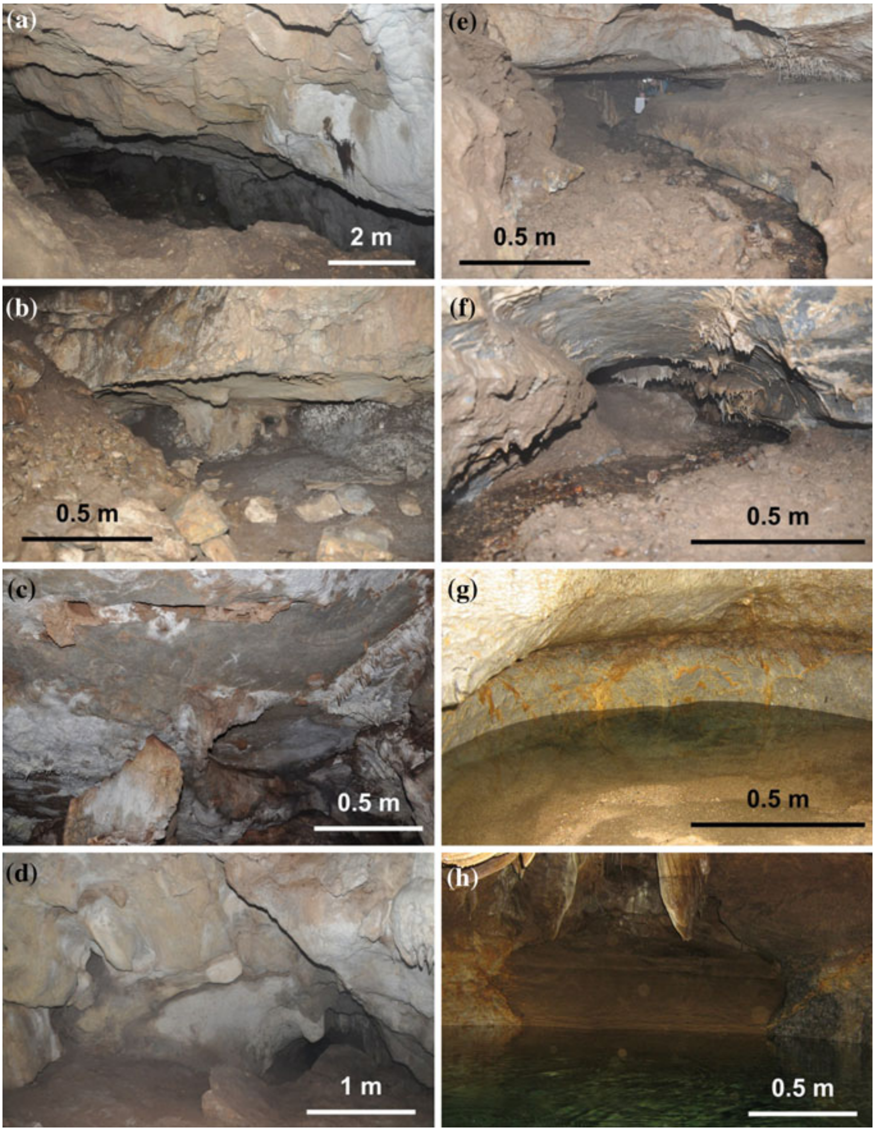


Fig. 5.8 Morphological features (2) in Aramiska Peštera: **a** Ceiling above the collapsed block in the Entrance Room (ER); **b** Paragenetic morphology of former ceiling (lower part of the collapsed block in **a**); **c** Flat ceiling and ceiling channels in the west part of ER; **d** Paragenetic ceiling channel and pendants (passage between ER and ROB); **e** Prominent paragenetic water table notch and flat ceiling with vadose stream incision in the Lower Stream Passages (LSP); **f** Vadose channel incised in a phreatic passage in the LSP; **g** Water-filled phreatic side passage in the LSP; **h** View of the end sump (Orle Lake) with clay-filled passage above water table. Photographs by M. Temovski

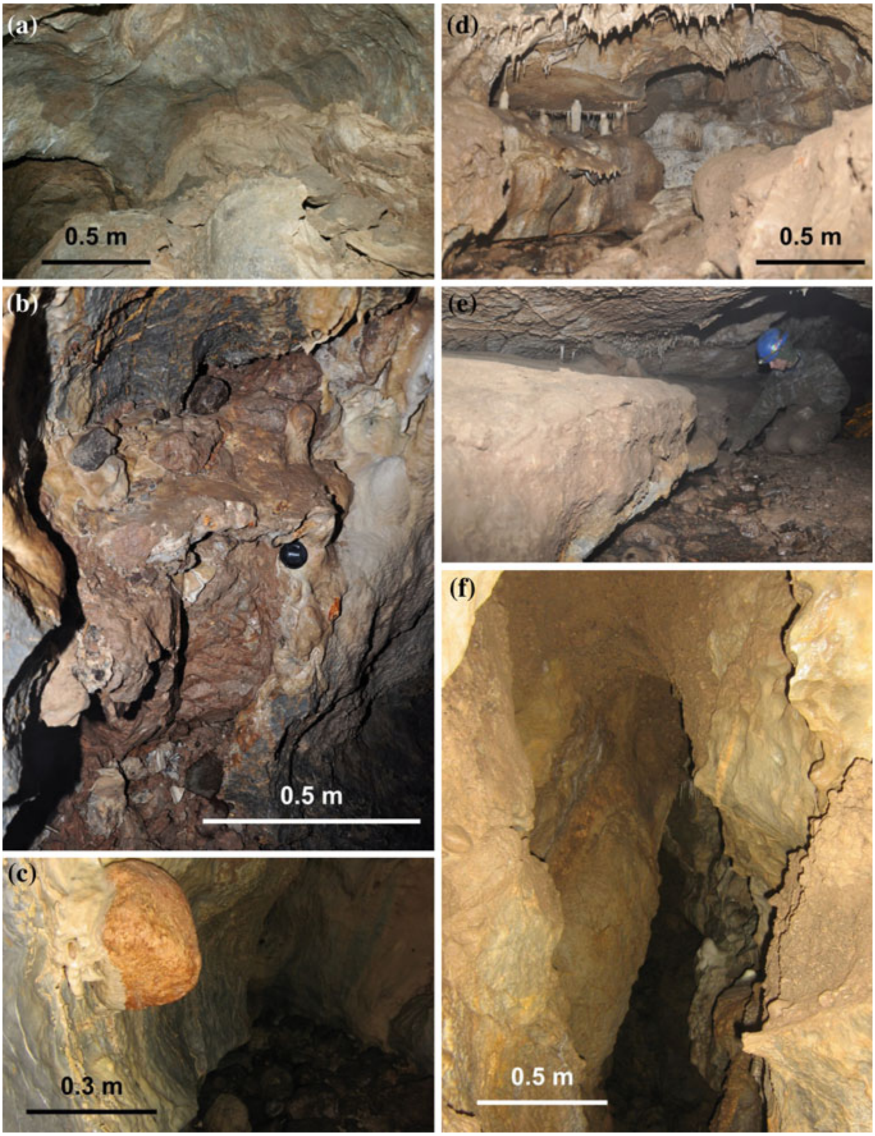


Fig. 5.9 Cave sediments in Aramiska Peštera: **a** Brown clay-filling passages (and detached from wall) in the USP; **b** Clay, sand, and gravel with bones filling niche in the USP; **c** Andesite cobble, 20 cm in diameter, stacked to the wall by flowstone above the passage floor (USP); **d** Coarse fluvial sediments in the channel, with sand and clay in a paragenetic notch, covered with flowstone in the LSP; **e** Gravel and pebbles deposited in a stream channel, with sand and clay in a paragenetic notch (LSP); **f** Sand- and gravel-filling ceiling channel and wall niches in a phreatic passage (USP). Photographs by M. Temovski

Table 5.1 Mineralogical composition of clay sediments in Aramiska Peštera

Sediment (sample)	Mineral composition
Pale brown clay (AR01)	Montmorillonite, kaolinite, sanidine, fluorapatite, muscovite, quartz
Sandy layer in AR01 (AR02)	Muscovite, albite, sanidine, montmorillonite, kaolinite, quartz, cristobalite, fluorapatite

of the Room of Bones has mineralogical composition of montmorillonite, kaolinite, sanidine, muscovite, quartz, fluorapatite (Table 5.1). Fluorapatite is deriving from bones found close to the sampling site, and the clay, mica, feldspar, and quartz minerals are likely from the overlying pyroclastic formations (Vitačevo and/or Mariovo Formations).

Sandier layer from the AR01 sample had the same mineral composition with also albite and cristobalite. These clays have similar mineralogical composition to similar clays in the other caves of Vitačevo karst and were brought by allogenic waters draining and eroding the pyroclastic rock-covered surfaces.

Coarser sediments are found covering vadose parts in the Upper and Lower Stream Passages. This includes brown sands, found covering floor in the Lower Stream Passage, and filling the ceiling of paragenetic channels in the Upper Stream Passages.

Cobbles and larger fluvial clasts are found all along the active stream passages as well as in the now inactive passages, as in the Below Pit Passage, where such blocks can be up to 1 m in diameter. They are composed of volcanic rock (usually andesite), originating from the pyroclastic rocks, more typical for the Mariovo Formation. Smaller pebbles are also found all along this vadose stream passages, down to the Orle Lake.

Breakdown material covered the floors at most of the upper parts of the cave, especially in the Entrance Room, Room of Bones, as well as in the Below Pit Passage and Flowstone Room. In the Entrance Room below, some of the collapsed blocks paragenetic flat ceiling and small channels can be seen.

Typical vadose speleothems (stalactites, stalagmites, curtains, and flowstone) are found throughout the cave. Thicker flowstone deposits are covering passage floor in the Flowstone Room, as well as in the Entrance Room and Room of Bones. In the Room of Bones, some human bones are also covered by flowstone deposits, quite destroyed by treasure hunters. A skull was collected for age determination (Manakovik 1971), but results were never published.

5.1.1.3 Hydrological Characteristics

Water is flowing in the Upper and Lower Stream Passages only in spring and autumn and after heavy rain, and they are dry during summer and winter. The lower sump (Orle Lake) water level oscillates up to 1 m between dry and wet seasons.

Table 5.2 Field measurements of pH, Electronic conductivity (EC) and temperature (*t*) of stream and drip water in Aramiska Peštera

Location	Date	pH	EC (μs/cm)	*t* (°C)
Upper stream (st.104–105)	31.03.2013	8.07	126	6.1
Upper stream (st.106)	31.03.2013	7.72	149	6
Upper sump (st.106)	31.03.2013	7.85	137	6.7
Lower stream (st.11–12)	03.03.2013	7.77	156	6.2
Lower sump (Orle Lake)	03.03.2013	7.65	163	8.3
Drip water (above Orle Lake)	03.03.2013	7.62	704	10.2

Some field analyses of pH, EC, and temperature of the stream, lake, and dripping waters in the cave show clear difference between the allogenic water in the stream passages with low dissolved content and slow moving autogenic dripping waters with high dissolved content, forming flowstone and dripstone speleothems (Table 5.2).

Considering the distribution, thickness, and structure of limestone rocks in the upper part of Kamenica Valley, and the only discharge point of this karst system being Zelen Izvor spring, 2.5 km downstream from the cave at the contact of limestone with siliciclastic rocks, water of Aramiska Peštera is likely draining to Zelen Izvor. The water level in the Orle Lake is located 45 m below the cave entrance at 615 m a.s.l., and 105 m above Zelen Izvor, giving a general water table gradient of 4.2 m/100 m.

5.1.1.4 Speleogenesis

Aramiska Peštera is a ponor cave with vadose passages leading to epiphreatic and phreatic passages formed by sinking waters of Kamenica River. The evolution of the cave is connected to the downward evolution of the karst system due to lowering of base level with incision of Kamenica River. Lowering of base level, lowered the position of the spring in the output part of the karst system (Zelen Izvor locality), which led to vadose incision and development of passages at lower elevation toward the newly formed water table. The upper parts of the cave are paragenetic passages formed by upward dissolution due to increased sediment deposition. Applying the same gradient between the present water table in Aramiska Peštera and Zelen Izvor spring to the paragenetic passages shows correlation with cave Temna Peštera–Dragožel, which correlates with a terrace developed at 550 m elevation. This indicates that the paragenetic development of passages in the upper parts may be connected to general aggradation in the lower part of Kamenica Valley.

Considering the geomorphological evolution of Kamenica Valley, formed after the draining of the Central Macedonian Lake (as late as Middle Pleistocene; Dumurdžanov et al. 2004), and first incised in Tikveš Basin deposits (Mariovo and Vitačevo Formations), then superimposed on the Cretaceous limestones and flysch, Aramiska Peštera is likely as old as Late Pleistocene, with first development of phreatic passages due to seepage along the Kamenica riverbed, then increasing capture combined with lowering of spring position (Zelen Izvor locality) in the downstream parts of the valley leading to vadose development of passages. Period of large aggradation in the spring area forced paragenetic development of passages in Aramiska Peštera, with later downward development of passages due to lowering of spring position with Kamenica River incision. Periods of stable spring position in between incisions of Kamenica River led to development of at least four levels of passages below the paragenetic passages. The lowest level is still active with only small vadose stream in wet season (spring and autumn) leading to Orle Lake, although during these periods Kamenica River is still flowing on the surface due to sediment in riverbed which prevents complete under capture of surface waters.

5.1.2 An Unroofed Cave in Kamenica Valley

Along Kamenica Valley, downstream from the confluence of Gaber and Crkvište streams, at two locations close to the present riverbed, there are thick exposures of flowstone remnants on surface (Figs. 5.5 and 5.10).

Fig. 5.10 Flowstone outcrops in a small gully in the downstream location. Photographs by M. Temovski

At the first (downstream) location, on the right side of the river, flowstone deposits cover larger area (~ 150 m^2) and have more preserved morphology, comparing to the second (upstream) location, where flowstone blocks can be found along some collapsed limestone blocks on the left side of the river.

The thickness of the flowstone in the unroofed cave is up to 1 m at places, with general direction of flow to the SW. The elevation of the outcrop in the downstream part is between 613 and 618 m (Fig. 5.11), with the upstream location in between. The speleothems were deposited in a vadose setting in a cave that was developed in dip direction to the SW.

This cave can be a vadose cave that developed toward the former water table before the incision of Kamenica reached this elevation. As evident from Aramiska Peštera and Garnikovska Propast, thick flowstone speleothems are deposited at 40 m and deeper below the bottom of the valley, where there is still an intermittent surface flow. On the right side of the valley above the unroofed cave, on the slope of the gorge there are number of solutionally enlarged fractures, some of them coated with flowstone. They could have been the shafts supplying the cave below.

Another possibility that has to be considered, due to the proximity of the nearby paleovalley filled with stratified tuff of Vitačevo (Pliocene) Formation, is that this cave developed in a previous phase toward the NW–SE-oriented paleovalley to the west of this location. Incision of Kamenica River later in Pleistocene cut through this cave, leaving only patches of flowstone in the unroofed cave and exposing the shafts in the upper parts of the gorge slopes. Future dating of speleothems will help answer this question.

5.1.3 Dragoželska Propast

Dragoželska Propast (propast meaning pit in Macedonian) is located 1.4 km to the NW of Aramiska Peštera, near to the road that leads to Dragožel Village, with entrance located at 750 m (Fig. 5.5).

The cave is formed in Turonian limestones in the western limb of Kamenica Anticline, along a prominent fault line—the Dragožel Fault.

5.1.3.1 Morphology

Dragoželska Propast is 71-m-deep cave with three morphological units: the Entrance Shaft, the Big Room, and the Lower Passage (Figs. 5.12 and 5.13).

The Entrance Shaft is a 50-m-deep dome-like shaft formed along the intersection of two fractures with WSW–ENE and NNW–SSE directions, with width from 2 × 1 m at the entrance to 3 × 6 m in the lower parts. In the upper part, the shaft is developed more along the ENE fracture, but at 20 m depth, it enlarges along the NNW–SSE fracture as well, thus creating a cross-like shape on plan view. In the

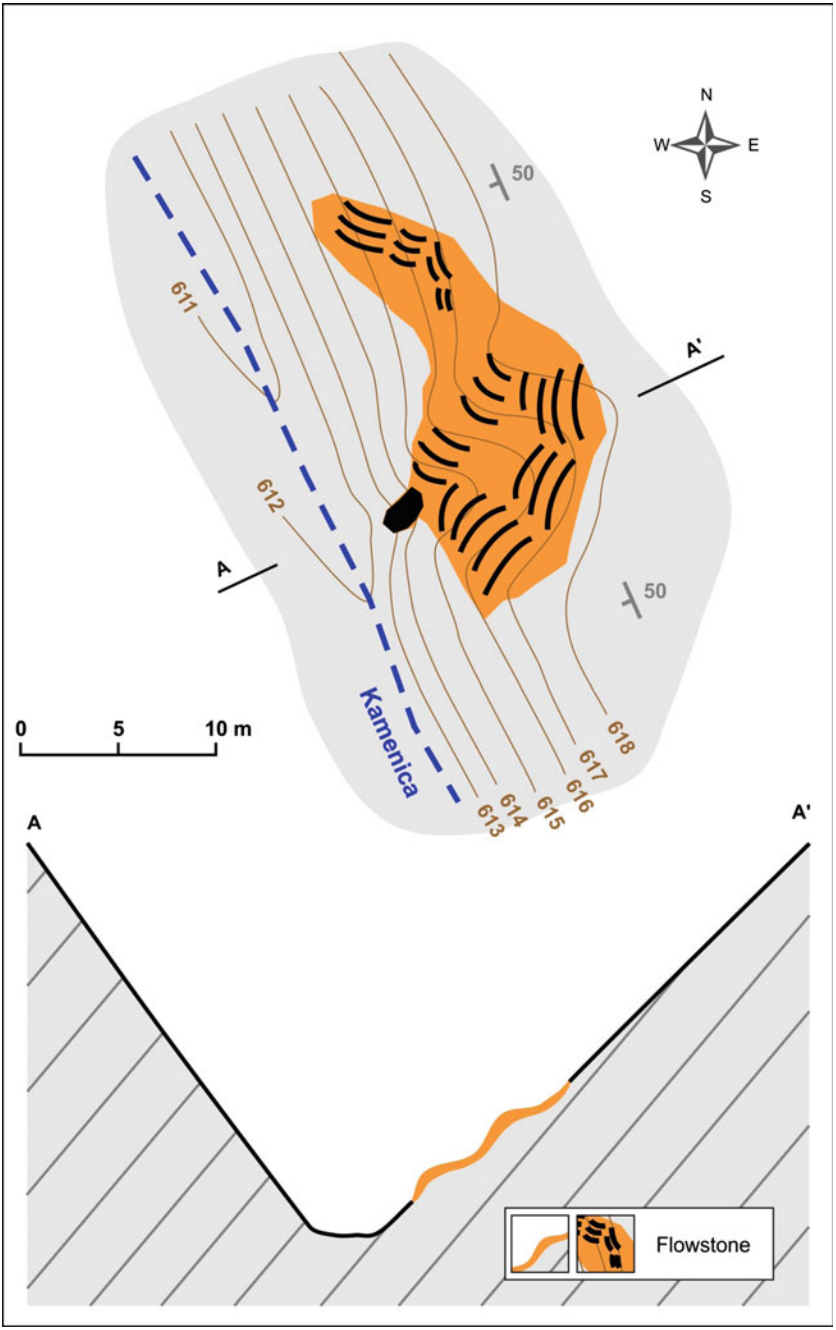


Fig. 5.11 The unroofed cave in Kamenica Valley (downstream location)

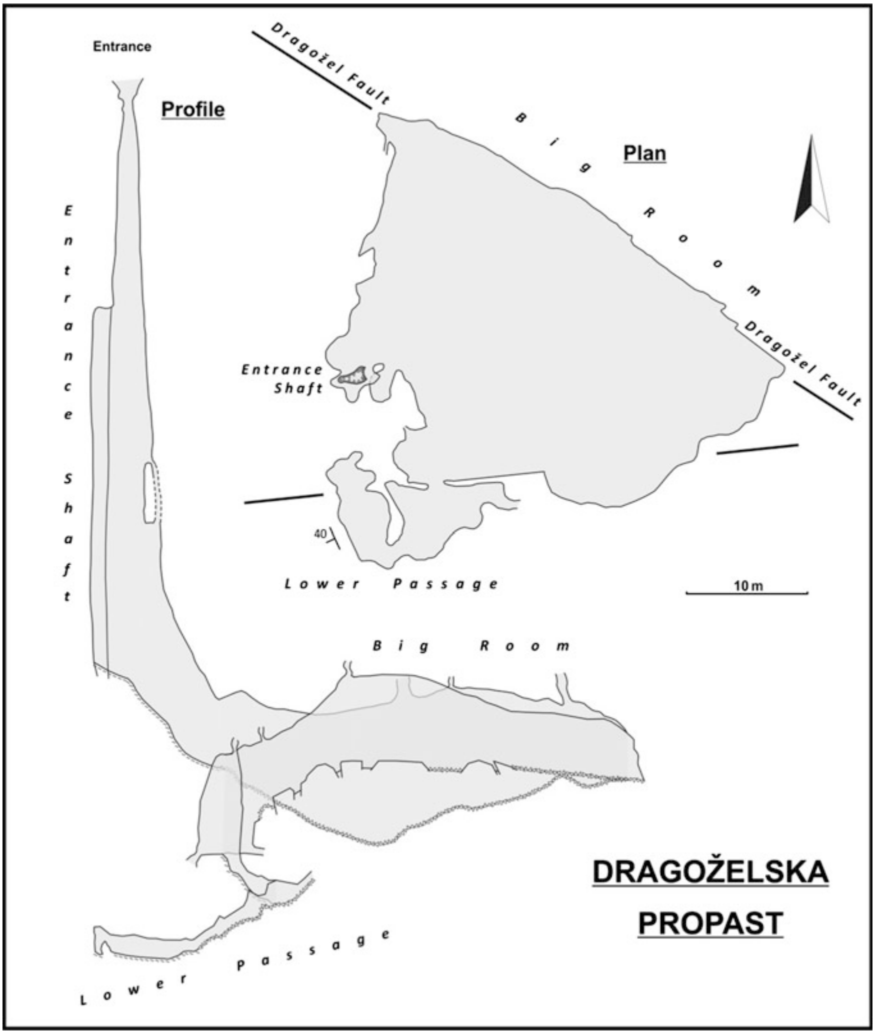


Fig. 5.12 Simplified map of Dragoželska Propast. For more detailed cave map, see Appendix

deeper parts, the passage is more developed along the NNW–SSE fracture, with the WSW–ENE fracture becoming less distinctive.

The walls are covered with clay and also stacked agglomerates from the pyroclastic rocks can be found in some solutional channels along the shaft wall.

The Big Room is the most prominent morphological feature, having a triangular shape in plan view with dimensions of 38 × 30 × 30 m, and ceiling ranging from 4 to 10 m and up to 18 m along the northern wall. It is formed at the intersection of two faults, one with WSW–ENE direction and the other, more prominent, in NW–SE direction. The second fault is actually continuation of Dragožel Fault line, which can

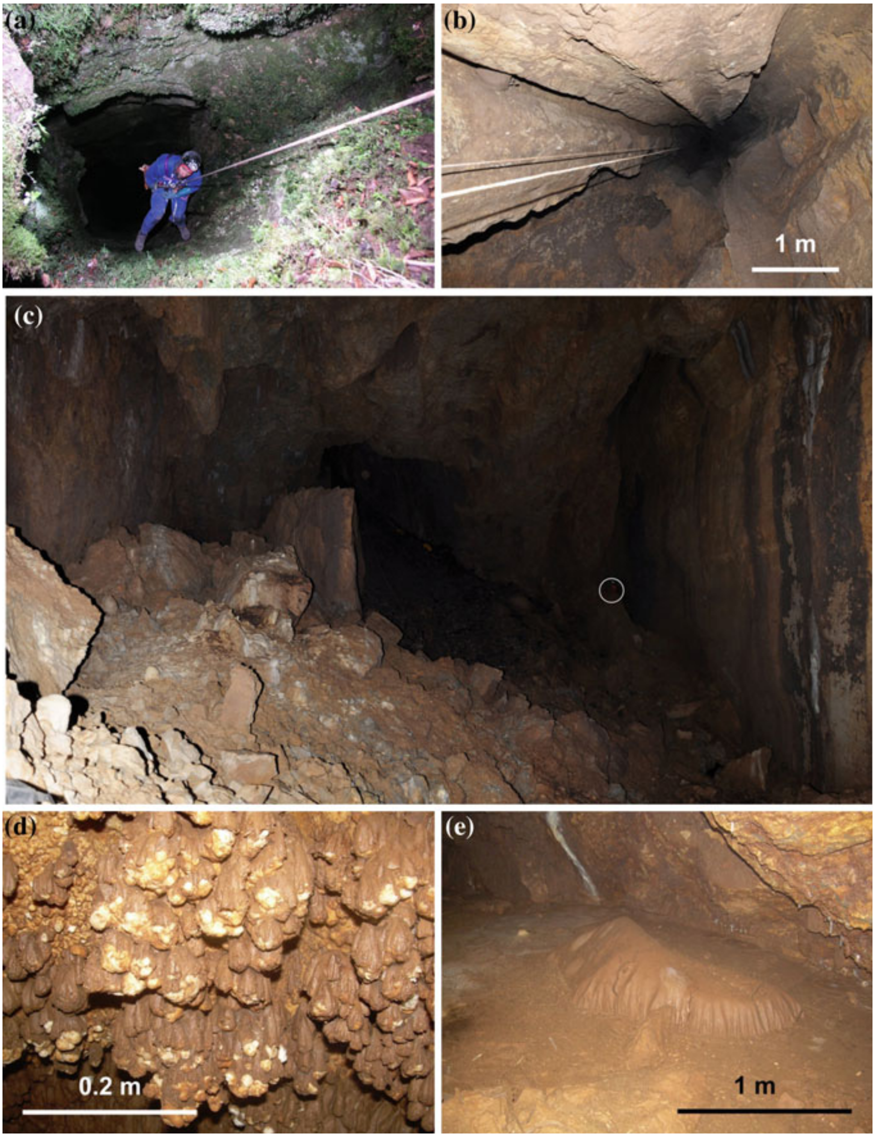


Fig. 5.13 Characteristic features in Dragoželska Propast: **a** The upper part of the Entrance Shaft, close to the surface; **b** The lower part of the Entrance Shaft, view from below (note the pyroclastic cobble in the wall channel); **c** Panoramic view of the Big Room (from the eastern part of the room), with Dragožel Fault to the right (*circled* caver for scale); **d** Brown clay covering popcorn speleothems (Lower Passage); **e** Clay-filled floor in the lowest part of the cave (Lower Passage). Photographs by J.-Y. Bigot (**a**) and M. Temovski (**b**–**e**)

be followed from Begnište to Dragožel villages. It is described as syn-sedimentary fault along the Tikveš Paleogene Basin (Arsovski 1997). Although Dragožel Fault is more prominent, fractures with WSW–ENE direction are more frequent. They are probably of younger age than Dragožel Fault, connected to Neogene–Quaternary tectonics (Kochneva et al. 2006; Boev and Jelenković 2012). The same WSW–ENE-directed fracture along which the entrance shaft is formed can be clearly seen in the ceiling of the Big Room guiding several smaller shafts. The Big Room is mostly enlarged by collapse between dense network of shafts that formed along WSW–ENE and NW–SE fractures and faults. The floor is covered with breakdown material, except close to the Entrance Shaft and below some shafts (as the one in the eastern part of the room), where we can see surface sediments such as tuff, soil, and even some bones deposited. Clay deposits can be seen filling pockets and wall channels mostly along the northern wall.

The third morphological unit is the Lower Passage. It has two small rooms, the first has dimensions of 10 × 10 × 7 m, with morphology controlled by the WSW–ENE fault controlling the southern wall of the Big Room and bedding of strata, dipping to SW by 40°. The lowest room has dimension of 10 × 3 m and is mostly developed along the strike of strata, with beds seen on the SW wall dipping to the SW by 40°. The NW part of this passage is cut by the WSW–ENE fault. The ceiling is 1.5 m high and the floor is covered with dark brown clay. On the SW wall, popcorn speleothems are found covered with clay deposits.

Most of the morphology seen in the cave is vadose, with shafts the prominent passage type, with small vadose channels also found on shaft walls. Most of the cave is affected by breakdown processes, removing evidence of former passage morphology. This is typically seen in the ceiling of the Big Room, but also in the Lower Passage.

5.1.3.2 Cave Sediments

Dark brown clay is found covering (filling) floor in lower parts of the cave. Such clay can be also found filling small voids (pockets, fractures) on the walls along the Entrance Shaft and the north wall of the Big Room, and remnants of it are found at places on the ceiling in the Big Room as well. X-ray analysis of a sample (DR01) from a small channel on the north wall showed composition of quartz and clay minerals (montmorillonite, halloysite-7Ä, illite), with a yellow layer (sample DR02) found in the same sample having similar composition with goethite, montmorillonite, calcite, muscovite, and quartz.

Mineral composition of the brown clays indicates origin from weathering of the overlying pyroclastic deposits.

Coarser allochthonous sediments composed of andesite cobbles originating from the pyroclastic agglomerates of Mariovo Formation are found in small wall channels and below the Entrance Shaft.

Breakdown debris and blocks are the most widespread sediments, especially in the Big Room, where they completely cover the floor.

Flowstone speleothems can be found along the north wall in the Big Room, and in the Lower Passage popcorn speleothems are found on the ceiling and wall, some covered with clay, indicating late deposition (or redeposition) of clay by ponding of vadose waters.

5.1.3.3 Speleogenesis

Dragoželska Propast is a vertical cave formed by vadose waters along the intersection of faults and prominent fractures in a fault zone. Due to high fracturing along the Dragožel Fault, many shafts have developed, which later resulted in collapse of highly fractured bedrock and enlargement of the Big Room, with north wall bounded by the Dragožel Fault. This can be seen in the Entrance Shaft and at the ceiling of the Big Room. In the upper parts, the control of strata is less prominent, but in the lower parts, passages are more controlled by strike and dip of strata.

Clay sediments are deposited in ponding waters, choking passages as in the lowest part of Lower Passage.

Considering the age of Dragožel Fault, cave development was probably active here prior to the deposition of Vitačevo Formation in Tikveš Basin, although older morphology cannot be clearly separated. Same brown clay can be found covering walls and filling small pockets also along the north wall (Dragožel Fault). The morphology of the ceiling along the Dragožel Fault also indicates phreatic development.

Between Dragoželska Propast and Kamenica Valley, sediments of Vitačevo Formation can be found filling paleodepressions, interpreted as paleovalley with drainage to the SE. It is possible that there was a phase of cave development along the Dragožel Fault connected with the evolution of this paleovalley, prior to the deposition of Vitačevo Formation, which eventually ceased karstification in this area (Fig. 5.14).

Most of the cave passages, having vadose morphology, are developed along the WSW–ENE fault and fractures, connected with the evolution of Kamenica Valley in Pleistocene, cutting first in the Tikveš Basin deposits, and later into the underlying Cretaceous limestones.

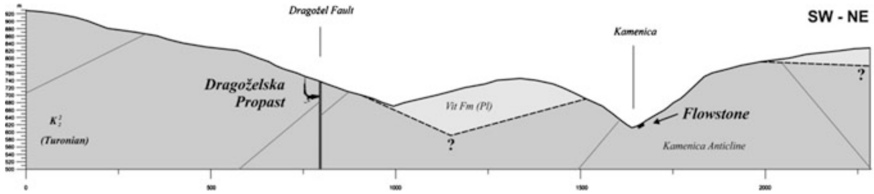


Fig. 5.14 Cross section of Kamenica Valley showing relationship of Dragoželska Propast to local geological structure and topography

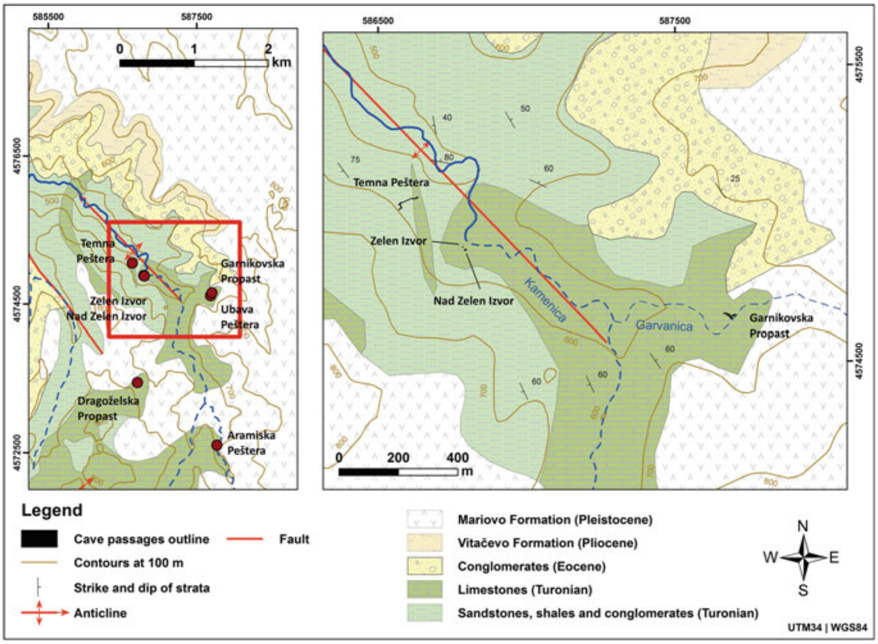


Fig. 5.15 Location of Garnikovska Propast and other caves in the downstream part of Upper Kamenica Valley. Geological data modified after Rakićević and Pendžerkovski (1970), Hristov et al. (1965), Geološki Zavod–Skopje (unpublished)

5.1.4 Garnikovska Propast

Garnikovska Propast is located in Garvanica River valley, a tributary stream to Kamenica River, 400 m east from the confluence (Fig. 5.15). The entrance to the cave is on the right side of the valley, 5 m above the riverbed, at 625 m elevation.

The valley has steep longitudinal profile and is incised below a river terrace that is preserved above the cave at 660–670 m. Lower terrace is seen some 200 m to the NW, located at 630 m elevation.

The cave is developed in Turonian limestones on the right limb of NW plunging Kamenica Anticline.

5.1.4.1 Morphology

Garnikovska Propast is a 149-m-long and 63-m-deep ponor cave with steep vadose passages leading to less inclined and sub-horizontal vadose and epiphreatic tube-like passages. The cave is mainly developed in NW direction along the strike of limestones, dipping to the NE by 60°, with parts developed along WSW–ENE- and SSW–NNE-oriented fractures (Fig. 5.16).

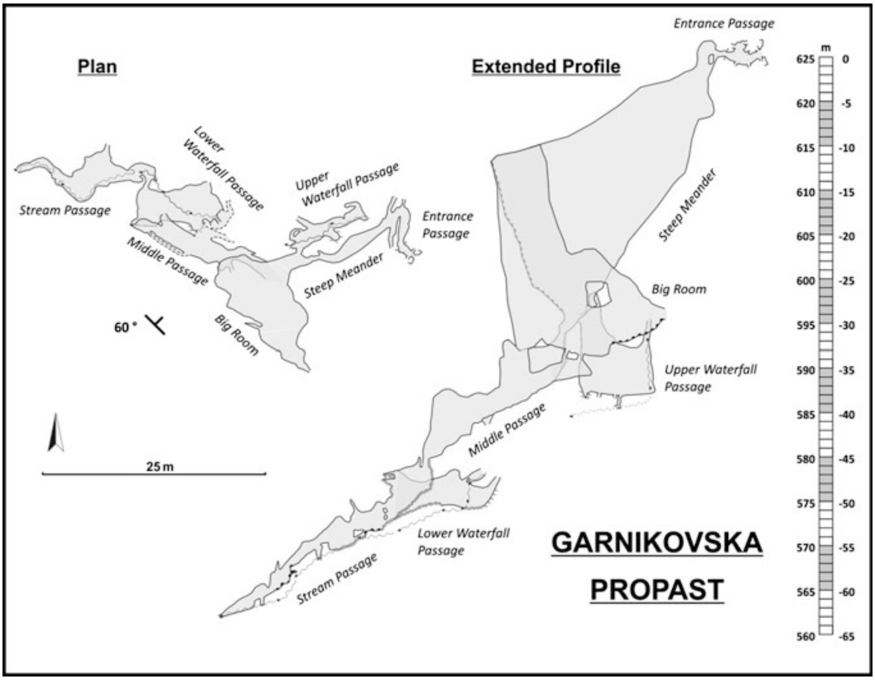


Fig. 5.16 Simplified map of Garnikovska Propast. For more detailed cave map, see Appendix

The entrance is through collapsed blocks on the right side of Garvanica valley, from where a small passage leads to the Steep Meander, a steeply inclined meandering vadose passage, developed along a WSW–ENE fracture. The Steep Meander joins the Big Room, from where the cave takes strike direction with Middle Passage continuing to the lower still active section.

The lower section of the cave (Lower Waterfall Passage and Stream Passage) has NW strike-oriented general direction interchanging with parts developed along WSW–ENE-oriented fractures. A small stream is active in wet season, coming from the Upper Waterfall Passage, through the Lower Waterfall Passage down along the Stream Passage, where it has carved a vadose canyon in a small tubular passage.

Paragenetic morphologies are clearly seen in the Big Room and Lower Waterfall Passage (Fig. 5.17). In the Big Room, coarse clastic sediments are covering floor and walls to the SW and east, with a profile of pebbles and cobbles seen where Steep Meander joins this room, while on the SW end, big rounded pyroclastic-derived boulders are choking a tributary passage. Above these deposits, paragenetic wall and ceiling channels are rising in northern direction. The Big Room is the largest passage in the cave with, greatly enlarged by paragenesis due to increase of sediment supply, with northern parts of the room now covered by large dripstone and flowstone deposits. Paragenetic channels rise more than 10 m above the floor of the room.

Thick coarse sediments (pebbles, cobbles) are also filling the western wall in the Lower Waterfall Passage fining up to sand and clay deposits.

Paragenetic alluvial notches are also seen on the wall near lowest part of the Stream Passage, with few cobbles stacked by flowstone to the wall, now hanging 1 m above the present sand-covered floor. The cave continues downward with a narrow passage, 63 m below the entrance.

5.1.4.2 Cave Sediments

Brown to gray brown clay and silt deposits are found through out the cave, filling passage floors, niches, ceiling channels, and passages as well. They are filling passage floor and niches in the Upper and Lower Waterfall Passage and are seen deposited above coarser sediments in the NW wall of the Lower Waterfall Passage. Sample (GAR01) from gray brown silt from the Upper Waterfall Passage showed mineral composition of montmorillonite, sanidine, muscovite, quartz, albite-calcian, hematite, and magnesiohornblende-ferroan. The composition is similar to clay and silt deposits in the caves of the Vitačevo karst, originating from weathering of the pyroclastic deposits of Mariovo Formation.

Coarse-grained deposits (sand, pebbles, cobbles, and boulders) of the same origin are found filling passage floors. Cobbles and boulders of andesitic rock are chocking a side passage in the SE end of the Big Room, and pebbles of cobbles are also seen in eroded profiles at the contact of the Steep Meander and Big Room, and Middle Passage, and Lower Waterfall Passage.

Breakdown deposits as blocks and breakdown debris are seen in the Entrance Passage and the Bid Room.

Thick speleothem deposits are deposited in the Big Room, making it the most decorated room in the Vitačevo Karst, with both dripstone and flowstone speleothems. Flowstone speleothems are also deposited in the Stream Passage and are coating walls of the Steep Meander.

5.1.4.3 Hydrological Characteristics

Intermittent vadose water flow is flowing in the Upper and Lower Stream Passages, with two waterfalls, one in each part. The water flow is only active in spring and autumn, when surface stream is still active. The water is sinking somewhere in the Garvanica stream, upstream of the cave entrance, with no visible sinkhole. The sinkhole is not collecting all surface stream water, with more water flowing in the surface stream than in the cave. The reason for this may be the combination of sediment covered stream bed, and sediment-filled cave passages that limit the amount of water able to penetrate in the cave, although the cave passages are large enough to collect all of the surface stream water. The stream in the cave continues in a little less inclined passage from the lowest penetrable position in the Lower Stream Passage, which is at 562 m a.s.l., 52 m above the location of the Zelen Izvor spring.

Fig. 5.17 Characteristic features of Garnikovska Propast: **a** The Steep Meander. Caver marks the entrance to the Upper Waterfall Passage (UWP); **b** SE part of the Big Room, with an upstream passage filled with pyroclastic-derived cobbles and boulders; **c** Corroded surfaces and small vadose channel incised from a stream in the UWP; **d** Large dripstone and flowstone speleothems in the Big Room; e Paragenetic features (pendants, ceiling channel) in the eastern part of the Big Room; **f** Brown clay covering cobbles in the upper parts of the NW wall in the Lower Waterfall Room. Photographs by M. Temovski

5.1.4.4 Speleogenesis

Garnikovska Propast is similar to Aramiska Peštera in morphology, sediments, and evolution, although with more pronounced vertical extent. Cave passages were formed mostly in vadose to epiphreatic environment, connected to the lowering of water table, with new passages developing at lower elevations after drop in water table position. They are mostly developed in NW direction along the strike of steeply dipping strata, and WSW–ENE- to SSW–NNE-oriented fractures. General organization of passages includes vadose passages developed along WSW–ENE- to SSE–NNE-oriented fractures leading to epiphreatic passages formed mostly along NW (strike) direction, with also paragenetic development modifying passages or greatly increasing passage size (as in Big Room).

Located below Garvanica valley, a tributary to the main Kamenica Valley (Fig. 5.18) and at closer distance to Zelen Izvor, the main output location of the karst system, than Aramiska Peštera, lowering of water table produced greater gradient than in Aramiska Peštera, responsible for the greater vertical development of the cave. Rise of water table due to aggradation in the main (Kamenica) valley led to an increase of sediment deposition, producing paragenetic cave development. While paragenetic morphologies are also seen in the lower parts of the cave, the large paragenetic channels in the upper part in the Big Room may correspond to the same phase of aggradation (connected to development of Temna Peštera–Dragožel and the terrace at 550 m) as the upper paragenetic passages in Aramiska Peštera. Later further incision led to removal of sediment and exposing of paragenetic morphology. Present active parts are developing due to sinking of surface stream in Garvanica valley during wet season or high rain, producing vadose passage morphology. Surface stream in Garvanica valley is larger than in the cave due to choking of valley floor with sediment allowing only partly sinking of surface water.

The evolution of the cave is connected with the evolution of the karst system due to the incision of Kamenica Valley. Kamenica River started its incision, after the draining of Central Macedonian Lake [as late as Middle Pleistocene, Dumurdžanov et al. 2004], first in the pyroclastic deposits of Mariovo Formation, than in the underlying Cretaceous rocks. Gradual incision shifted the position of the spring of

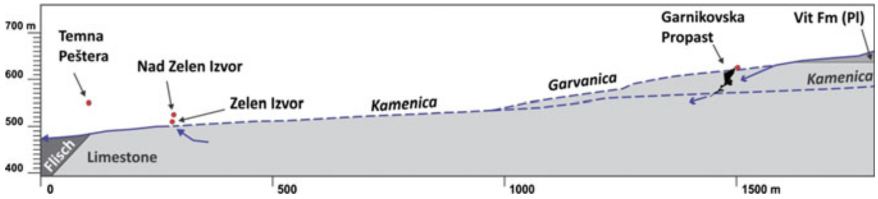


Fig. 5.18 Longitudinal profile of Kamenica and Garvanica rivers with caves Garnikovska Propast, Temna Peštera, Zelen Izvor, and Nad Zelen Izvor

this karst system, lowering the water table, producing cave passages at lower level. As this area is closer to the spring of the karst system, the effect of the lowering of water table has been bigger, creating higher gradient with bigger vadose zone. Base-level rise due to aggradations in the main valley (corresponding to terrace at 550 m in Zelen Izvor locality) led to rise of water table and paragenetic development of passages, with later lowering allowing removal of sediment and further vadose development. As a result of the high energy of the water due to high gradient, coarser deposits were deposited far below the entrance with andesite boulders of up to 1 m in diameter.

5.1.4.5 Mala (UBAVA) Peštera

Mala Peštera is a small cave, located 40 m to the SW from Garnikovska Propast. The entrance is on the left side of Garvanica Valley, at 650 m a.s.l. It was first explored by cavers from PSD Orle from Kavadarci in the 1960s. It is a vadose cave with parts completely filled with coarse fluvial sediments. General direction of the cave is to the SW, with steeper upstream parts and sub-horizontal downstream parts (Fig. 5.19). It is probably part of the same cave system as Garnikovska Propast, with cave passages later cut by the valley. Remnants of cave features can be seen in on the right side of the valley opposite of Mala Peštera. The cave was completely filled with sediments, which were later eroded by vadose waters. There are numerous stalactites on the ceiling in the downstream part.

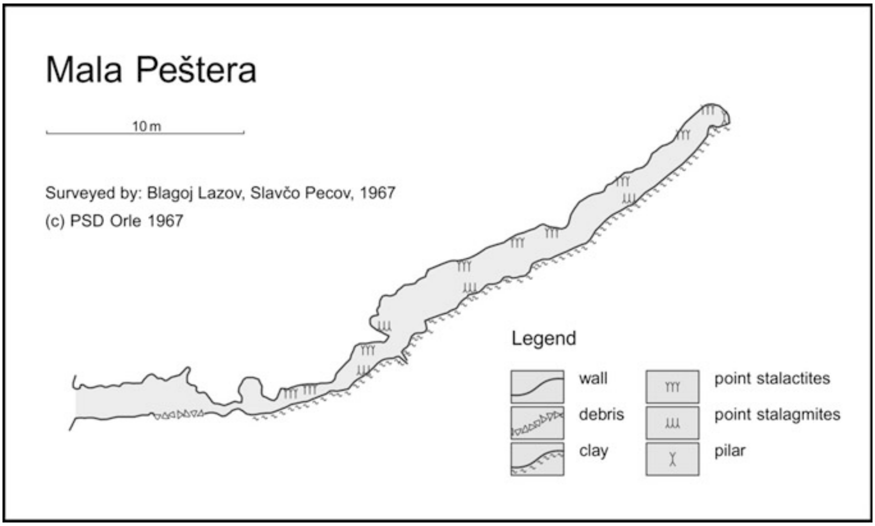


Fig. 5.19 Extended profile of Mala (Ubava) Peštera modified after PSD Orle (1967)

5.1.5 Caves at Zelen Izvor Locality

Zelen Izvor ("Zelen" meaning green and "Izvor" meaning spring) is the largest spring in Vitačevo karst area, draining the karst terrains of the upper Kamenica basin. It is located 1.6 km ESE from Dragožel Village and 1.4 km south of Garnikovo Village. There are three caves in this locality (Fig. 5.15), two of which are at the spring (Fig. 5.20): one is the actual spring, called Zelen Izvor Cave (Green Spring Cave), and the other is 15 m above the spring, called Nad Zelen Izvor Cave (cave above the Green Spring). The third one, Temna Peštera–Dragožel, is located 200 m to the NE from them at 550 m a.s.l.

The caves and the spring were known to the local population from Garnikovo and Dragožel villages (now almost depopulated) and were first registered by cavers from PD Orle from Kavadarci, mapping Nad Zelen Izvor Cave and Temna Peštera–Dragožel.

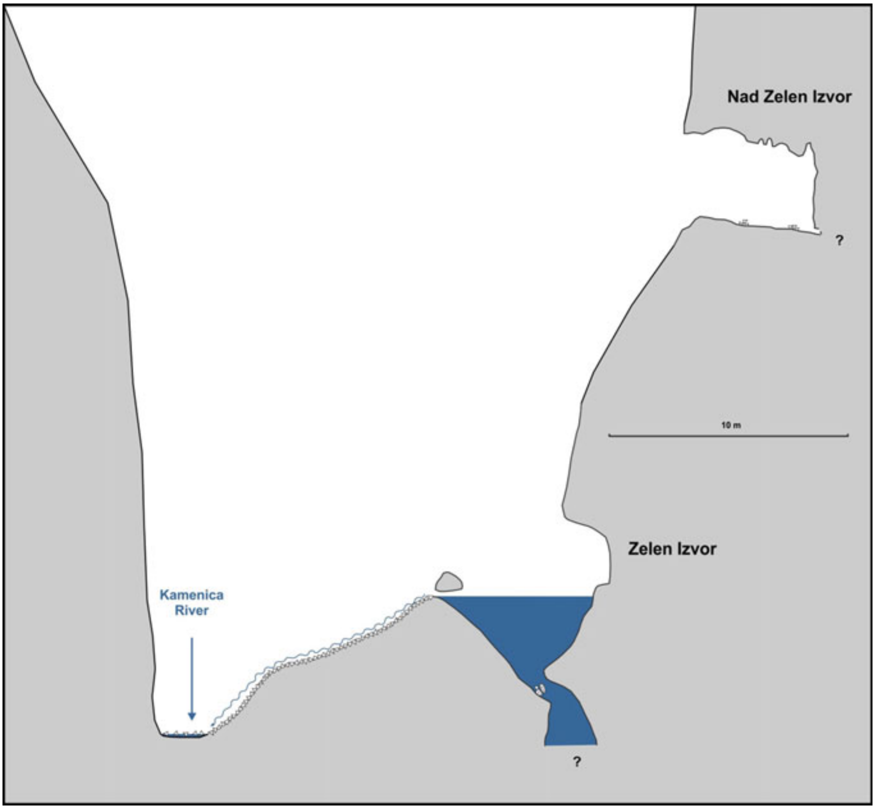


Fig. 5.20 Cross section showing relationship of Zelen Izvor Cave, Nad Zelen Izvor Cave, and Kamenica River

There are three river terraces in the valley of Kamenica River near the caves, two of which at 545–550 m a.s.l. and at 495–500 m a.s.l., are best exposed on the right side of the valley, right opposite of Temna Peštera–Dragožel, and the terrace at 530 m a.s.l. is located on the left side below Temna Peštera–Dragožel (Fig. 5.25). Remnants of these terraces can be seen also in the canyon to the SE, although they are quite destroyed.

These river terraces indicate stable position of valley floor with lateral erosion, which guided the speleogenesis in this area, fixing the spring location at the terrace elevation, and influencing cave development at that elevation. They correspond well to the caves in this vicinity, with Temna Peštera–Dragožel corresponding to the highest terrace (545–550 m), Nad Zelen Izvor at 530 m, and the present spring, Zelen Izvor (which is perched 5 m above the local riverbed) little above the terrace at 495–500 m a.s.l.

5.1.5.1 Zelen Izvor Cave

Zelen Izvor Cave is 7 m long, 1–1.5 m wide, mostly water-filled passage with NE direction. It is located at 510 m, 5 m above the riverbed of Kamenica Valley, with the spring perched above the river (Fig. 5.21).

Zelen Izvor Cave, as well as Nad Zelen Izvor Cave, is developed in Turonian limestones of NW plunging Kamenica Anticline, close to the contact with underlying clastic rocks. The position of Zelen Izvor spring, which is 5 m above Kamenica riverbed, is perched probably due to collapse of the left side valley slope. The discharge of Zelen Izvor was measured using the floating method, with values of 250 l/s in April 2011 and 190 l/s in January 2013. The discharge in summer was not measured, but it was noted to be smaller. The spring is perennial, comparing to Kamenica River, upstream from the spring, flowing only in spring and autumn.

First dive attempt in the spring was done by Bojan Petkovski and Dančo Gjorgjijevski from Cave Diving Club Vrelo from Skopje in September 2012, reaching depth of 6 m.

The spring is developed along a SW–NE fracture, with water rising from a side passage formed along a fracture with same direction, connecting with the Upper Passage by a SE-oriented passage. This diversion is probably due to choking of previous output location by collapse in the valley, with the water flow rising and discharging through an older passage. Cave floor is covered with breakdown material and clay deposits.

Some preliminary field analysis of water from the spring showed pH of 7.23, EC of 456 µS/cm, and temperature of 11.6 °C.

5.1.5.2 Nad Zelen Izvor Cave

Nad Zelen Izvor is a small 5-m-long, 6-m-wide cave with ceiling at ~3 m. It is located little to the SE and 15 m above Zelen Izvor, with the entrance at 525 m

Fig. 5.21 Location of Zelen Izvor and Nad Zelen Izvor caves and spring (*upper left*); closer look of Zelen Izvor spring (*upper right*); and the confluence with Kamenica River (*down*). Photographs by M. Temovski

Fig. 5.22 Panoramic view of Nad Zelen Izvor Cave. Photograph by M. Temovski

elevation a.s.l. The floor is covered with sediments, mostly sand, with some breakdown debris as well (Fig. 5.22). There is a small sediment-filled passage on the southern wall. This small room is little elongated along a fracture-oriented SW–NE. On the ceiling, mostly in the eastern part, there are ceiling pockets and channels with sediment seen in some of them. The cave is a fossil part of the same cave system as Zelen Izvor, formed when Kamenica Valley was at higher location, possibly connected with the terrace at 530 m, which is preserved only in small parts on both sides of the valley, 100 m downstream from the cave.

5.1.5.3 Temna Peštera–Dragožel

Temna Peštera–Dragožel is located 200 m NE from Zelen Izvor, on the left side of Kamenica Valley, with entrance at 550 m a.s.l., 80 m above the present riverbed, right opposite of the river terrace at 545–550 m a.s.l.

The cave is formed in a lens of Turonian limestones in the SW wing of the NW-oriented plunging Kamenica Anticline. The situation here is probably more complicated with some secondary folds in the SW wing, with limestones in the cave dipping to the SE by 50°. They are highly fractured by SW–NE- to W–E-oriented fractures.

Morphology

Temna Peštera–Dragožel has 125 m of passages, mostly horizontal, except at the upstream part where there is an 8-m-deep sump. There are two entrances, both modified by erosion due to slope retreat (Fig. 5.23).

Although the limestone in which the cave is formed is heavily fractured in several directions, passages are mostly formed along the prominent fractures with WSW–ENE direction. The general direction of the cave is to the ENE.

Although genetically there is not much difference, due to presence of sediments we can separate two major parts in the cave: the downstream and upstream part.

The downstream part is basically one passage with ENE direction, formed along and between several prominent fractures with a small part (a bend toward east near

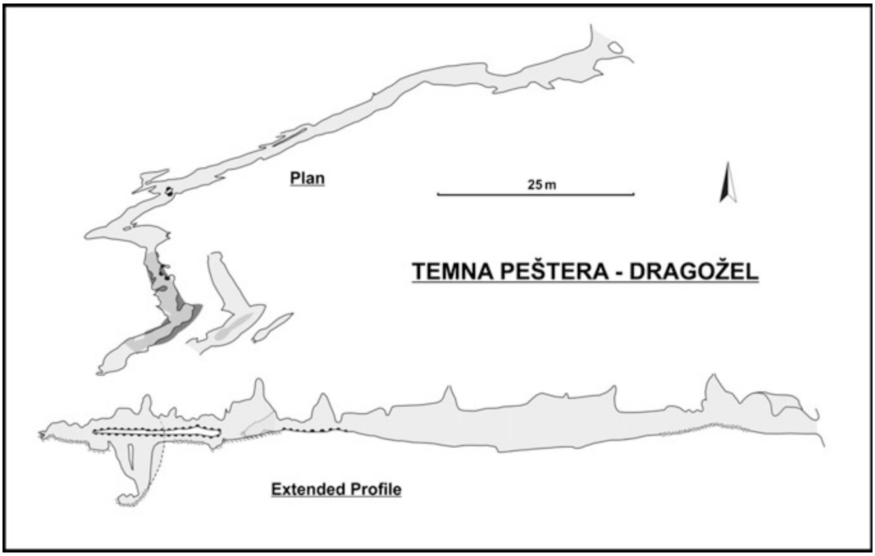


Fig. 5.23 Simplified cave map of Temna Peštera–Dragožel. For more detailed cave map, see Appendix

the entrance), that is guided by strike and dip of strata. In profile view, this passage is basically horizontal, with floor covered by coarser fluvial sediments and breakdown debris. The passage floor is inclined to the middle part, due to later flushing of sediments along a small passage emerging from the north side. On cross sections, we can see several notches in the upper parts, with smaller vadose channel incised in the passage floor. Right after the small bent, there is a paragenetically formed flat ceiling with some pendants and cupolas continuing toward the entrance (Fig. 5.24).

The upstream part has two parts formed along the fractures with WSW–ENE and W–E direction, connected with a NNW-directed passage. This part is cross-cut by number of fractures along which number of paragenetic channels developed with some of them still filled with sediment. In the southern passage, there is a vertical part, which at 8 m depth turns horizontally toward WSW and ends with a clay choke. This part is a former phreatic sump. Considering small size and direction of poorly preserved scallops on the wall, this sump formed in a shallow phreatic environment by waters that discharged upward. Later, it was completely filled with clay and silt sediments. Above the sump, there is also a passage to the WSW, which ends with a clay choke. In the upper parts of these passages, there is a false floor of 30- to 50-cm-thick flowstone, which deposited above clays that were later removed. There are number of pendants, solutional pockets, and cupolas on the ceiling above, most of them now covered with speleothems.

Cave Sediments

Most prominent sediments in Temna Peštera–Dragožel are brown silt and dark brown clay. They are mostly found covering passages in the upstream part. They

Fig. 5.24 Characteristic features of Temna Peštera–Dragožel: **a** Pendants, pockets, and flat ceiling on passage walls in the downstream part; **b** Passage below false floor flowstone deposit, after erosion of sediments, downstream part; **c** The main passage with some wall notches; **d** False floor flowstone deposits, downstream part; **e** Lower and upper part of the passage separated by false floor, upstream part; **f** Ceiling channels and pockets; **g** Septaria boxwork on the lower side of the false floor with remnant clay sediments. Photographs by M. Temovski

Table 5.3 Mineral composition of clay and silt in Temna Peštera–Dragožel

Sediment (sample)	Mineral composition
Brown clay (TEM02)	Montmorillonite, halloysite-7A, kaolinite, sanidine-potassium, muscovite, quartz
Brown silt (TEM01)	Kaolinite, quartz, sanidine-potassium, albite, clinochlore, muscovite, hematite, magnesiohornblende

are similar to clays in the other caves in Kamenica Valley. X-ray analyses suggest that their origin is likely from weathering of pyroclastic deposits from the Vitačevo and Mariovo Formations (Table 5.3).

In the downstream part, we can also find some pebbles from volcanic agglomerates from the same pyroclastic deposits, which were probably deposited due to aggradation in Kamenica Valley, connected to the terrace at 545–550 m.

Breakdown deposits are found in the downstream part composed of detached limestone blocks, while in the upstream part collapse of the flowstone floor produced flowstone breakdown material.

Vadose flowstone deposition is more prominent in the upstream part, with thick flowstone deposits, columns, stalactites, and stalagmites.

Speleogenesis

Temna Peštera–Dragožel formed along prominent fractures in a shallow phreatic and epiphreatic environment. Remnants of this phase can be seen in the upstream sump, and in the downstream passages, where former phreatic passage floor is incised by later vadose stream (Fig. 5.25).

Due to river aggradation (connected to the river terrace at 545–550 m), sediments started to accumulate first in the upstream sump, then completely filling the sump and filling lower parts of downstream passage. With sediments covering the lower parts of the passages, dissolution was directed to the ceiling and passages developed paragenetically in the upward direction. In the upstream part, bypass passage developed above the sump, which might have started after settling of water table in the cave, but evolved more rapidly after filling of the sump. This also helped in easier filling of the sump. As passages filled with sediments, channels, pendant, and solutional pockets developed in the ceiling. They are best exposed above the sump and the false floor, where most of them are now covered with speleothems.

After lowering of water table, thick flowstone deposited above clay sediments in the upstream part, and vadose waters eroded the clay sediments in the downstream part.

As the water table continued to drop, clay sediments were flushed from the upstream passages, creating flowstone covered false floor, and vadose waters incised a channel in the floor of the former phreatic passage, depositing volcanic derived coarser material such as gravel and pebbles.

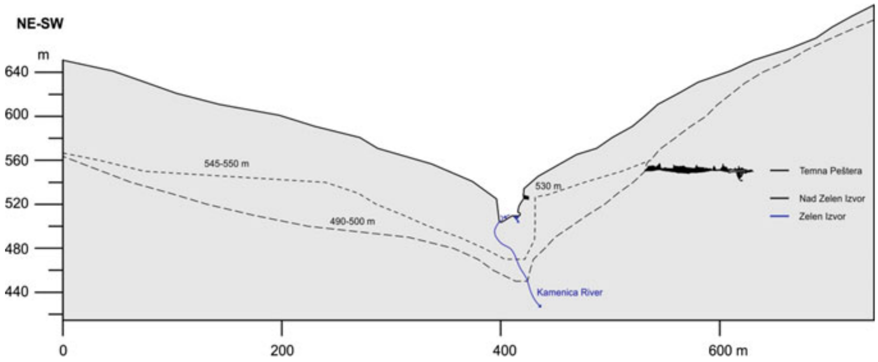


Fig. 5.25 Caves at Zelen Izvor locality and their correlation to river terraces

Further vadose development of the cave resulted in exposure of the sump and breakdown of the flowstone false floor, as well as breakdown in the downstream passage.

5.1.6 Budimirica Cave

Budimirica Cave is located in the NW part of the Vitačevo Plateau (western part of the Tikveš Basin) in the downstream part of Kamenica Valley. The entrance is located at 400 m a.s.l., on the right slope of the gorge-like valley (Fig. 5.26). It was first described by Manakovik (1971), considered as younger than Aramiska Peštera, as it is located at lower elevation in the downstream part of Kamenica River, interpreting its evolution with the successive draining of the Central Macedonian Lake and incision of Kamenica River.

The cave is developed in the eastern part of a tectonic block built of Cretaceous (Turonian) massive limestones steeply dipping to the SE by 50°. This block is connected to the east to the clastic Turonian formation by the regional NW–SE-oriented Dragožel Fault.

5.1.6.1 Morphology

Budimirica Cave is 105 m long consisting of two branching passages (Left and Right Passage; Manakovik 1971) with the NE general trend.

The main (Left) passage is 50 m long, 1–10 m high, and the 2–8 m wide (higher at the entrance). It is sub-horizontal (slightly inclined toward the entrance) in the first 30 m, and much more inclined (~25°) in the second part (Fig. 5.27). In between these parts in the Left Passage, there is a large pit (5 m long, 1.5 m wide, and 1–1.5 m deep), which was most likely excavated by some treasure hunters

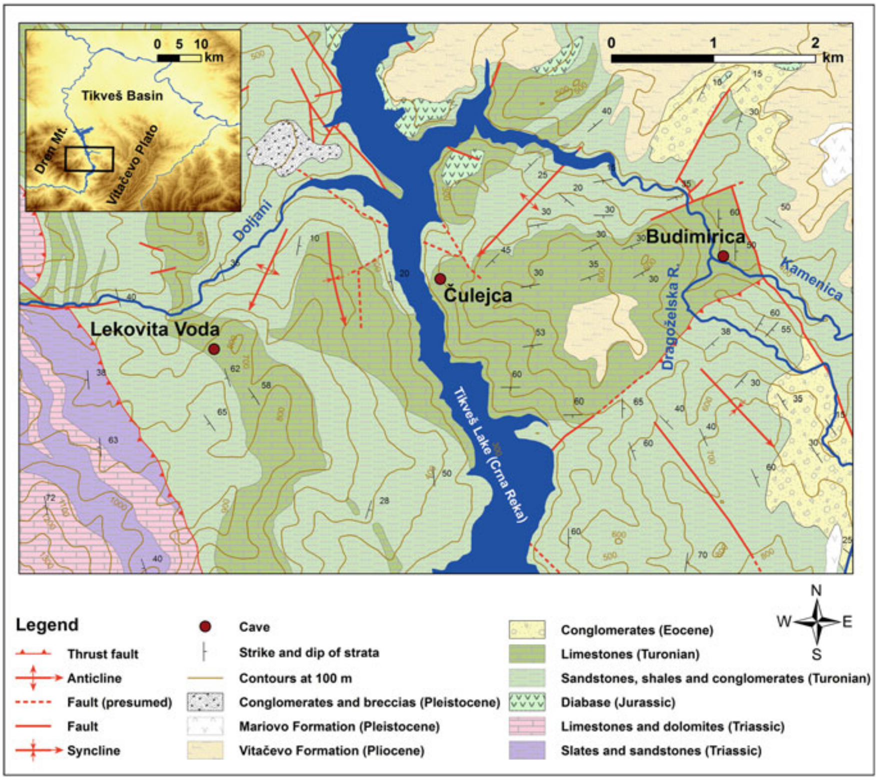


Fig. 5.26 Geological map of the lower Kamenica Valley. Geological data modified after Dumurdžanov et al. (1976), Hristov et al. (1965), Rakićević et al. (1965), Rakićević and Pendžerkovski (1970), Geološki Zavod–Skopje (unpublished)

(common occurrence in the area). In the second part, the floor is mostly covered with several generations of flowstone (big part of which is eroded) and ceiling breakdown material. Small-scale features are mostly small paragenetic channels, pendants, and various below sediments features (Fig. 5.28).

The Right Passage is 45 m long, narrower in the first part, and up to 6 m wide in the second part, with ceiling up to 2 m high. There is more ceiling breakdown in this passage. Remnants of the older flowstone deposits can be found on the NW wall, and only small patches of the coarser yellowish deposit are seen, mostly covered by breakdown material. The walls and ceiling are carved with small below sediment solution features and paragenetic channels (Fig. 5.28). Collapse of the ceiling has occurred mostly after washing of sediments, when the roof became unstable due to the dense network of paragenetic channels. Example of this can be seen in the middle of the passage, where there is a big collapse block with pendants and solution channel on the lower side, but flat surface on the upper side and above it on the ceiling from where it detached.

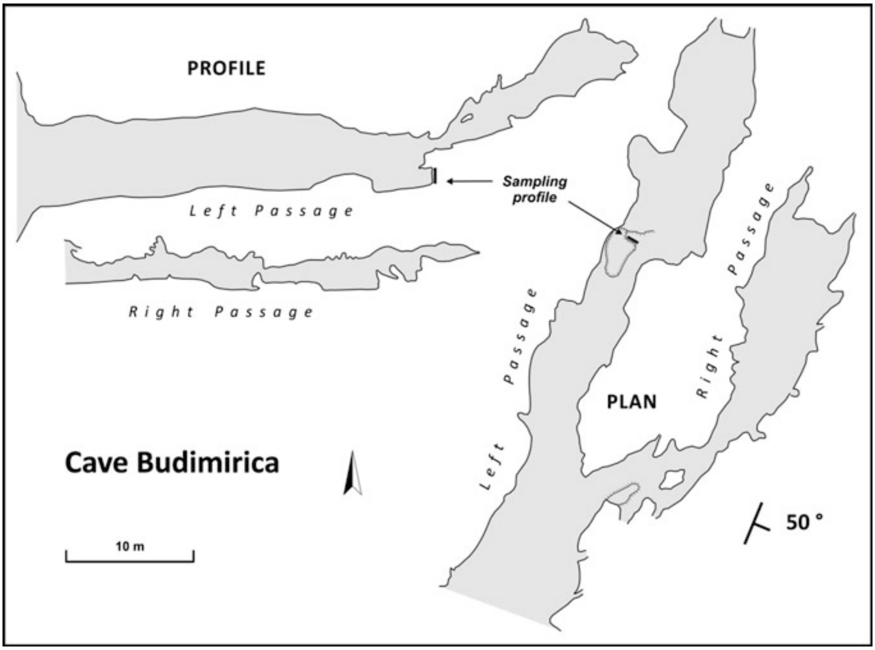


Fig. 5.27 Simplified cave map of Budimirica Cave. For more detailed cave map, see Appendix

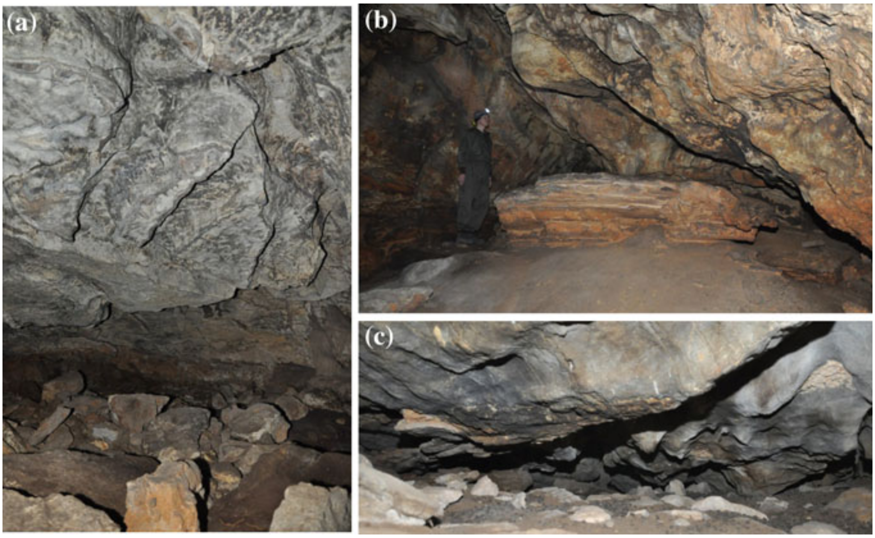


Fig. 5.28 Paragenetic morphology in Budimirica Cave: **a** Paragenetic channels in the Right Passage; **b** thick flowstone deposits in uppermost part of the Left Passage, with paragenetic wall and ceiling morphology; **c** the paragenetic channels and pendants above the sampling profile. Photographs by M. Temovski

In the small end in the north side of the Right Passage, there is some dark brown clay, commonly found in other caves of Vitačevo Plateau (Aramiska Peštera, Dragoželska Propast, Garnikovska Propast, Temna Peštera–Dragožel, Čulejca), which originates from weathering of pyroclastic deposits of Vitačevo and Mariovo Formations.

Right opposite of Budimirica, on the other side of Kamenica Valley (Fig. 5.29) there is a small remnant of a cave (Karši Budimirica cave). This cave is 11.5 m long, 7 m wide, and 12.5 m high, with SW direction, and it is located at the same elevation as cave Budimirica. This cave is filled with flowstone, quite similar as the thick flowstone in Budimirica.

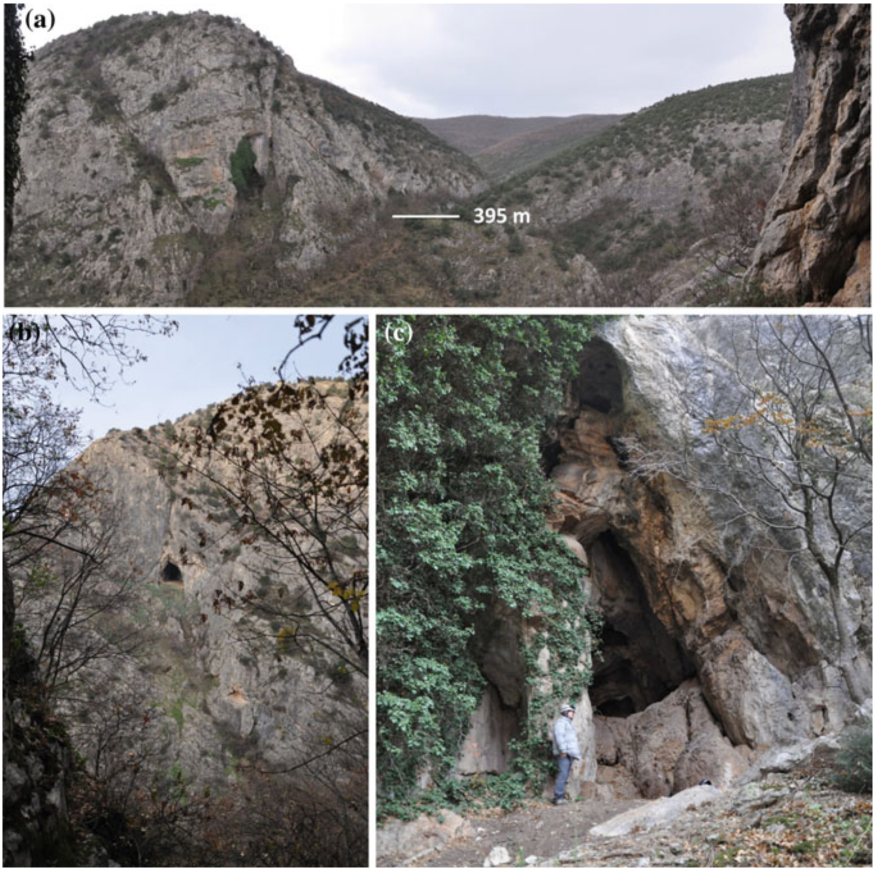


Fig. 5.29 The Karši Budimirica Cave. **a** Karši Budimirica Cave viewed from the entrance of the Budimirica Cave; **b** the opposite view to **a**; **c** the Karši Budimirica entrance with thick flowstone deposits. Photographs by M. Temovski

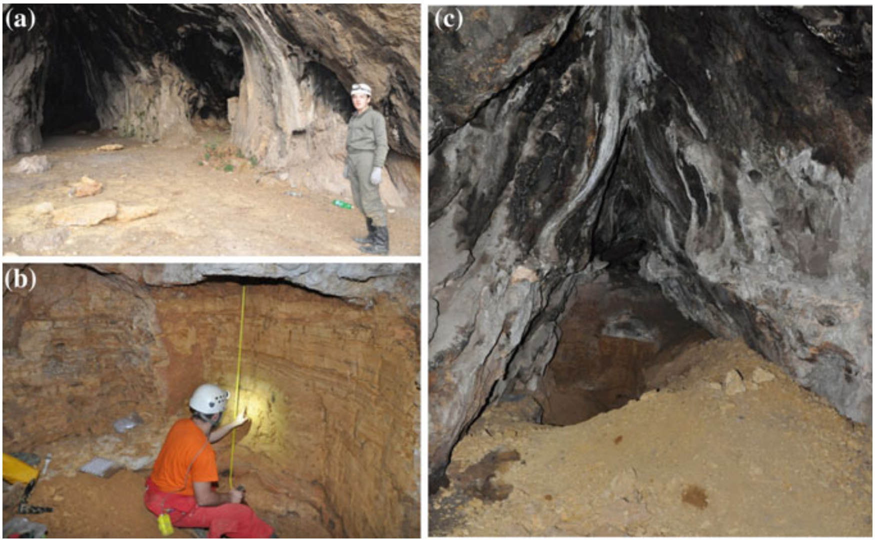


Fig. 5.30 Characteristic features in Budimirica Cave: **a** Entrance part of the Budimirica Cave; **b** sediment profile sampled for paleomagnetic dating; **c** the end of first part in the Left Passage with a view to the pit and sampling profile location. Photographs by M. Temovski

5.1.6.2 Cave Sediments

There is a good view of the cave sediments in the pit located in the Left Passage. In the NE profile, they start with flowstone at the bottom of the pit, and then, 1.5-m-thick deposits of yellow to orange silt, clay and sand, covered by 30-cm-thick collapsed flowstone block. Above this flowstone block, there is yellowish gravel, sand, and silt up to 1 m thick (Figs. 5.30, 5.31, 5.33). To the SW part of the pit, these sediments are eroded and covered with brownish breccia (Fig. 5.32) deposit in which several bones and teeth were found, and one molar determined as Ursus Speleaus (Garevski 2012, pers. comm.). Toward the entrance, these sediments are covered with 10- to 15-cm-thick organic deposit (sheep and/or cow defecation deposit).

Breakdown deposits are found throughout the cave, with breakdown flowstone blocks mostly seen in the Left Passage, while mostly limestone breakdown blocks are covering floor in the Right Passage. Younger speleothem flowstone and dripstone deposits are seen in the upper parts of the cave, although they are mostly inactive. The passage walls especially in the Left Passage are covered by a black coating from the frequent fire burning done by shepherds.

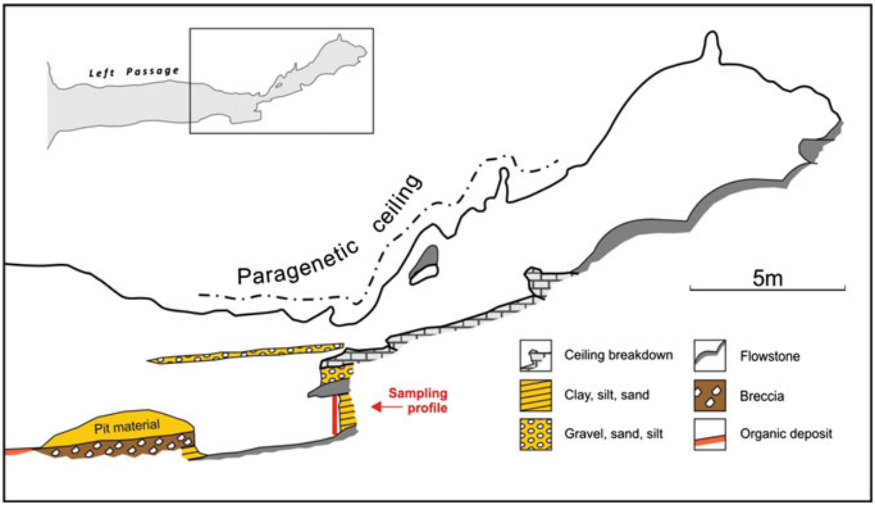


Fig. 5.31 Detail of the Left Passage with sediment relationships and location of sampling profile

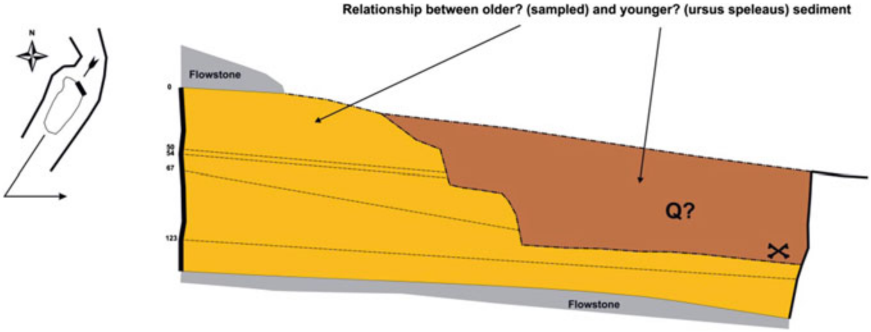


Fig. 5.32 Relationship of sampled sediments to other cave fills and position of major unconformities (*dotted line*)

5.1.6.3 Paleomagnetic Dating of the Pit Sediment Profile

The yellow sediments from the NE profile in the pit were sampled for paleomagnetic dating. The profile is 155 cm deep, starting from the upper flowstone (collapsed) plaque to the bottom flowstone. Several principal depositional interruptions are expressed in the profile (Fig. 5.33). Bedding planes at 50, 53, and 67 cm are expressed by dark film (most probably Mn compounds) and desiccation cracks filled by overburden sediments. Plane at 53 cm also shows small neptunian dykes resulting from water escaping from water-saturated clayey deposits. Planes at 79, 103, and 123 cm are expressed only by dark (Mn) lamina or band. Desiccation cracks are

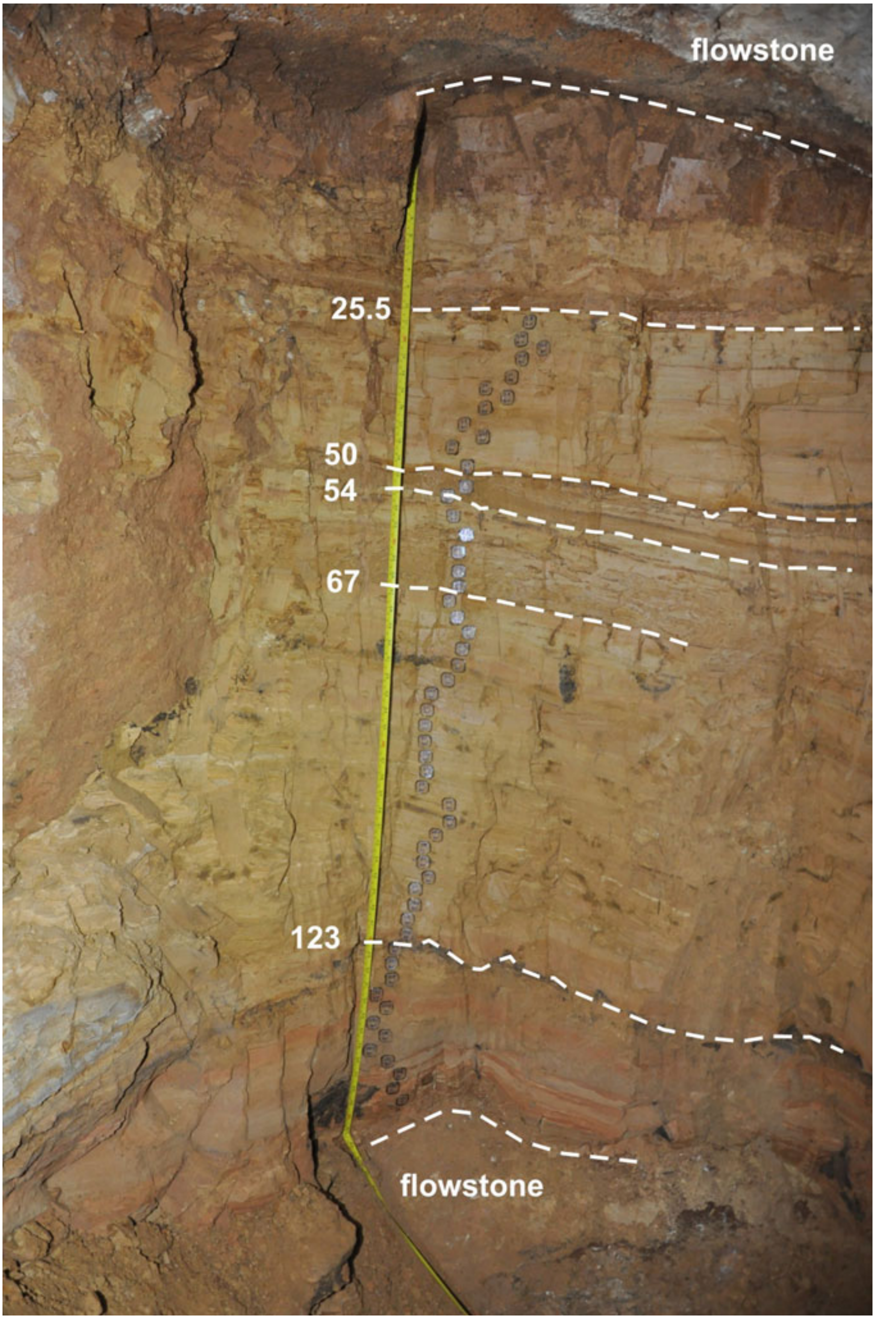


Fig. 5.33 Photograph of the sediment profile with position of paleomagnetic sampling boxes and major unconformities

developed on plane at 131 cm. Plane at 123 cm represents principal lithological boundary with distinct erosional relief and change both of lithology and color.

Paleomagnetic results The yellow sediments in the profile were sampled (from the unconformity at 25.5 cm to the lower flowstone at 155 cm) by high-resolution method (Zupan Hajna et al. 2008); that is, samples located in each 2–3 cm. Paleomagnetic properties (Fig. 5.34) were investigated in 56 samples (Bosak et al. 2013). The mean NRM and MS moduli values are given in Table 5.4. The sediments are characterized by a low scatter of NRM intensities (3.24–51.2 mA m^{-1}) and MS values (101–872 × 10^{-6} SI units; Fig. 5.35). Samples are characterized by low up to intermediate NRM and MS magnetic values.

In the respect to unconformity planes, the sampled segment of the profile may be divided into three parts. The sediments from the profile showed only normal

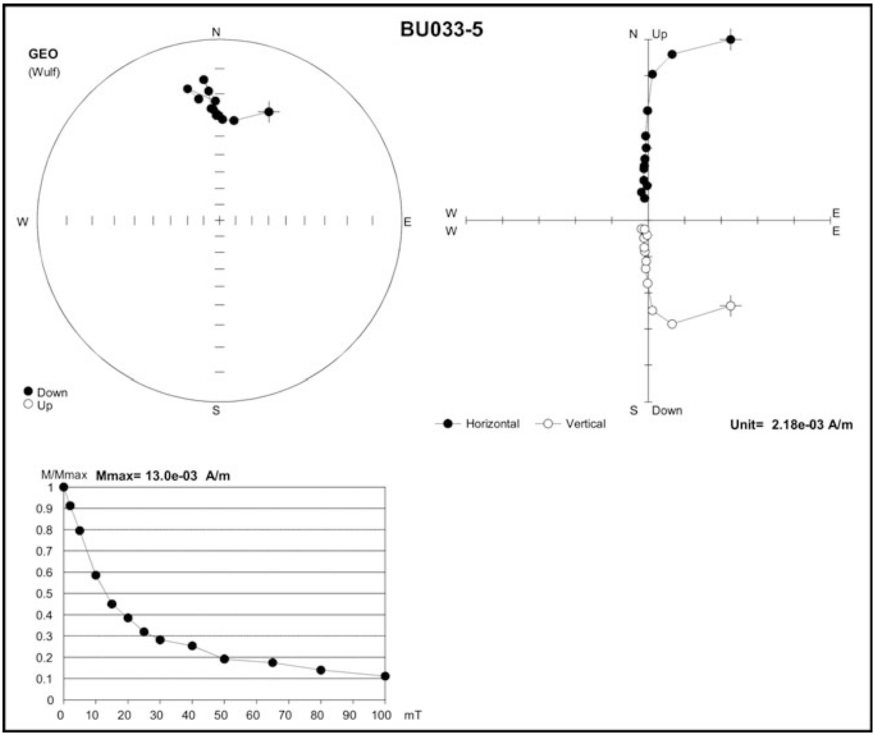


Fig. 5.34 Example of AF demagnetization of sample (position 33.5 cm) with normal paleomagnetic polarity from the Budimirica Cave. A stereographic projection (*upper left*) of the natural remnent magnetization of a sample in the natural state (cross section) and after progressive AF demagnetization. Zijderveld diagram (*upper right*)—*solid circles* represent projection on the horizontal plane (*XY*), *open circles* represent projections on the north–south vertical plane (*XZ*). A graph (*lower left*) of normalized values of the remanent magnetic moments versus demagnetizing fields; *M* modulus of the remanent magnetic moment of a sample subjected to AF demagnetization

Table 5.4 Mean paleomagnetic values and standard deviations in Budimirica Cave

Budimirica Cave	NRM (mA m^{-1})	MS × 10^{-6} (SI)	Interval (m)[a]
Mean value	19.17	360	0.28–1.51
Standard deviation	10.67	163	
Number of samples	56	56	

[a]From top to base

polarized magnetization. Mean values of paleomagnetic directions of the whole profile and its segments are documented in Table 5.5. The values clearly document two different groups of samples; the first one (the upper and middle parts with similar paleomagnetic directions), and the second one (the lower part).

Mean values of paleomagnetic directions calculated from the upper and middle parts (rather yellowish) of the section are very close to the present magnetic field (the value of mean paleomagnetic declination of 2.6° is close to the present magnetic declination for the Macedonian area with value of 2.7°). The deposition of this segment occurred within the Brunhes chron and sediments are most probably not older than 780 Ka. The lower (rather reddish) part of the profile shows the value of mean paleomagnetic declination of 7.3°, i.e., different from the overlying sediments. The declination indicates clockwise rotation of about 5° and probably much older age of this segment.

However, preliminary results of $^{234}U/^{238}U$ dating of a flowstone sample from below the yellow sediments, carried by Helena Hercman at the Institute of Geological Sciences, Polish Academy of Sciences (Bosak 2013, pers. comm.,) indicate age of 83 (+16/−14) Ka, which makes the overlaying clastic sediments younger than 83 Ka.

Mineralogy The X-ray analysis of two samples (BUD01—between paleomagnetic samples Nos. 67 and 123 and BUD02 between Nos. 123 and 131) was performed to detect whether sediment contains volcanic admixture or material derived from weathering volcanic/volcaniclastic sources. Orange sandy clay from upper part of the profile (BUD01) contains quartz, muscovite, kaolinite, goethite, talc, dolomite, and smectite (montmorillonite). Orange sand from lower part of the profile (BUD02) contains: calcite, muscovite, quartz, goethite, kaolinite, talc, smectite (montmorillonite), and sanidine (Table 5.6).

The presence of smectite (montmorillonite) and sanidine indicates that the source rocks were also composed of volcanic rocks or volcaniclastics. Sanidine is a typical rock-forming mineral of K-rich alkaline volcanic rocks and a principal rock-forming mineral of Kožuf 6.5–1.8 Ma old volcanic rocks (Boev and Jelenković 2012). Smectite (montmorillonite) is a layered clay mineral, product of intensive acidic weathering of volcaniclastic material. Talc is a product of reaction of dolomite or most likely is derived from Vardar Ophiolite suite forming also part of the basement of the Tikveš Basin. The X-ray-detected mineralogical composition in both samples is very similar, only sanidine is present only in the lower sample.

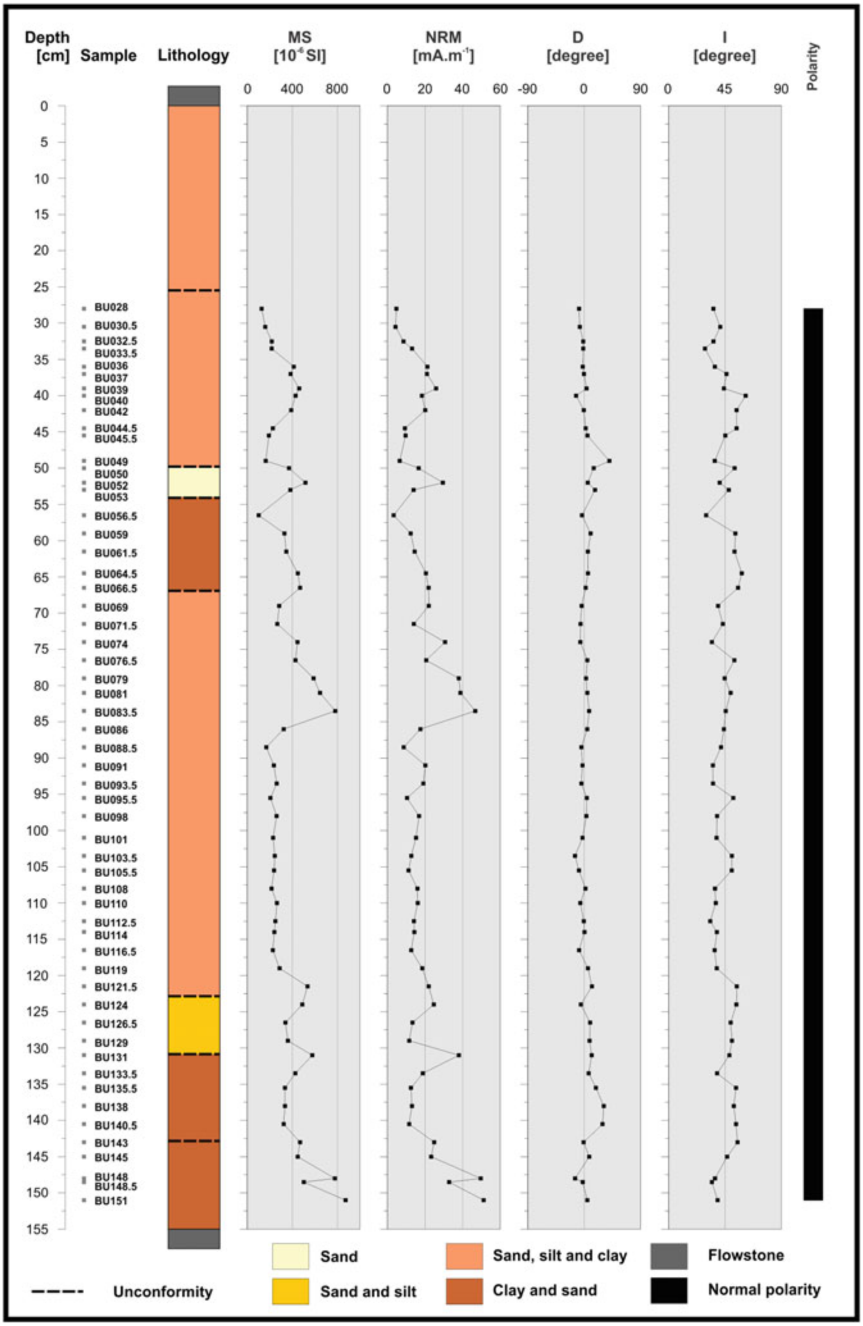


Fig. 5.35 Basic magnetic properties, Budimirica Cave

Table 5.5 Mean paleomagnetic directions, Budimirica Cave: *D*, *I*—declination and inclination of the NRM; α_{95}—semi-vertical angle of the cone of confidence calculated according to Fischer (1953) at the 95 % probability level; *k*—precision parameter; *n*—number of analyzed samples

Segments (cm)	Polarity	Mean paleomagnetic directions		α_{95} (°)	*k*	*n*
		D (°)	*I* (°)			
28–151	N	2.59	45.21	2.47	56.15	56
28–45.5	N	357.97	44.09	5.38	5.87	11
56.5–121.5	N	359.79	43.76	2.96	79.8	28
124–151	N	7.31	47.85	5.41	51.47	13

Table 5.6 Mineral composition of clay and sand from Budimirica Cave

Sediment (sample)	Mineral composition
Orange sandy clay (BUD01)	Quartz, muscovite, kaolinite, goethite, talc, dolomite, montmorilonite
Orange sand (BUD02)	Calcite, muscovite, quartz, goethite, kaolinite, talc, montmorillonite, sanidine-potassium

5.1.6.4 Speleogenesis

Passages in Budimirica Cave are formed along strike direction in phreatic to epiphreatic environment. Vadose flowstone speleothems below the yellow clastic sediments in the pit profile in the Left Passage (Figs. 5.31 and 5.33) indicate lowering of water table in the primary passage, leading to vadose deposition of flowstone. Later deposition of yellow clastic sediments (clay, silt, sand, and gravel) indicates aggradation and base-level rise. As a result of this aggradation, the passages developed in upward direction producing paragenetic morphologies. Later, lowering of water table started removal of yellow deposits and deposition of younger flowstone speleothems. The youngest phase is connected to erosion of the flowstone and yellow clastic deposits with deposition of local breccia sediments, likely connected with frost shattering due to the opening of entrance by slope retreat.

Paleomagnetic analysis of the yellow clastic sediment indicates age younger than 780 Ka (Brunhes chron). Preliminary results from ^{234}U/^{238}U dating of the underlying flowstone (83, +16/−14 Ka) refine the age of yellow sediments as younger than 83 Ka, with the cave older than 83 Ka. Correlation between the aggradation in the cave with deposition of yellow sediments and paragenetic development to the remnant of a terrace at the same elevation (395) opposite of the cave, 80 m above the present Kamenica River, indicates paragenetic development due to base-level rise in Kamenica River. At the same relative elevation (80 m) above Kamenica River, remnant of a terrace is seen in Zelen Izvor locality, with aggradation and paragenetic development connected to it also registered in Temna Peštera–Dragožel, and other

Table 5.7 Speleogenetic phases in Budimirica Cave, their timing and correlation with regional geological and geomorphological evolution

Speleogenetic phase	Geological and geomorphological setting	Timing
Primary cave development in phreatic environment along strike in SW direction	Connected to Kamenica Valley incision (or connected to Čulejca cave system?)	Middle to Late Pleistocene (or Pre-Pleistocene?)
Shifting of strike-oriented passage formation down dip, and flowstone deposition in vadose environment	Lowering of base level—incision of Kamenica Valley	Age of flowstone = 83 Ka (+16/−14), Bosak (2013, pers. comm.)
Deposition of yellow clastic deposits and paragenetic development	Rise of base level—regional aggradation in Kamenica Valley (terrace at 395 m)	Normal polarized magnetization (Brunhes chron), Late Pleistocene (younger than 83 Ka)
Removal of sediments, flowstone deposition	Lowering of base level—incision of Kamenica Valley	Late Pleistocene
Enlarging of entrance by slope retreat erosion, deposition of local breccia due to frost shattering (Ursus Speleaus bones)		

upstream caves in Kamenica River. This indicates regional aggradation in Kamenica River, which raise the position of the water table and forced paragenetic cave development at and below water table (Table 5.7).

The question remains regarding Karši Budimirica Cave, whether it is a cave developed at the same elevation as Budimirica Cave but in opposite direction (along strike) connected to the former base-level position in Kamenica River, or it is a remnant of the same cave system, developed before Kamenica Valley, later cut by Kamenica River with caves afterward evolving separately.

Another peculiar thing is about the general direction of Budimirica Cave. The cave is developed to the south along the strike of massive limestones, steeply dipping to the east, with Kamenica River developed in ENE to NE direction. It is problematic why Budimirica Cave continued to develop in the same direction, considering that the downstream parts of the valley (developed in the same limestone block) were at lower elevation. One possibility is the structural control of favorable bedding planes in the massive limestone, with Budimirica Cave maintaining the same strike orientation after shifting down dip at lower elevation adjusting to the incision of the valley. Another possibility is that the primary cave development is connected to an earlier phase directed to the SW, prior to the incision of Kamenica River, may be connected to Čulejca Cave to the west (Fig. 5.36), and later cut by Kamenica River with its consequent evolution connected to the evolution (incision and aggradation) of Kamenica Valley.

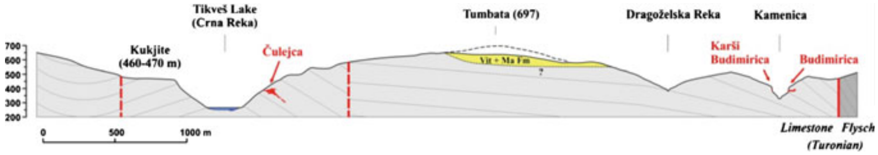


Fig. 5.36 Cross section showing the relationships of Budimirica Cave and Čulejca Cave to Kamenica and Crna Reka valleys

5.1.7 Čulejca Cave

Čulejca Cave is located in Crna Reka Valley, on the NW edge of Vitačevo Plateau, 1 km southward from the confluence of Crna Reka and Kamenica River (Fig. 5.26). Čulejca has small entrance located at 390 m a.s.l., 125 m above Tikveš Lake (265 m a.s.l.), 190 m above the former riverbed of Crna Reka (200 m a.s.l.), before the construction of the artificial Tikveš Lake.

The cave is formed in Turonian limestones on the northwestern tip of Vitačevo Plateau in a small tectonic block, as part of a NW wing of SW trending anticline, with strata dipping to the NW at ~40°.

5.1.7.1 Morphology

Čulejca Cave is ~600-m-long cave, with total depth of ~100 m, of which 503 m length of cave passages are mapped, down to 64 m of depth. The cave has large, tube-like phreatic passages rising generally to the south, interchanging between parts developed along fractures and bedding partings (Fig. 5.37).

Generally, we can separate the lower (northern) section of the cave (Lower Passage, Lower Room, Poolfinger Room, Upper Room), developed in SW–NE direction, mainly along high-angle fault structure with SSW–NNE orientation; and the upper (southern) section of the cave with SW–NE direction (Guano Room, Left and Right Upper Passage). In between there are passages (Debris Passage, Matarka Passage, and New Passage), mainly rising along the dip of prominent bedding planes, interchanging with parts formed along SW–NE- to S–N-oriented fractures (Fig. 5.38).

The cave has an erosional entrance with small dimensions (0.4 m in diameter), which was opened due to valley slope retreat. The entrance is through a small passage with cupolas, highly affected by condensation corrosion, leading to the Guano Room. The main passage continuation of the upper section is to the SW of the Guano Room where the phreatic passage ends with breakdown choke.

The upper part, the section between Guano Room, Left and Upper Passage and New Passage, is developed in or along the contact of yellow paleokarst deposits.

Fig. 5.37 Characteristic morphological features in Čulejca Cave (1): **a** Upward view from the Lower Room, with ceiling covered with mammillary speleothems and clay; **b** Poolfinger Room with false ceiling (pool speleothems and flowstone) and breakdown (mostly speleothems); **c** Guano Room, with Debris Passage rising from *right*; **d** Lower part of Debris Passage with fracture guided phreatic passage leading to Upper Room, and Lower Passage leading to Poolfinger Room; e Upper part of Upper Room with ceiling pockets, cupolas; **f** Upward view of Debris Passage with general phreatic morphology and paragenetic ceiling. Photographs by A. Mihevc (**c**), J.-Y. Bigot (**e**) and M. Temovski (**a**–**f**)

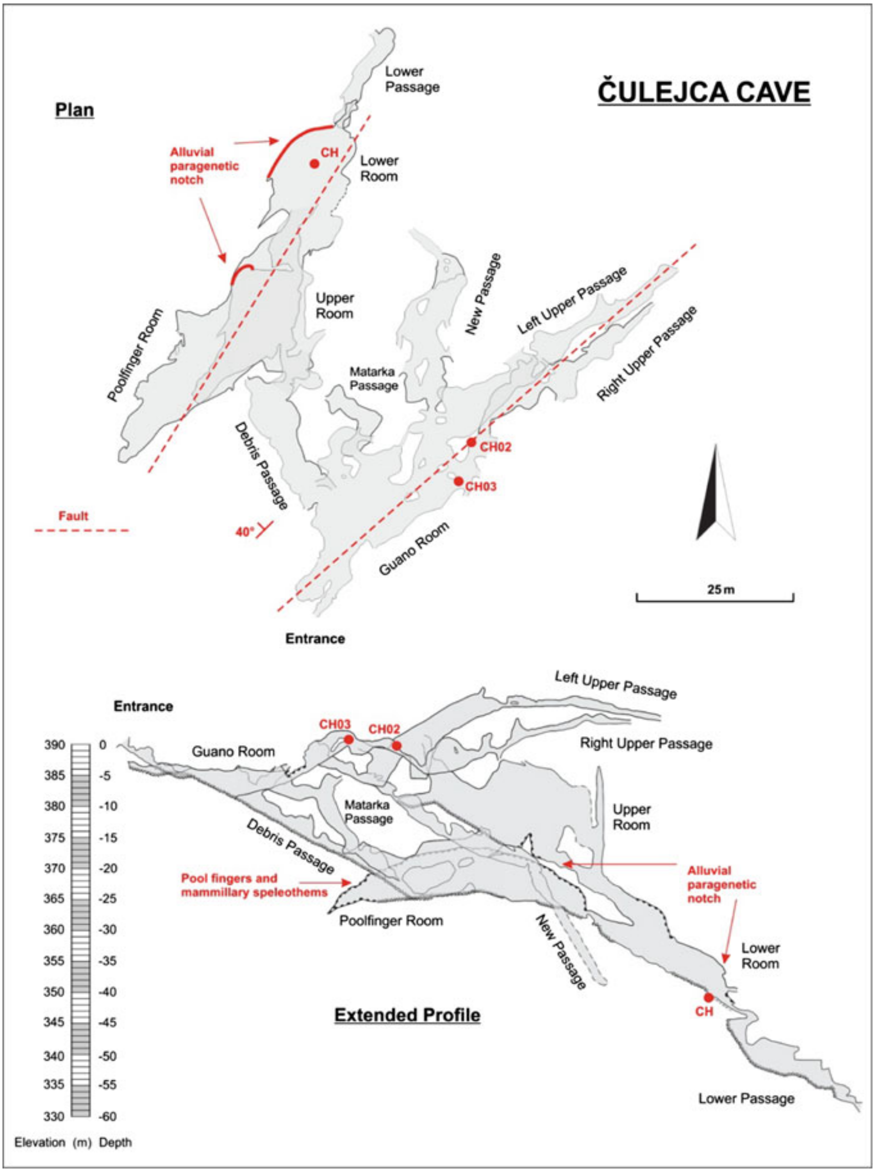


Fig. 5.38 Simplified map of Čulejca Cave. For more detailed cave map, see Appendix

These paleokarst deposits are cut by SW–NE-oriented fault, which guided the anastomotic phreatic passages developed within. The paleokarst cave itself looks like it was developed along the same fault structure, which was later reactivated. Displacement of phreatic morphologies along the fault indicates that the fault was active also after formation of the anastomotic passages.

The lower section, especially Lower Room, Upper Room, and Poolfinger Room, has largest dimensions, with floors filled with clay sediments, and walls and ceilings filed with pool speleothems (mammillary speleothems and poolfingers). Pool speleothems, such as poolfingers and calcite coatings are found also in clay deposits (e.g., connection between Poolfinger Room and Debris Passage).

These two sections are connected with the Debris Passage, a rising phreatic passage developed along the dip of strata, with paragenetic ceiling and debris-filled floor. Matarka Passage and New Passage are also connected to the upper section to the north of Debris Passage. Their bottom parts are choked with debris (Matarka Passage) and clay sediments (New Passage) and are likely connecting the upper section with the lower section as well, with Matarka Passage connecting to the Poolfinger Room, and New Passage coming from below the Lower Passage. They have rising phreatic morphology and are developed along the dip and strike of strata, with New Passage also influenced by S–N-oriented fracture.

Left and Right Upper Passage are mostly developed along the contact with and within paleokarst deposits cut by SW–NE fault. They have vadose to tubular morphology, with parts connected to paleokarst deposits having anastomotic phreatic morphology (along the contact with paleokarst or along the fault) connecting to the Guano Room to the SW. The NE parts are covered with clay and vadose speleothems, with small vadose incision in the floor, at present leading small and intermittent vadose flow toward the New Passage.

Paragenetic morphology is clearly evident in the cave, with both phreatic and vadose paragenetic features registered. Sediment deposition in primary phreatic passages has led to upward paragenetic development, greatly increasing passage size. This is most evident for the northern section of the cave, namely Lower Room, Poolfinger Room, as well as Debris Passage. Paragenetic features (pendants, grooves, ceiling channels) are clearly seen all along the ceiling of Debris Passage. Sediment distribution indicates that these passages have been completely filled with fine-grained sediments. Paragenetic morphology is less evident or absent in passages (Matarka Passage and New Passage) to the east of the former.

Alluvial notches, which are paragenetic features developed along the water table and can represent former base-level positions (Farrant and Smart 2011), are seen on the northern wall in the Upper Room (at 370 m a.s.l.) and Lower Room (353 m a.s.l.), connected with coarser fluvial sediments (Fig. 5.39a, d). The alluvial notch at 370 m a.s.l. corresponds with small water-level corrosion notch on mammillary pool speleothems in between the Upper Room and Debris Passage (Fig. 5.39c), as well as with water-level mark in the New Passage (Fig. 5.39h).

Their connection with coarser sediments and development on cave walls in passages which were previously filled with fine-grained sediments indicates different paragenetic developments, one connected with the primary phreatic cave development, and the other overlain later in a vadose setting.

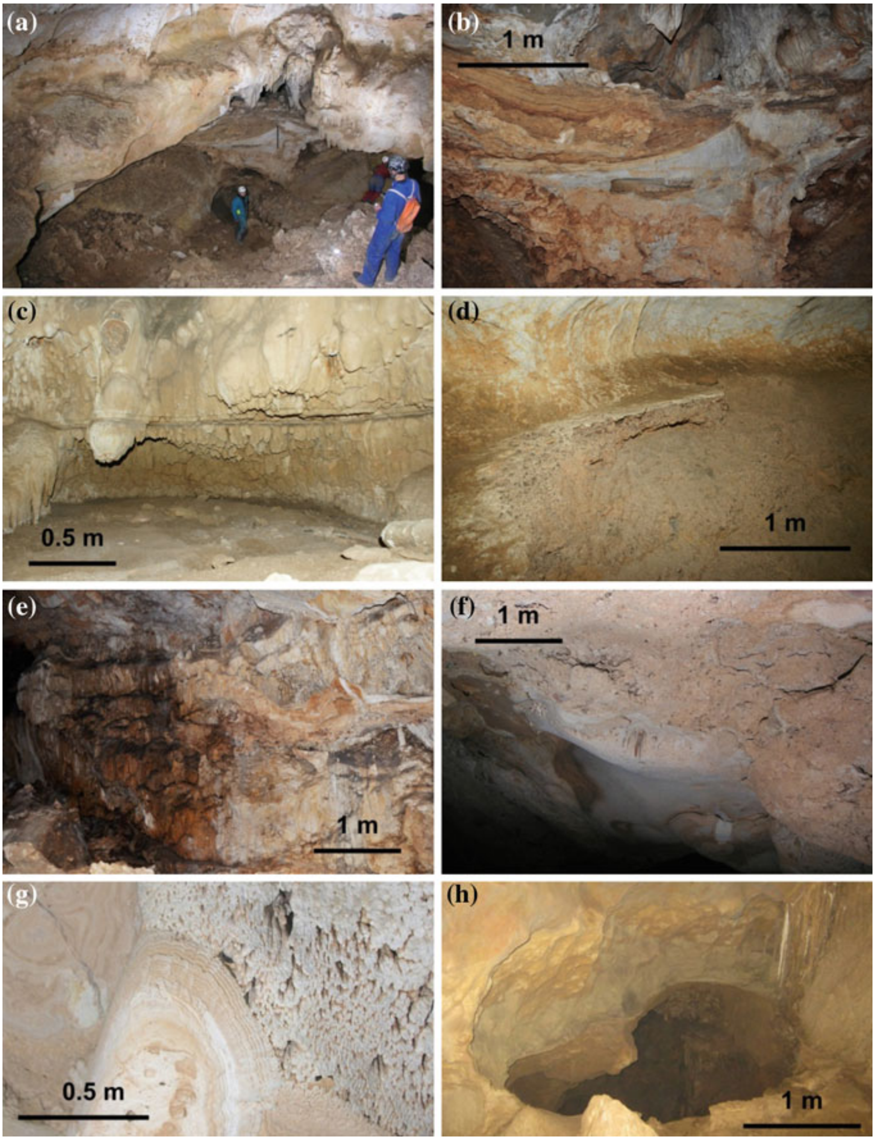


Fig. 5.39 Characteristic morphological features in Čulejca Cave (2): **a** Paragenetic wall notch (Lower Room); **b** Clay-covered flowstone above pool deposits (Lower Room); **c** Water-level mark in mammillary speleothems (Upper Room); **d** Paragenetic wall notch at the same elevation as **c** (Upper Room); **e** Paragenetic wall notch below false floor at the same elevation as **c** and **d** (Poolfinger Room); **f** Corroded lower parts of stacked poolfingers, at the same elevation as **c** and **d** and **e** (Poolfinger Room); **g** Closer view of the corroded poolfingers in **f**; **h** Water-level mark at same elevation as **c**–**f** (New Passage). Photographs by A. Mihevc (**c**, **d**), J.-Y. Bigot (**a**, **f**, **g**), and M. Temovski (**b**, **e**, **h**)

Table 5.8 Mineralogical composition of clay and paleokarst deposits in Čulejca Cave

Sediment (sample)	Mineral composition
Reddish brown clay (CH)	Montmorillonite, halloysite-7Ä, kaolinite, calcite, muscovite, quartz
Paleokarst filling (CH02)	Rutile, goethite, clinochlore, muscovite
Paleokarst filling (CH03)	Montmorillonite, kaolinite, goethite, rutile, muscovite, clinochlore

5.1.7.2 Cave Sediments

Primary phreatic passages are filled with yellow and brown clay deposits. The yellow deposits probably originate from erosion of the paleokarst deposits, while the brown clay deposits are likely from weathering of pyroclastic deposits from Vitačevo and/or Mariovo Formation. X-ray analysis of a sample of reddish brown clay from the Lower Room (Fig. 5.38; Table 5.8) showed composition similar to the clays described in caves of Kamenica Valley: montmorillonite, halloysite-7Ä, kaolinite, calcite, muscovite, and quartz.

Paleokarst deposits are found in the upper section, although their distribution may be larger but concealed by cave deposits. Their distribution suggests that they were deposited in a cave with SW–NE direction. They are likely originating from the Cretaceous siliclastic rocks, with mineral composition (Fig. 5.38; Table 5.8) indicating possible pyroclastic contribution as well.

Clinochlore is found in both samples and might be from ophiolitic rocks. Some ophiolitic rocks are seen in the Upper Passages, and ophiolitic rocks are also found along faults in the Cretaceous rocks, as part of the Vardar ophiolitic complex.

Pool speleothems (Fig. 5.40) are widespread in the Poolfinger Room, the Lower Room, and the Lower Passage. They include mammillary speleothems, poolfingers, and cave rafts. The poolfingers are the most fascinating, with various sizes and different morphologies. They are found all along the Poolfinger Room and the passage leading to the Lower Room, at lower elevations interchanging with clay sediments. At places poolfingers are stacked to each other resembling stacked candles. Clays found with poolfingers are covered with aqueous calcite coatings, indicating that the deposition of the pool speleothems happened in a clay-filled pool setting. Lower parts of some stacked poolfingers seen at the ceiling of Poolfinger Room have clear dissolution morphology indicating later dissolution.

Pilled cave rafts are also found with other pool deposits below a flowstone plaque in the Lower Room.

Pool speleothems change gradually or are covered by thick flowstone speleothems, as seen in ceiling of Poolfinger Room and in the Lower Room. Such situation shows that the deposition of speleothems started in a clay-filled pool setting, which gradually filled up and changed to vadose deposition of flowstone. In the Lower Room, thick flowstone deposits are covered by re-deposited brown clays and coarser clastic sediment, which correspond to the alluvial paragenetic notch seen above them, and are likely connected to backflooding from Crna Reka.

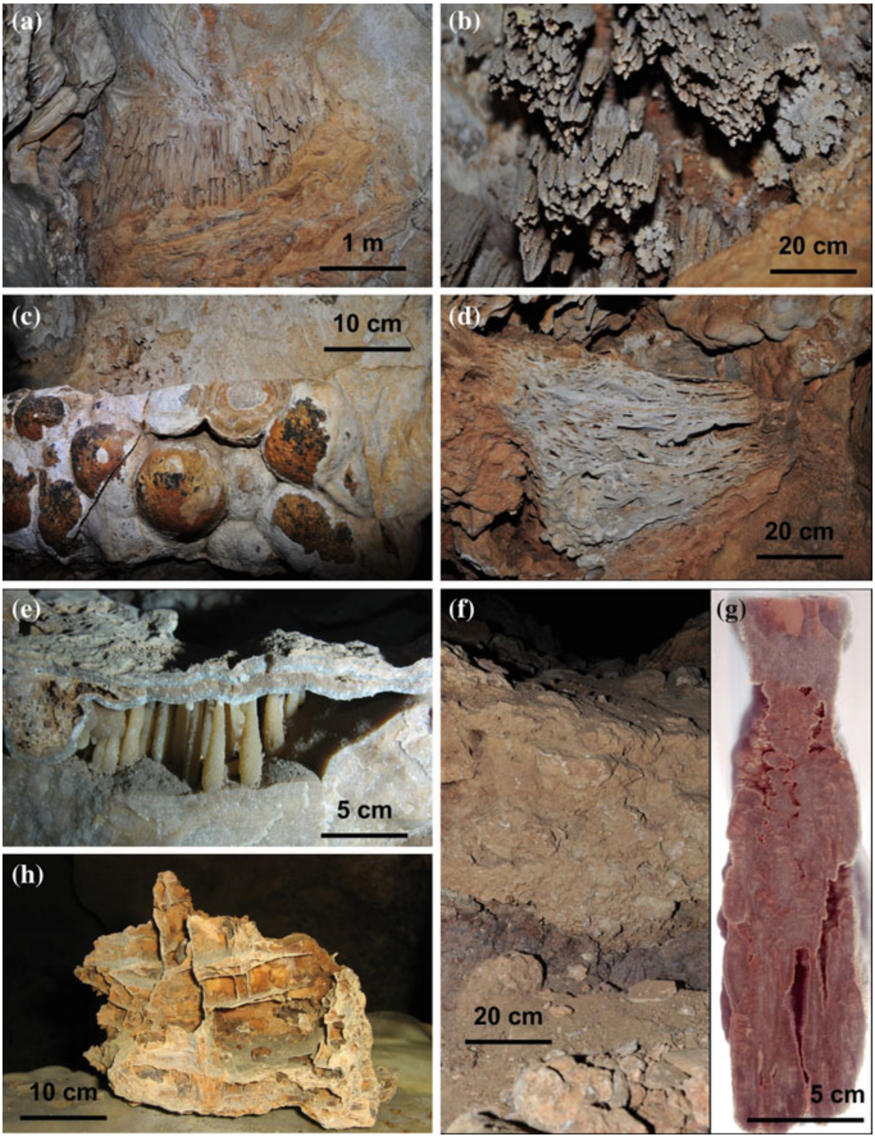


Fig. 5.40 Cave deposits in Čulejca Cave: **a** Poolfingers on the SW wall in Poolfinger Room; **b** Close-up of poolfingers in **a**; **c** Mammillary speleothems on south wall in Poolfinger Room; **d** Pilled cave rafts in the Lower Room; **e** Small poolfingers in the Poolfinger Room; **f** Brown clay deposits covered by redeposited breakdown and clay sediments; **g** Cross-cut of a poolfinger sample from Poolfinger Room; **h** Septaria boxwork with calcite deposited in clay fractures (Lower Room). Photographs by M. Temovski

The older pool and flowstone speleothems, as well as the clastic deposits, and rock morphologies are also covered by younger flowstone and dripstone speleothems.

In the Guano Room, as well as in the small-side passage that connects the Upper Room and the Debris Passage, there are white aragonite stalagmites and stalactites.

Condensation corrosion-affected curtains are also seen in the Upper Room.

5.1.7.3 Speleogenesis

Čulejca Cave is a phreatic cave with passages rising to the south along SW–NE-oriented faults, connected with rising passages formed along prominent bedding partings dipping to the NW. Two sub-horizontal sections can be seen in the cave: the lower in the Poolfinger Room, and the upper in the Guano Room. They are connected by rising phreatic passages (Debris Passage, Matarka Passage, and New Passage) developed generally along the dip and strike of prominent bedding partings.

Distribution of fine-grained sediments, passage organization, and paragenetic morphology indicates formation of passages toward higher elevation due to rise of base level. This has led to deposition of sediments in less active routes and upward paragenetic enlargement of passages, which were later abandoned, with water flow establishing more efficient routes.

The Lower Passage and Lower Room are rising along SSW–NNE fault toward the Poolfinger Room, which is sub-horizontal and represents cave development phase toward more stable base level. Rise in base level shifted cave development toward the upper part (Guano Room). The Lower Passages were filling up with sediments, and more efficient routes were gradually established toward the upper section. Sediment deposition forced paragenetic upward development in Poolfinger Room, Lower Passage, Upper Room, and Debris Passage, which gradually led to development of more efficient routes through Matarka Passage and then New Passage, which is the youngest passage to develop toward the upper section, rising from a different location from below the Lower Passage (Fig. 5.41).

This interpretation is in agreement with passage size, distribution of phreatic paragenetic morphology and clastic sediments.

The Left and Right Upper Passage are likely the youngest passages, with later vadose incision after lowering of base level. The main present vadose flow, although very small and intermittent, is from these passages toward the New Passage.

While the main passage formation is connected to per ascensum speleogenesis due to rise of base level, the removal of sediments is after lowering of base level. Continuous incision of Crna Reka lowered the base level, which led to removal of sediments. Periodical aggradation in Crna Reka Valley led to backflooding and deposition of coarser fluvial sediments (or redeposition of clay fragments) and formation of alluvial notches along the water table. These alluvial notches, seen in the Upper Room (at 372 m) and Lower Room (at 353 m), therefore represent positions of base level in Crna Reka Valley. These backflooding events, forcing

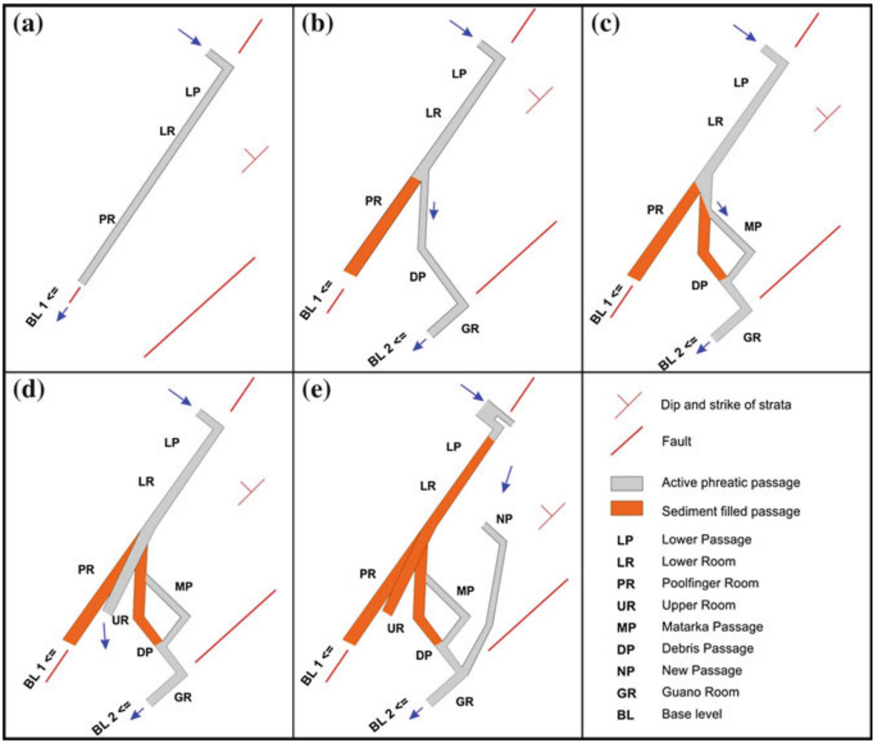


Fig. 5.41 Schematic representation of plan pattern development with phreatic passage formation along faults and bedding partings due to base-level rise and sediment deposition

aggressive water from Crna Reka, also led to dissolution of poolfingers as seen on the ceiling in Poolfinger Room (Fig. 5.39f, g).

Considering the position of Čulejca Cave with regard to the evolution of Tikveš Basin in Pliocene and Pleistocene, and distribution of Pliocene (Vitačevo Formation) and Pleistocene deposits (Mariovo Formation), the first phase of cave development (per ascensum) might be connected to deposition of sediments (Vitačevo Formation) in Pliocene–Pleistocene Central Macedonian Lake. The area of Vitačevo Plateau as part of the Tikveš Basin was covered by deposits of Vitačevo and Mariovo Formations, deposited in Pliocene and Early Pleistocene, respectively. Remnants of deposits of Vitačevo Formation found on Tumbata (697 m) above Čulejca Cave, as well as the distribution of Vitačevo and Mariovo Formations indicates that this whole western part of Vitačevo Plateau was covered by Pliocene and Early Pleistocene deposits.

Development of rising phreatic cave passages can be due to base-level rise as a result of Pliocene lacustrine deposition. During Late Pliocene and Pleistocene, the cave system would have been closed due to complete covering of the Plateau with Vitačevo and Mariovo Formations (Figs. 5.42 and 5.75). Travertine layers are

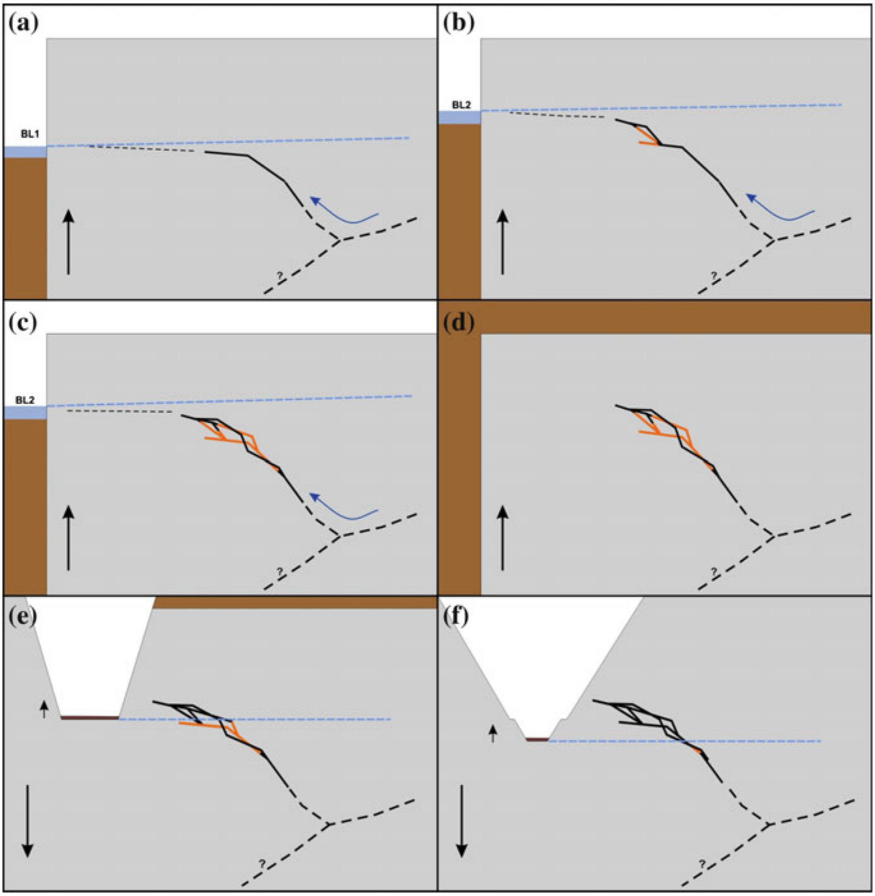


Fig. 5.42 Interpreted evolution of Čulejca Cave with regard to the geomorphological evolution of Tikveš Basin and Crna Reka Valley. **a**–**c** Per ascensum formation of rising phreatic passages with sediment deposition and paragenesis due to base-level rise (deposition of Vitačevo Formation in Tikveš Basin); **d** Fossilization of the karst system due to burying of Vitačevo Plateau by deposits of Tikveš Basin (Vitačevo and Mariovo Formation); **e**–**f** Per descensum evolution of Čulejca Cave, with removal of sediments, deposition of pool speleothems and paragenetic development due to periodical aggradations in Crna Reka Valley

found within Vitačevo Formation up to 500 m a.s.l. and might correspond to the closure of the karst system.

After draining of Central Macedonian Lake and start of incision of Crna Reka, lowering of base level led to removal of sediments and deposition of speleothems in a pool to vadose environment. As Crna Reka incised faster than its tributary Kamenica River, the upper parts of the karst terrain, which were previously recharging Čulejca Cave, would have stayed covered and there would have been lack of aggressive water recharge in Čulejca Cave. This is in good agreement with

Table 5.9 Correlation of speleogenetic phases with geomorphological and geologic events in Tikveš Basin

Period	Geological and geomorphological setting	Cave development	Cave features
Upper Miocene 5.96–5.32 Ma BP	Entrenchment of Vardar and Crna Reka due to MSC (?)	Per descensum	Not seen, hypothesized below the cave
Lower Pliocene	Pliocene deposition in Tikveš Basin	Per ascensum	Rising phreatic passages clay deposition in inactive parts
Upper Pliocene–Lower Pleistocene	Complete covering of karst areas with deposits of Vitačevo and Mariovo Formations		Fossilization of karst system
Upper early Pleistocene to late Pleistocene	Incision of Crna Reka first in Neogene deposits, then in Cretaceous limestones	Per descensum	Restricted recharge (covered upstream karst) deposition of flowstone and pool speleothems periodical river aggradation (clay deposition on flowstone, paragenetic wall notches, dissolution of pool speleothems)

the oversaturated water-depositing calcite in a pool environment. Small vadose recharge from exposed limestone due to caprock retreat close to the Crna Reka Valley or small recharge with long residence time from the karst system might have contributed to the oversaturation of the pools with regard to calcite.

Per ascensum phase of cave development due to base-level rise by Pliocene deposition would mean that a previous phase of karstification occurred which lowered the water table before the deposition of the Pliocene sediments. Possible reason for such base lowering prior to the Pliocene deposition can be the influence of the Messinian Salinity Crisis (MSC). Based on the evidence found in Macedonia (Dračevo), Greece (Thessaloniki), and Niš (Serbia), a marine gateway (Fig. 5.76) which connected the Dacic Basin (Eastern Paratethys) to the Aegean Sea prior and after the MSC was proposed (Clauzon et al. 2008). Although evidence of MSC in Tikveš Basin is not yet registered, the Pliocene deposits found along the Crna Reka Valley between Mariovo and Tikveš Basin indicate the Miocene age of the paleo-Crna valley, with the Quaternary Crna Reka following approximately the same course. At the confluence with Blašnica River, Crna Reka Valley is also cutting trough Pliocene deposits (Fig. 5.59).

Based on the morphological evidence, some base-level markers can be determined from the cave for both per ascensum and per descensum phases of speleogenesis (Table 5.9). Sub-horizontal position of phreatic parts considered as formed during the first phases of per ascensum speleogenesis as seen in Poolfinger Room and close to the entrance (Guano Room) give markers for Pliocene deposition at 365–370 m (Poolfinger Room) and 380–385 m (Guano Room). Alluvial paragenetic notches connected with coarse fluvial sediments and corroded pool speleothems, attributed to Crna Reka aggradation give markers for Crna Reka base level in Pleistocene at 353 m (Lower Room) and 370 m (Upper Room). The alluvial notch at 353 m may correspond with remnant of a terrace at 350 m located 2 km to the north at the confluence of Kamenica River with Crna Reka.

Paleokarst deposits in the upper section are likely older than Pliocene and were probably used as most favorable routes by the rising waters due to base-level rise which influenced the per ascensum speleogenesis. Their distribution is clearly seen in the upper section, and it is possible that passages in the lower section are also partly influenced by paleokarst deposits, with their distribution hidden by younger deposits.

5.2 Caves in the Western Part of Dren and Kozjak Mountains

5.2.1 Podot Caves and Gugjakovski Izvori

Podot is a flat surface in the valley of Crna Reka, with one markant terrace at 440 m a.s.l., covered mostly by tufa and tufaceous limestone with some carbonate breccia and conglomerate layers (Figs. 5.43 and 5.44). This terrace has more broken morphology to the east due to slope retreat and collapses. At the base of the terrace, there is a big spring discharging at 4 visible locations (Gugjakovski Izvori) with

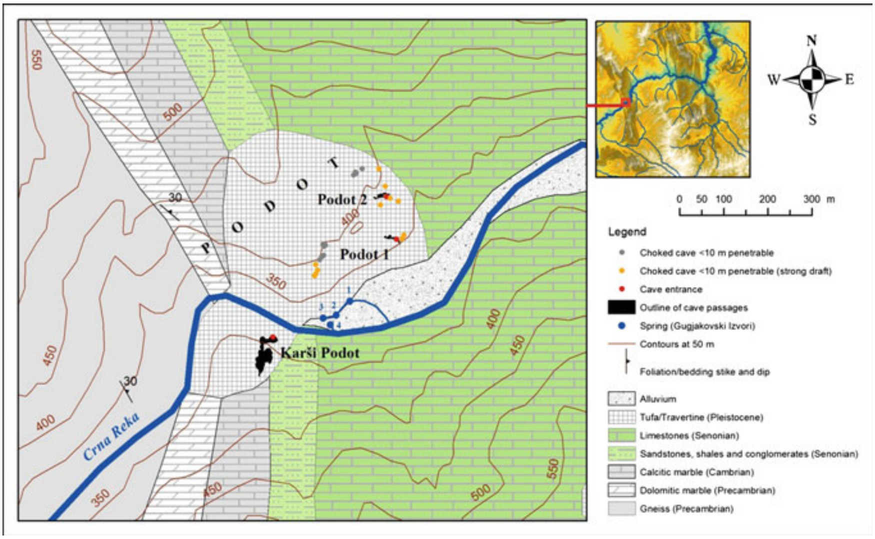


Fig. 5.43 Geological characteristic and location of caves and springs in Podot locality. Geological data modified after Dumurdžanov et al. (1976), Geološki Zavod–Skopje (unpublished)

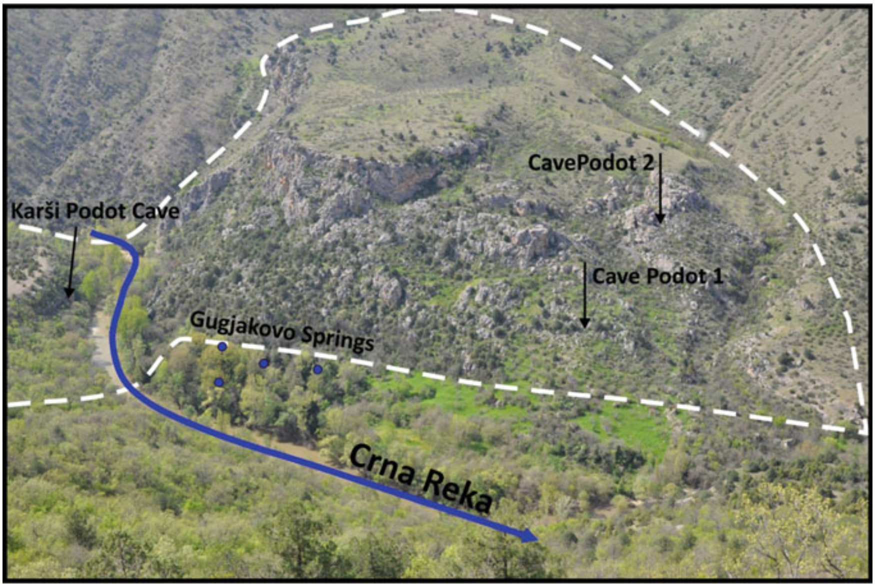


Fig. 5.44 View of Podot terrace with location of Gugjakovo Springs and caves Podot 1 and 2. *White dotted line* outlines travertine deposits

approximate discharge of 0.5 m^3 s^{-1} (the approximation was made after measurement at the two confluences with Crna Reka in July 2012, using the float method), but actual discharge might be much bigger. It is the largest spring along the valley of Crna Reka, downstream from the ones in Demir Hisar (Fig. 1.1) spring area.

There are number of cave entrances in this terrace, several of which with a strong draft, but most of them are penetrable for up to 10 m in a breakdown passage ending with collapse choke. In two of these entrances, it was possible to penetrate further inside, leading to caves Podot 1 and Podot 2. Cave entrances with or without draft are distributed in two localities, one associated with Podot 1 and Podot 2 caves, and the other above Gugjakovski Izvori.

5.2.1.1 Caves Podot 1 and Podot 2

Morphology

As the tufaceous limestones are largely affected by collapse, entrances and entrance parts of the caves are in breakdown deposits, in-between blocks, generally vertical leading to the main cave parts below. The entrance of Podot 1 is merely 40 cm in diameter.

In plan view, cave passages constitute a network pattern with fissure-guided passages developed along several fractures with SW–NE, WSW–ENE, and WNW–ESE to NW–SE general direction (Figs. 5.45 and 5.46). Passages have generally bigger

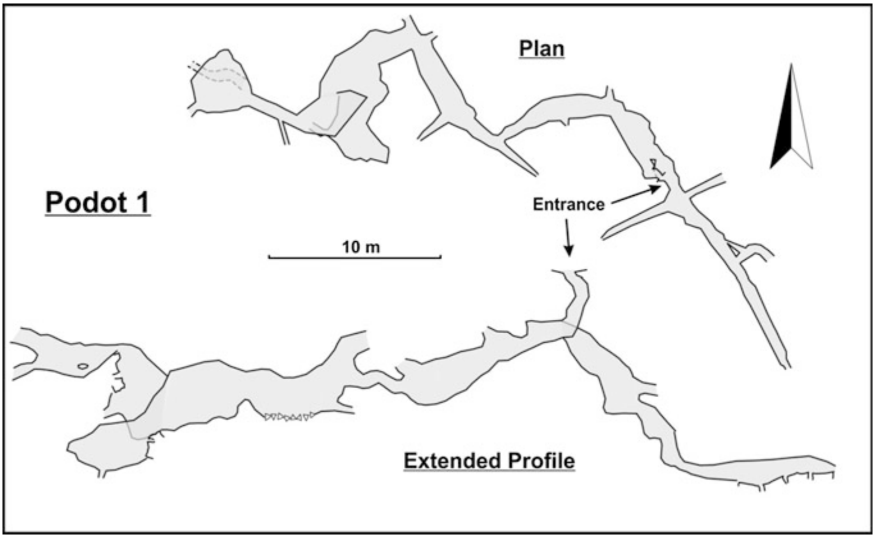


Fig. 5.45 Simplified map of cave Podot 1. For more detailed cave map, see Appendix

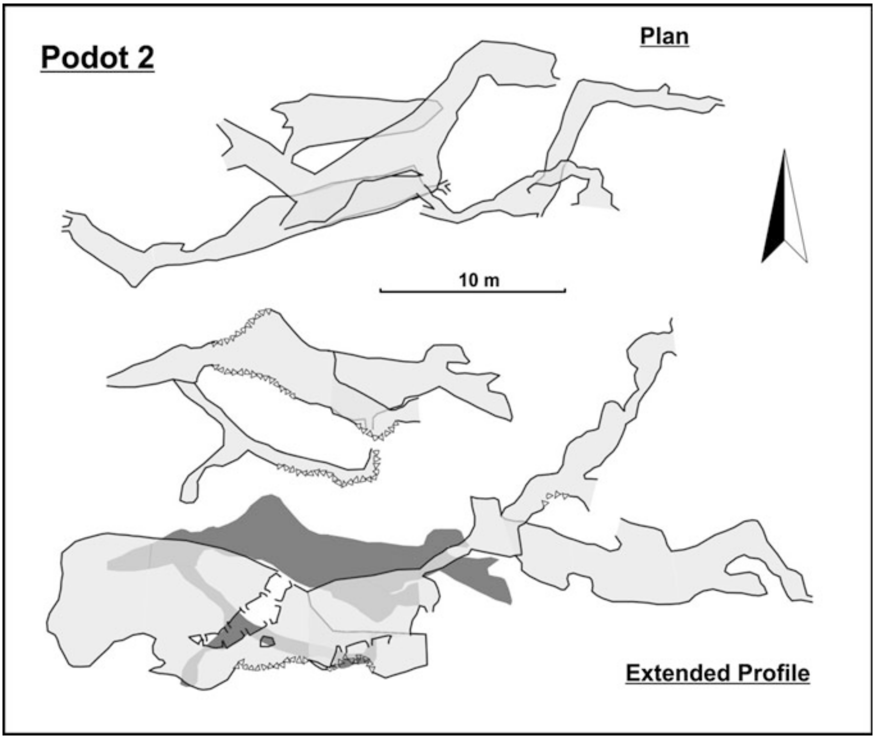


Fig. 5.46 Simplified map of cave Podot 2. For more detailed cave map, see Appendix

Fig. 5.47 Characteristic features of Podot caves: *Upper left* The entrance to Cave Podot 1; *Upper right* Mammillary calcite-coated walls in Cave Podot 2; *Down* Closer look of broken mammillary coatings. Photographs by M. Temovski

height than width and appear to have phreatic morphology, although morphology is difficult to observe due to collapse and later coating with pool speleothems (Fig. 5.47).

In vertical dimension, passages are mostly horizontal with two (Podot 2) to three notable levels (Podot 1). Their development is likely connected to former positions of the water table, determined by the position of Crna Reka riverbed. The levels in Podot 1 correspond to the terrace at 350 m (Fig. 5.48).

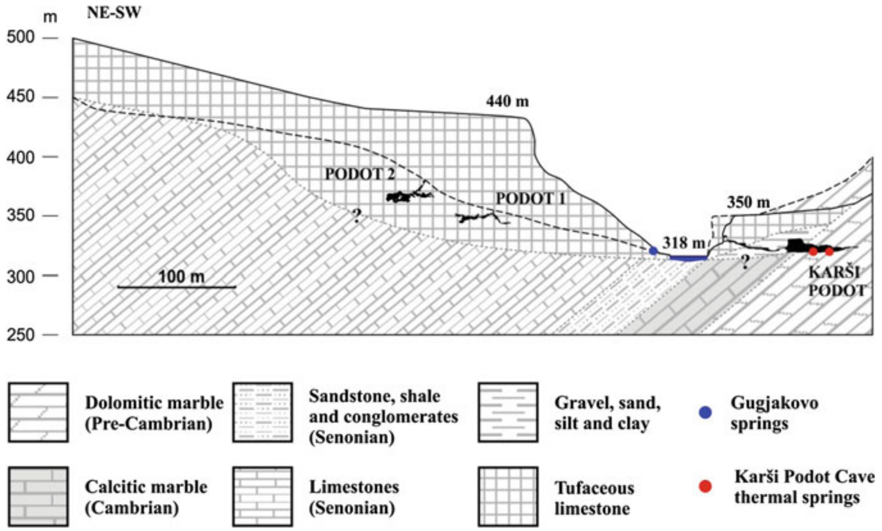


Fig. 5.48 Cross section of Podot locality showing caves, springs, and terraces

Cave Sediments

Passages are affected by collapse processes, with breakdown deposits covering most of passage floors. In the lower levels, passage walls are covered by coatings and mammillary speleothems, which were likely deposited by oversaturated waters in ponded environments. The best examples are in cave Podot 2, in a small passage in the northern part of the cave.

5.2.1.2 Gugjakovo Springs

Gugjakovo springs are discharging water in at least 4 different localities. Springs 1, 2, and 3 are at the contact of Travertine with alluvial deposits converging in a small river connecting with Crna Reka, while Spring 4 is in the alluvial deposits closer to the river connecting to Crna Reka little upstream from the others (Fig. 5.43).

Opposite of Gugjakovo springs in Karši Podot Cave, there is a thermal spring with temperature of 23 °C (Chap. 4).

5.2.1.3 Smaller Caves, Collapses

A number of smaller caves are found in Podot terrace, generally in two localities: in the eastern part in proximity to Podot 1 and Podot 2 caves, and in the middle part above Gugjakovski Izvori. They have passages of less than 10 m, generally with collapsed morphology ending in a choke. Some of them, in both localities, have

Table 5.10 Some physical and chemical parameters of Gugjakovski Izvori; temperature (*T*) in °C; electronic conductivity (EC) in μS/cm; total hardness (TH) in dH; concentrations in mg/l

Date	*T*	pH	EC	TH	HCO_3	Ca	Mg	Cl	Fe	Mn	NO_3	SO_4	Analysis
29/04/2012	/	7.95	702	/	/	/	/	14	0	/	5	/	Lab
23/07/2012	17	7.26	740	14.5	518.5	27.23	50.8	8	0.025	0	2.7	0	Lab

strong draft of cool air. They are generally in the lower elevations close to the spring or to the caves. In between these localities, there is a rift-like depression 30 m wide with SE–NE direction. It is a collapsed structure with come cavities seen on the SE wall (Fig. 5.43).

5.2.1.4 Speleogenesis

The cave development in the tufaceous limestone deposits of Podot terrace is connected to the evolution of the riverbed of Crna Reka. Periods of stable base level led to development of horizontal passages corresponding to the spring position. Incision of the valley lowered the spring position and water table, producing passages at lower level. Spring position shifted to the SW as Crna Reka incised in valley, with higher level passages in the NE part.

Podot 1 and 2 caves have been formed in phreatic to epiphreatic environment, with their evolution connected to the lowering of water table due to incision of Crna Reka. Horizontal development of passages was connected to periods of stable base level. With lowering of water table, subaqueous mammillary and coating speleothems have been deposited in oversaturated perched pools.

As Crna Reka incised in riverbed, the spring shifted to lower position, with cave levels development in stable periods. Slope retreat processes triggered collapse of cave passages, with numerous, breakdown choked small caves left, as well a large collapse structure between the spring and caves Podot 1 and Podot 2. Gugjakovo springs are the present discharge points of this system, with active cave passages in the background of the springs, not yet reachable.

Temperature of water from Gugjakovo springs (17 °C) is little higher (cf. Zelen Izvor with temperature of 11.3 °C) which might be due to mixing with thermal waters (Table 5.10). Thermal waters with temperature of 23 °C are discharging in Karši Podot Cave.

Diffuse vadose recharge is also contributing to dissolution of the porous tufaceous limestones and might have also contributed to the deposition of pool speleothems, but this is rather small amount considering the small surface area of tufaceous limestones.

5.2.1.5 Source of Water

The spring and caves in Podot tufaceous limestones are the output part of the karst system. There are three karstifiable formations underlying the tufaceous limestones: dolomitic marbles (Precambrian), overlain by calcitic marbles (Cambrian), and limestones (Cretaceous–Senonian) separated from the former by Senonian clastic rocks (sandstone, shale and conglomerates). The dip of this whole pre-Cenozoic section (as part of Veprčani monocline) is to the ENE by 30–50°. Water could be supplied from any these karstifiable formations, with the tufaceous limestones allowing by-passing of the impermeable clastic formation. Considering the dip of

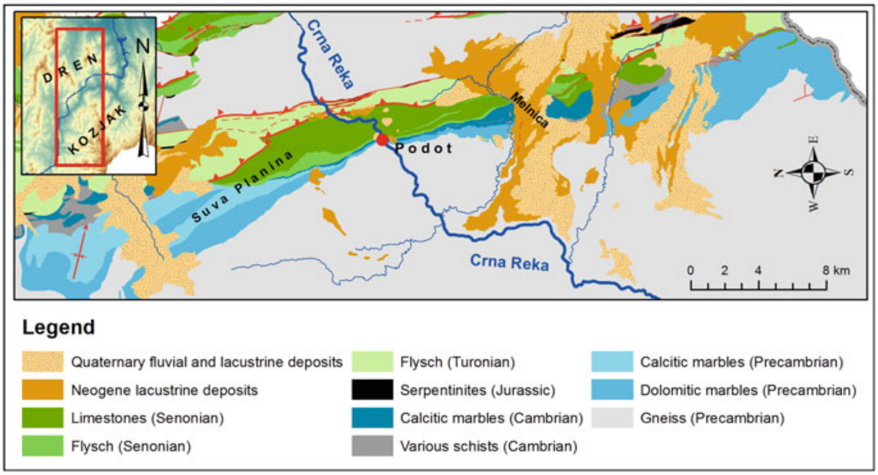


Fig. 5.49 Extent of karst rocks with Suva Planina as possible recharge area of Gugjakovo Springs (Podot locality)

strata water from the Cretaceous limestones will more likely discharge in the downstream part, at the lowest position of contact with Turonian clastic (~ 15 m lower than the spring), although only one very small spring was found in the downstream part, and the formation is clearly karstified. Water can be supplied from the marble formations, probably more from the Cambrian calcitic marble. This Cambrian formation continues to the north where it overlays Precambrian calcitic marbles (which thin out to the south), and recharging may be all along this outcrop up to Suva Planina to the NE, as well as from the dolomitic marble (Fig. 5.49). They probably mix with thermal waters coming from south at the spring area.

5.2.2 Pešti Cave

Pešti Cave is located at 1135 m a.s.l. on the eastern slope of Garvan–Četiri Buki mountain segment in Dren Massif, 900 m SE of Trite Stragi (1476 m) and 1.4 km from Klen mountain pass, about 3.5 km north from Crna Reka (Figs. 5.50 and 5.54).

5.2.2.1 Morphology

Pešti Cave is a 200-m-long, 38-m-deep cave composed mostly of one big main passage in SE general direction (Fig. 5.51). Passage parts are developed along strike of strata (with NNW–SSE direction), with dip (to ENE by 55°) clearly visible on passage walls. In the lower parts, the passage turns little to the east, partly

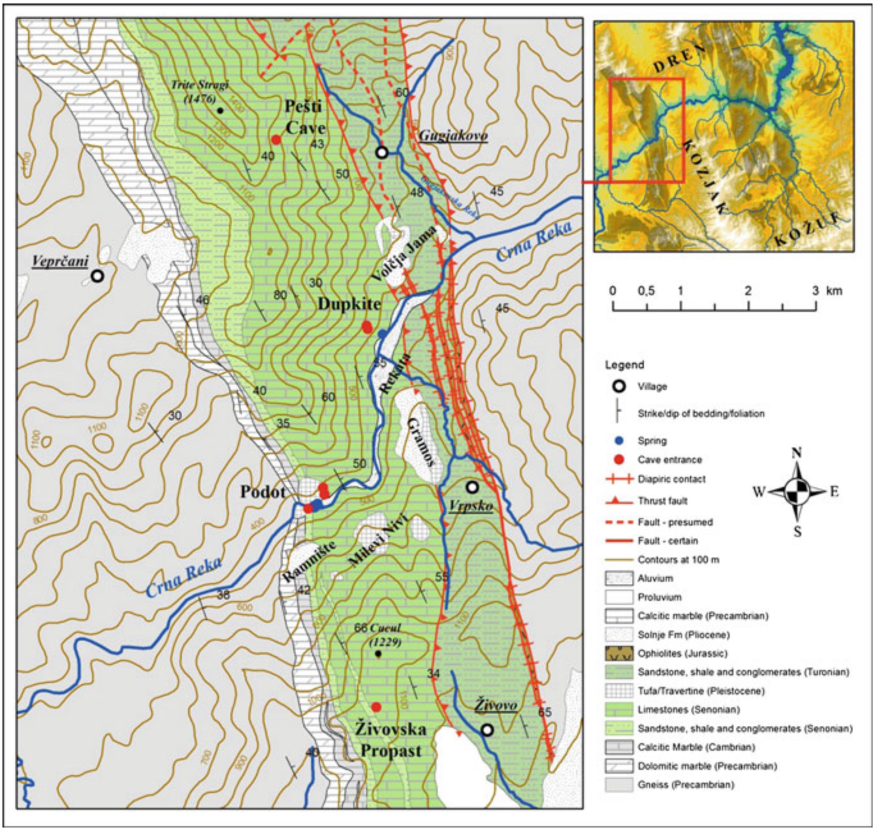


Fig. 5.50 Geological setting between Živovo and Gugjakovo villages with locations of Pešti Cave, Živovska Propast, Dupkite, and Podot caves. Geological data modified after Dumurdžanov et al. (1976), Geološki Zavod–Skopje (unpublished)

influenced by a WNW–ESE-oriented fracture. Passage morphology is difficult to observe, mostly obscured by speleothem deposits and breakdown. Vadose canyon morphology can be seen in the middle part, cut down in what appears to be a remnant of phreatic tube in the ceiling. Small down-dip-developed tributary vadose passages appear from the southwestern wall. At the end, the cave turns to the south ending with a clay-filled passage. The passage here has a flat paragenetic ceiling which is partly exposed after removal of sediments (Fig. 5.52).

In the middle of the cave, there is a side passage below the main passage. This passage (Lower Passage) has the same slope and direction with upper parts filled with clay and paragenetic ceiling morphology.

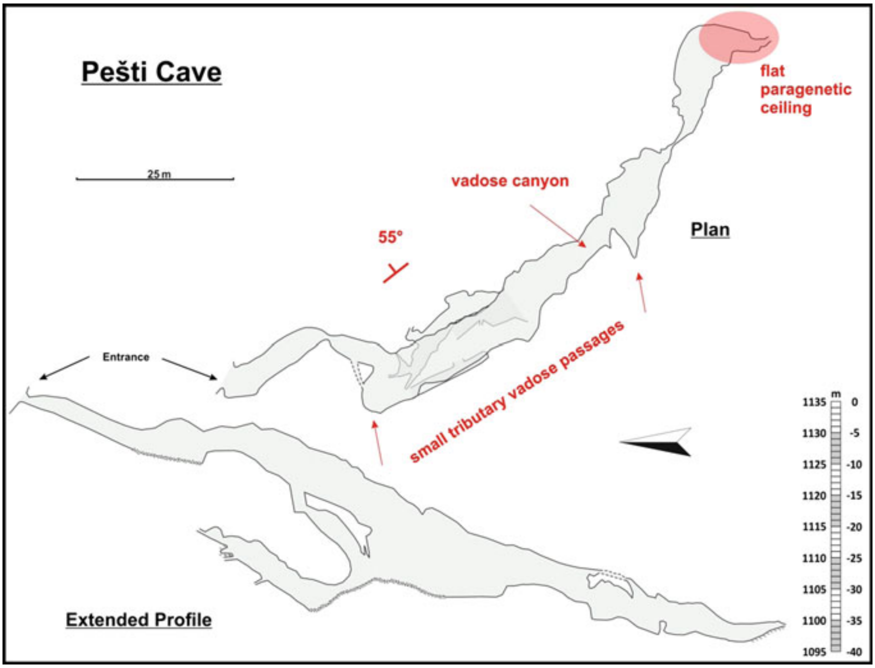


Fig. 5.51 Simplified map of Pešti Cave. For more detailed cave map, see Appendix

5.2.2.2 Cave Sediments

Red brown clay deposits are filling the lower part of the cave, partly covered by flowstone, and probably also filling other parts of the cave but covered by speleothems or breakdown material. X-ray analysis of a sample (PES01) from the clay choke at the end of the cave showed composition of calcite, clinochlore, muscovite, quartz, sanidine-potassium, and goethite.

Considering the location of the cave, the surrounding stratigraphy, and the orientation of cave passages, the source of sediments is likely from the Senonian clastic rocks (sandstones, shales and conglomerates) underlying the limestones and outcropping to the west at the contact with underlying Paleozoic and Precambrian rocks, which themselves originate from the Precambrian metamorphic complex to the west.

Breakdown processes are clearly very important for present morphology of the cave, with huge collapses of ceiling, mostly along bedding planes, producing breakdown debris and large limestone blocks. Breakdown of flowstone can be seen in the lowest part of the room, due to instability after removal of underlying clay deposits.

Passage walls are also covered with thick dripstone and flowstone speleothems throughout the cave.

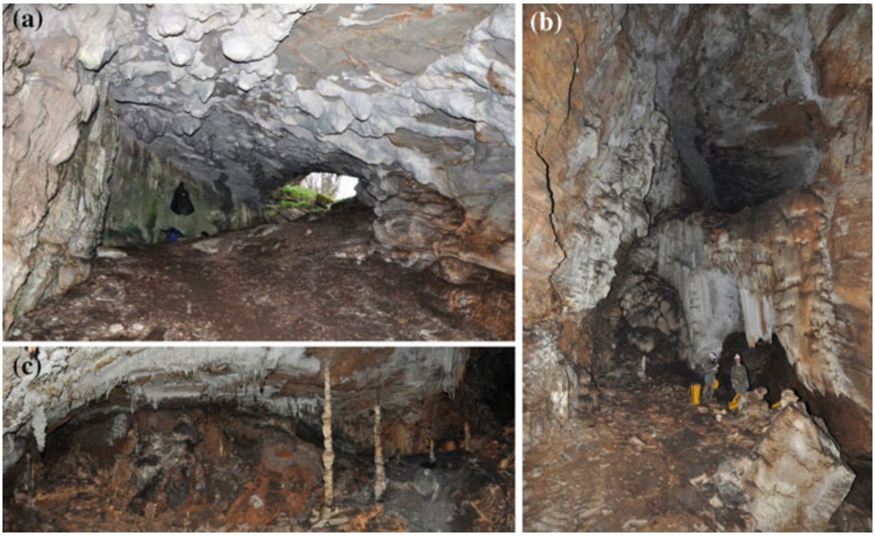
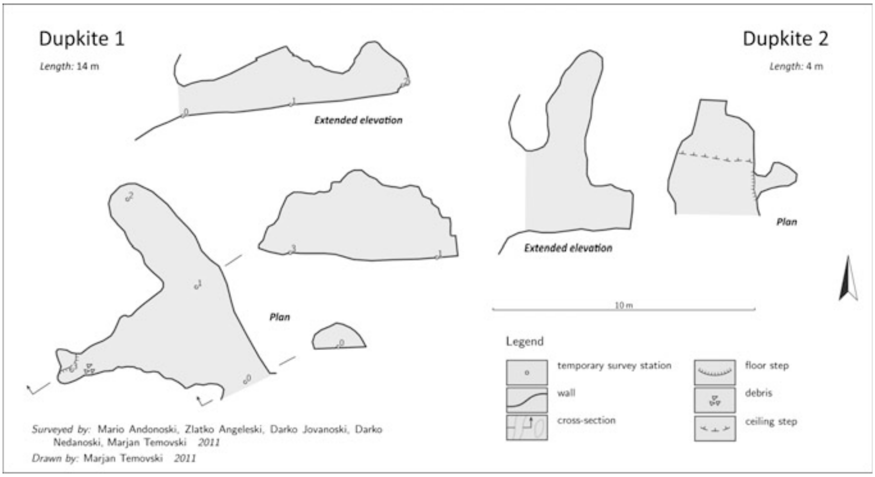


Fig. 5.52 Characteristic features of Pešti Cave: **a** View of the entrance part of the cave; **b** View of the middle part of the Main Passage, with large flowstone and dripstone speleothems. The Lower Passage is to the lower right part; **c** The lowest part of the cave, filled with *reddish clay*. Photographs by M. Temovski

5.2.2.3 Dupkite Caves

These are two small caves located at 460 m a.s.l. (Dupkite 1) and 490 m a.s.l. (Dupkite 2) on the left side of Crna Reka Valley in Rekata locality (Figs. 5.50 and 5.54), 145 m and 175 m, respectively, above Crna Reka riverbed. Dupkite 1 is larger with 14 m of passage length (Fig. 5.53). It has same SSE direction along the



Surveyed by: Mario Andonoski, Zlatko Angeleski, Darko Jovanoski, Darko Nedanoski, Marjan Temovski *2011*
Drawn by: Marjan Temovski *2011*

Fig. 5.53 Maps of caves Dupkite 1 and Dupkite 2 strike of thin-bedded limestones. Passage morphology was mostly destroyed due to breakdown. Below these caves at the riverbed of Crna Reka, there are two small karst springs.

5.2.2.4 Speleogenesis

Passage orientation and remnants of morphology in the cave indicate primary phreatic passage development in SE direction along the strike, with tributary vadose passages joining from west, developed along the dip. Vadose canyon was later incised in the main passage after lowering of base level, with later paragenetic development due to deposition of red clay deposits. The paragenetic development likely started in vadose environment, producing flat ceiling in the lower part after transition to phreatic environment due to complete infilling with clay deposits.

Sediments were likely brought by vadose streams from passages developed along the dip at the contact with the underlying clastic Senonian deposits at higher elevation in the NE dipping Veprčani Monocline.

The development of the cave was most likely controlled by base-level changes in the main Crna Reka Valley. Considering the direction of the cave, and the location of small remnants of caves (Dupkite 1 and 2) on the left side of Crna Reka Valley in Rekata locality, as well as small springs below them in the riverbed of Crna Reka (Fig. 5.50), this area may be the output part of the same cave system. Dupkite Caves are located below the Pliocene and Pleistocene deposits (Solnje and Mariovo formations), and their development is likely connected with evolution of Crna Reka Valley after the draining of the lake system in Pleistocene. It is also possible that this cave system was active prior to the Pleistocene incision of Crna Reka, with karst waters contributing to the deposition of travertine deposits of Mariovo Formation on Gramos and Milevi Nivi (Fig. 5.54).

5.2.3 Živovska Propast

Živovska Propast is located on the mountain ridge of Gola Skrka–Cucul segment (Figs. 5.50 and 5.54), at 1173 m a.s.l., 800 m south from Cucul (1229). The cave is formed in Senonian limestones, close to the contact with a lens of clastic rocks, part of Veprčani Monocline, dipping to the ENE by 50°.

It is a 115-m-deep cave with a network of shaft passages developed along the three sets of fractures with: NNW–SSE, N–S, and WSW–ENE direction. NNW–SSE and WSW–ENE fractures are more prominent ones with deeper shafts developed along them (Fig. 5.55). Passages end with a choke, with passages developed along the N–S-oriented fracture having smaller depth. The northern shaft developed along

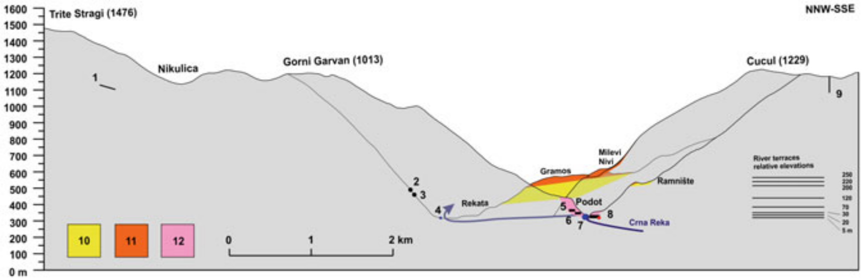


Fig. 5.54 Cross section of Crna Reka Valley with caves and springs and their relationship with Pliocene–Pleistocene sediments and terraces: *1* Pešti Cave, *2* Cave Dupkite 2, *3* Cave Dupkite 1, *4* small springs below Dupkite caves, *5* Cave Podot 2, *6* Cave Podot 1, *7* Gugjakovski Izvori, *8* Karši Podot Cave and thermal springs, *9* Živovska Propast, *10* Gravel, sand, and silt (Solnje Formation?, Pliocene), *11* Travertine deposits (Mariovo Formation?, Pleistocene), *12* Tufaceous limestone, tufa and carbonate conglomerates (Pleistocene?)

this fracture ends at 60 m, while the southern shaft, which is developed at the cross with the NNE–SSE fracture, ends at 65 m depth. The deepest part is in the northern shaft along the NNW–SSE fracture with passage ending with a choke at 115 m depth, while the only passage developed along the WSW–ENE fracture ends at 100 m depth.

Cave walls are covered with popcorn deposits in mostly in the deeper parts of cave passages.

Živovska Propast is a complex system of shafts developed along the three sets of fracture orientations. Passages end with chokes, so the depth measured is not representative of the cave development. The most prominent fracture direction is the NNW–SSE. As this area has been high above the Crna Reka base level at least since Miocene when the old valley of Crna Reka developed (see Sect. 2.4) and was not covered with sediments of Mariovo Basin, the cave may have been actively developing for a long period, with different fractures having bigger influence in given periods. If we consider the interpretation of age of fractures by geometry (Kochneva et al. 2006; Boev and Jelenković 2012) with fractures having Vardar direction (NNW–SSE to N–S) being older and WSW–ENE fractures as younger connected with the Neogene and Quaternary tectonics, and the continuous karstification throughout the Neogene and Quaternary, then passages may have been forming first along the fractures with Vardar orientation, with the passage along the WSW–ENE fracture being younger.

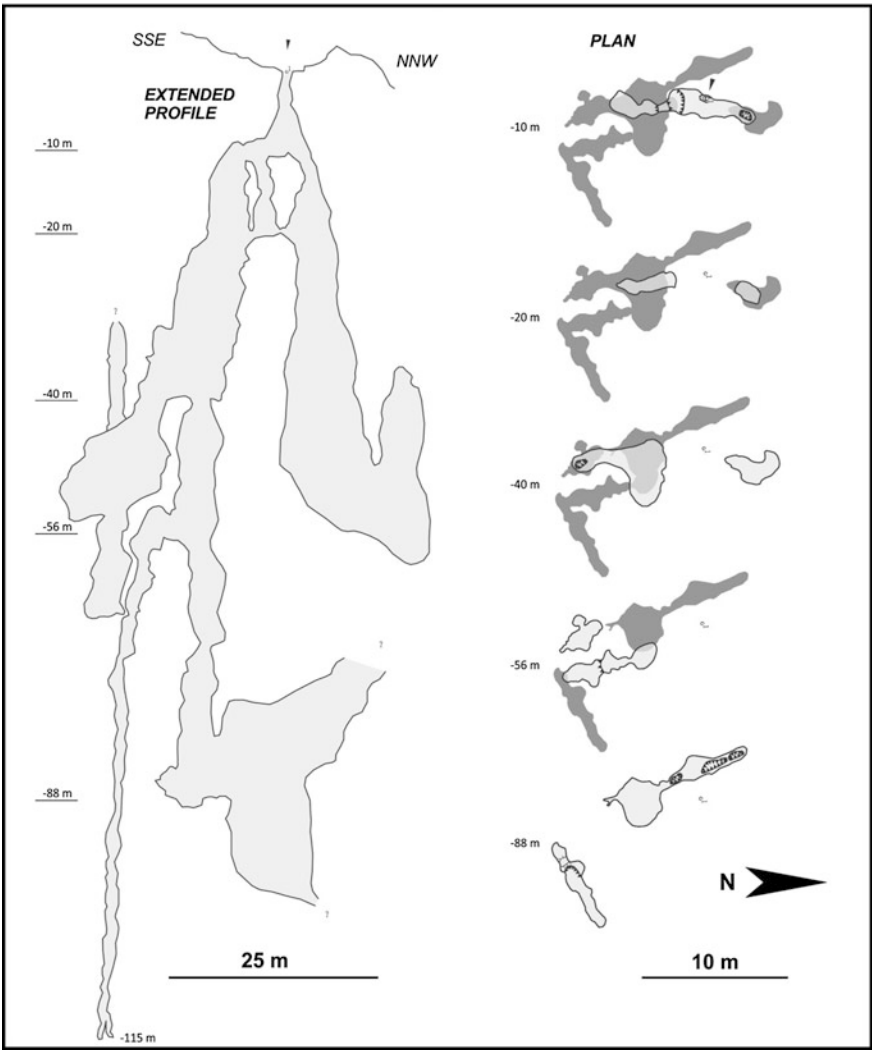


Fig. 5.55 Map of Živovska Propast with plan view at different depths, modified from SD Peoni (2005)

5.3 Caves in the Eastern Part of Dren and Kozjak Mountains

The eastern part of Dren Mountain, especially the terrains developed in Triassic rocks, is the least accessible and least explored parts of this area. This is also true for the eastern part of Kozjak Mountain, except the southern part toward Kožuf Mountain. Triassic limestones and dolomites are the most widespread karst rocks here. The exact relationship of dolomites and limestones has not been determined, with the whole carbonate formation treated as one unit. They are part of the Rožden Horst with clastic rocks of the Middle Triassic overlain by carbonate series of Upper Triassic (Dumurdžanov et al. 1976; Arsovski 1997), and possibly Jurassic (Robertson et al. 2012), highly deformed in a series of isocline folds.

In this eastern part of Kozjak and Dren mountains, Cretaceous limestones are outcropping at several locations, mostly to the NE. The Turonian formation lies to the east of Rožden Horst, with Triassic rocks being overthrust onto Cretaceous rocks.

Several caves have been reported from this are mostly discovered by cavers from PSD Orle. Few of them have been studied, mostly in the southern parts.

5.3.1 Cave Lekovita Voda

Cave Lekovita Voda is situated on the right side of the valley of Doljani River, a left-hand tributary to Crna Reka, 2.3 km to the WSW of Čulejca Cave (Fig. 5.26). The entrance is located in a small (most likely collapse) doline at 730 m elevation.

The cave is formed in Turonian limestones, overlaying clastic sediments, part of the Veles-Klepa-Tikveš segment, which is overthrust from the west by the Triassic rocks of Rožden horst. The Cretaceous series here are folded in several fold structures, with the limestones at the cave dipping by 60° to the SW.

The cave consists of a single horizontal passage, formed along the strike of the strata, with a NW orientation (Fig. 5.56). It is 90 m long, with quite big dimensions, 5–20 m wide and 6 m high. It is a remnant passage of a larger cave system.

In cross section, the passage has a phreatic elliptical morphology, elongated along bedding plane, with strata dipping to the SW, modified by paragenesis. At places remnants of clay deposits can be seen on passage walls and ceiling, although most of the cave walls are covered by flowstone deposits and coated in black due to frequent fire burnings in the entrance part.

Paragenetic morphology can be best observed in the SW part of the cave, where the passage is widest. Here, well-expressed yellow-stained pendants, anastomoses, and channels can be seen on ceiling and walls, with passage floor mostly filled with sediments (Fig. 5.57). Some flowstone deposits with gravel on the lower side are seen on the ceiling, exposed after removal of coarse fluvial sediments.

To the SW, the cave ends with quite large sediment fill, 2-m-thick gravel and sand with flowstone layers, covered by a sloping flowstone deposits up to the ceiling at 6 m height. Quartz and red violet schist fragments were easily spotted in the gravel sediments, most likely originating from the Middle Triassic schist rocks found to the west in Rožden horst.

On the southern wall, close to this sediment profile, there are clay, sand, and gravel deposits exposed on the wall and in a small-side passage or niche. Sample (LEK01) of yellow clay deposits in this location showed composition of montmorillonite, lizardite, goethite, fluorapatite, titanite, and quartz. Presence of

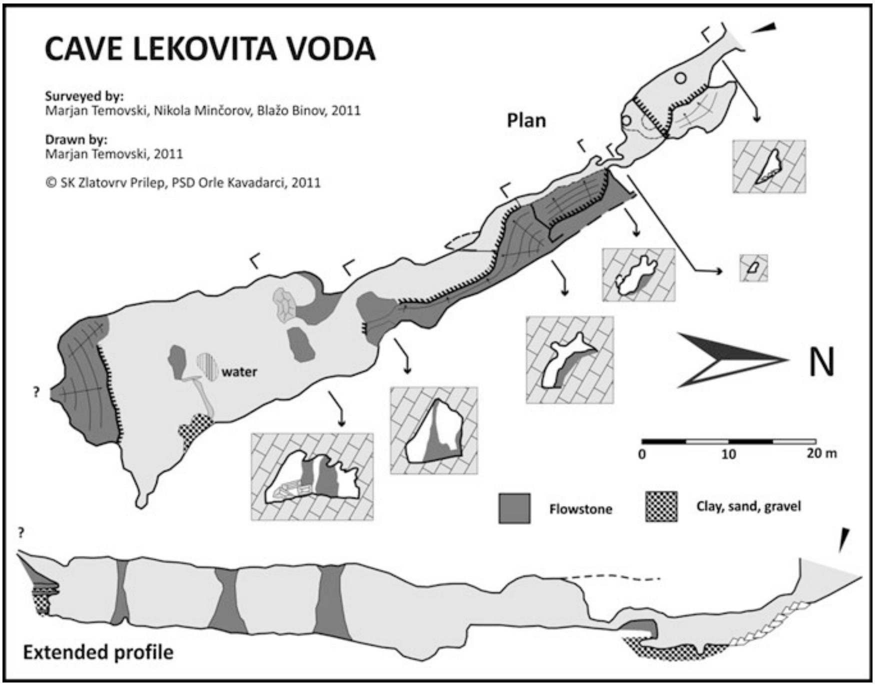


Fig. 5.56 Map of Cave Lekovita Voda

montmorillonite indicates volcanic/volcaniclastic source of sediments. Titanite is a detrital mineral likely coming from the Turonian flysch deposits located to west and underlying the limestones, as it is found in the sandstone sediments of this series (Dumurdžanov et al. 1976). Fluorapatite can be from fossil bones in the sediment, while lizardite can be from ophiolitic rocks, commonly found as diapiric bodies along fault structures in the surroundings.

The cave was formed in a phreatic to epiphreatic setting, with later paragenetic development of the phreatic passage due to sediment infilling. It is a remnant of a former larger cave system, which to the NW is cut by the slope retreat of Doljani valley, while to the SW is choked with sediments. The cave was continuing and developing to the N–NW toward, most likely fed by streams coming from the SW, from the eastern slope of Dren Mountain (Fig. 5.26).

The presence of volcaniclastic-derived sediments in the cave is unexpected, considering its location, and lack of Vitačevo and Mariovo deposits on the left side of Crna Reka Valley, which are considered as the source for montmorillonite in the cave sediments on Vitačevo Plateau. Most likely explanation for the lack of pyroclastic deposits on the left side of Crna Reka is that there were such deposits, but were later eroded by the rivers flowing along the eastern slope of Dren (Orle) Mt. Such situation is also seen on the left side of Crna Reka in Mariovo, 20 km to the SW, where only small patches of the Pliocene deposits are preserved,

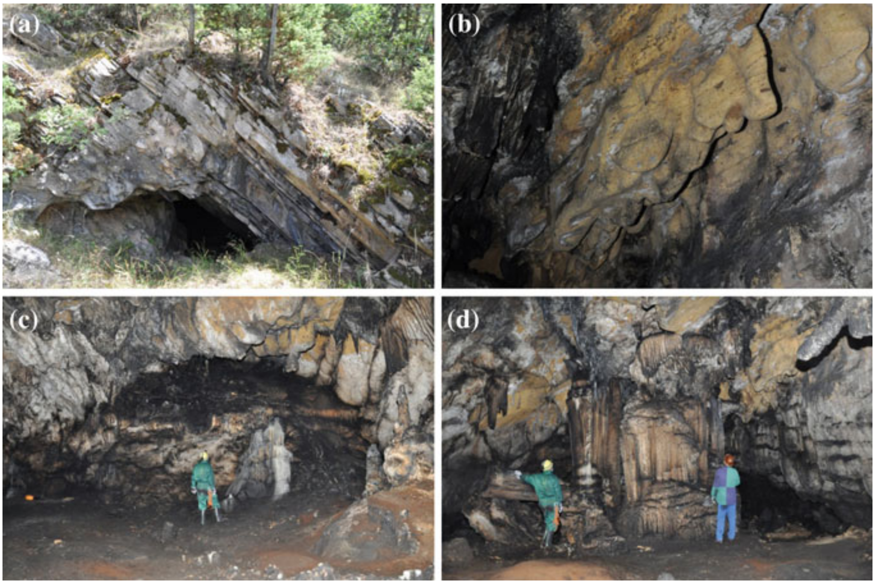


Fig. 5.57 Characteristic features of Cave Lekovita Voda: **a** The entrance with the beds dipping by 60° to the SW; **b** Paragenetic morphology on yellow-stained ceiling; **c** The sediment profile in the southern end of the cave; **d** Large column speleothems in the middle of the passage with yellow-stained paragenetic ceiling, and beds dipping to the left (SW) by 60° (view from the profile in **c**). Photographs by M. Temovski

comparing to the thick Miocene to Early Pleistocene deposits found on the right side (Manakovik and Andonovski 1984). Nevertheless, the origin of the pyroclastic is likely connected to the Kožuf volcanic complex to the south.

Cave Lekovita Voda is rather old cave, remnant of a larger cave system, which evolution is difficult to deduct, based on regional geomorphological and geological evolution. Its development is connected to the evolution of Doljani Valley, which in Quaternary was governed by the evolution of the Crna Reka Valley. As this part of Doljani River is quite close (1.6 km) to the main valley, changes in the Crna Reka Valley (incision, aggradation) have relatively quickly affected Doljani valley as well. The paragenetic development in the cave is connected to base-level rise in Doljani valley, which in turn should reflect base-level rise in the Crna Reka Valley.

The cave is located quite high above the present riverbeds of Doljani River and Crna Reka (Fig. 5.58): 300 m above Doljani River (at 430 m a.s.l., 1.7 km before the confluence with Crna Reka) and 530 above Crna Reka (200 m a.s.l. at the confluence with Doljani River).

Considering its elevation and location with regard to Doljani and Crna Reka valleys, the aggradation that influenced the filling of the cave and paragenetic development can be connected to the Late Pliocene–Early Pleistocene deposition (aggradation) in Tikveš Basin, or it can correspond to the early periods of

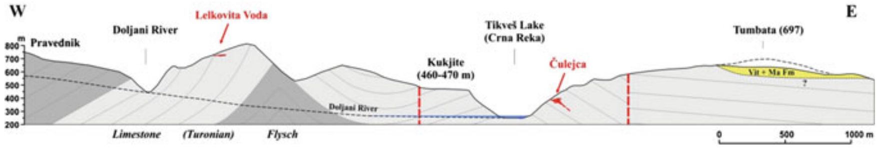


Fig. 5.58 Cross section showing the relationship of Cave Lekovita Voda and Čulejca Cave to Crna Reka and Doljani River valleys

Pleistocene incision of Crna Reka, after the draining of Central Macedonian Lake (which happened as late as Middle Pleistocene; Dumurdžanov et al. 2004).

5.3.2 *Cave Vodna Peš*

Cave Vodna Peš is situated on the right side of Crna Reka Valley, 1.6 km WSW from the confluence with Blašnica River, located at 740 m a.s.l., just below Vodena Peš (807) summit, and 475 m above Tikveš Lake (Fig. 5.59). The depth of Tikveš Lake here is ~25 m, so the cave is located 500 m above Crna Reka riverbed.

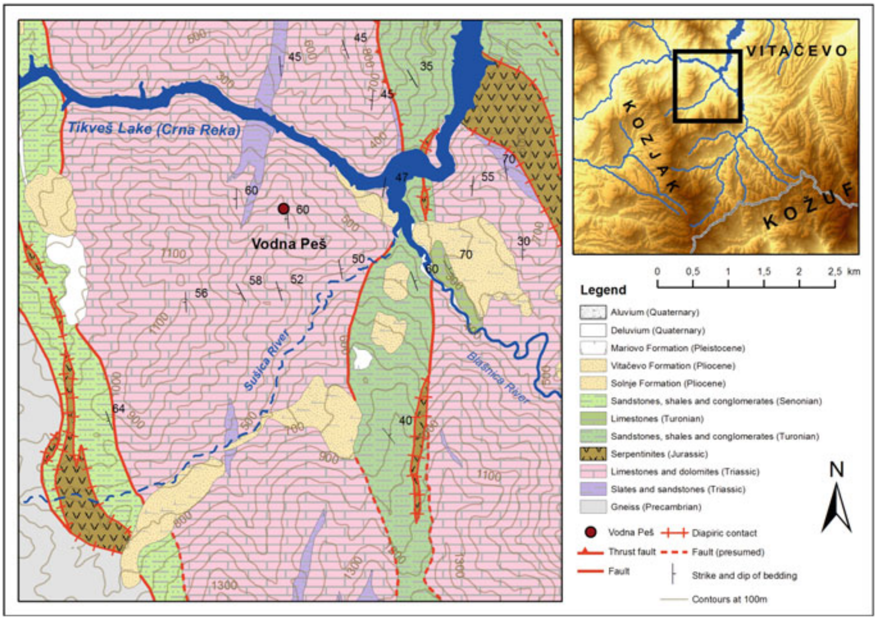


Fig. 5.59 Geological setting of Cave Vodna Peš. Geological data after Dumurdžanov et al. (1976), Geološki Zavod–Skopje (unpublished)

It is formed in Upper Triassic limestones which are part of the Rožden Horst. The limestones are highly folded to isocline folds, with underlying Middle Triassic clastic rocks exposed to the NW from the cave. The cave is developed in the western limb of an anticline with strata dipping to the NW by 60°.

5.3.2.1 Morphology

Cave Vodna Peš is a more than 230-m-long cave with NE general direction and biggest depth at 25 m (Figs. 5.60 and 5.61). It has a branch work pattern in plan view with three passages (West Passage, South Passage, and East Passage—an unmapped passage east from the South Passage), joining in a collapse room (Big Room). In profile, it has at least three horizontal levels, with passages rising in the NE part, which is most influenced by collapse. The entrance is erosional, opened due to slope retreat erosion (Fig. 5.62).

The Big Room has a triangular form in plan with large size, connecting to the west with the West Passage. The northern part has more or less horizontal floor, mostly covered with collapsed blocks and debris, with clay deposits seen in small-side passages along the northern wall. To the south, the floor is steeply inclined, covered with debris material, with several passages connecting with the room. In the lowest part of this southern side, the Big Room continues to the South

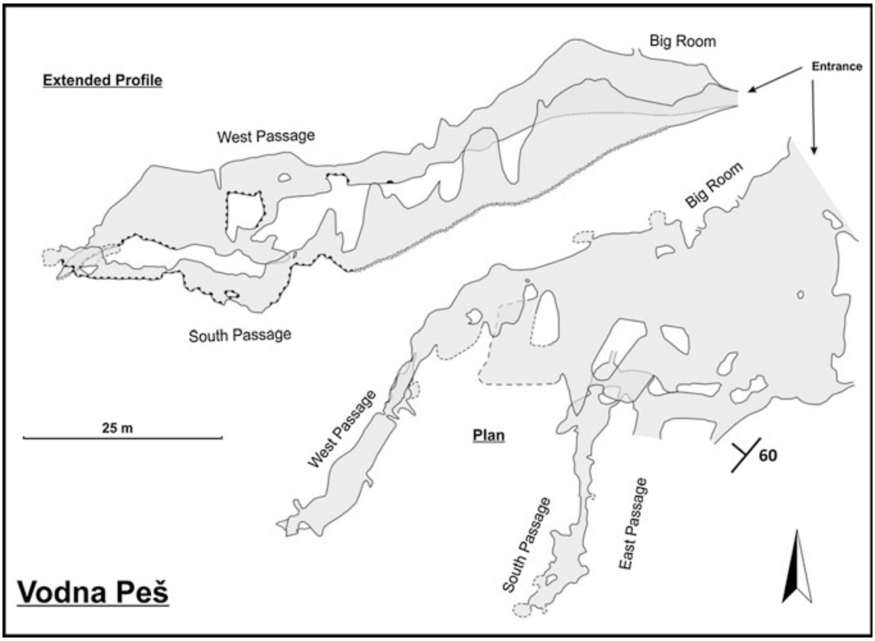


Fig. 5.60 Simplified map of Cave Vodna Peš. For more detailed cave map, see Appendix

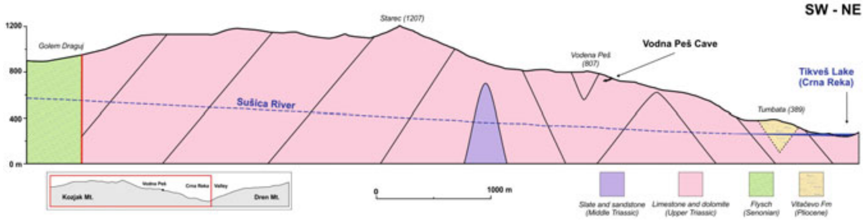


Fig. 5.61 Geological cross section through the NE part of Kozjak Mt., showing the relationship of Cave Vodna Peš to Crna Reka and Sušica River valleys

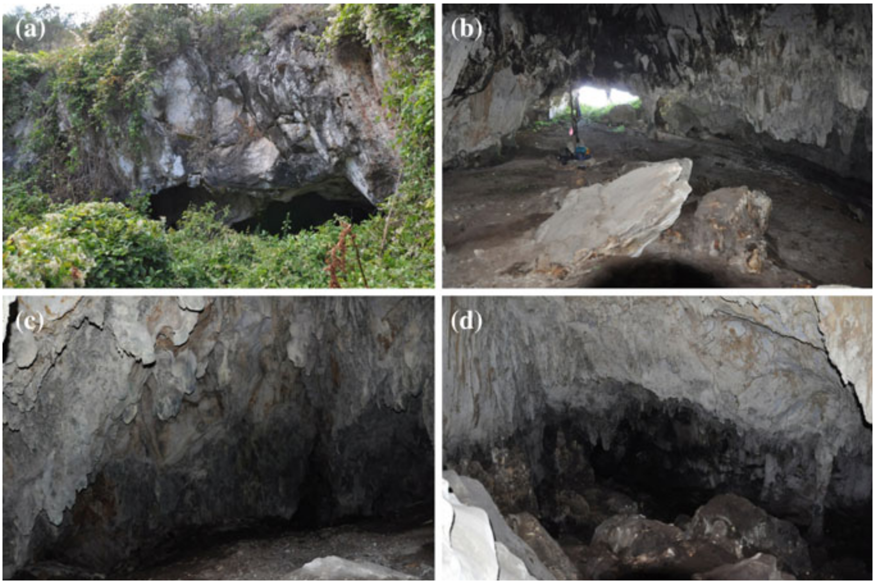


Fig. 5.62 Characteristic features of Cave Vodna Peš: **a** View of the entrance; **b** View of the Big Room toward the entrance; View of the Big Room toward the South Passage (**c**) and West Passage (**d**) with paragenetic morphology (pendant, channels) with some remnant sediment deposits on the ceiling. Photographs by M. Temovski

and East Passage. There are several fractures along which there is collapsing, one prominent having WNW–ESE direction.

The West Passage is ~65 m long, with a SW–NE direction in the lower part, developed along the strike of strata and in the upper parts turning to the ENE. The floor is covered by breakdown material and flowstone deposits, with remnants of clay-covered phreatic morphology indicating paragenetic development well preserved in the upper part close to the Big Room, although most of it is covered by dripstone and flowstone speleothems. The passage is generally rising to the NE toward the Big Room.

The South Passage is ~60 m long, in the lower section mostly developed along a NNE–SSW-oriented fracture, with some parts having NE direction developed along the strike of strata. In the upper part, the passage continues to the east, joining with the East Passage and connecting to the north with the Big Room. The lower parts are covered with clay and flowstone deposits, with big flowstone-collapsed blocks after removal of sediments, while in the upper parts the passage is covered with breakdown debris and younger speleothem deposits. Paragenetic morphology, with pendants and ceiling channels is seen at several places, mostly covered with speleothems. The passage is generally rising to the NE toward the Big Room.

The East Passage (not mapped), located to the east of the South Passage, is similar in morphology, direction and size to the South Passage, having a little higher elevation.

5.3.2.2 Cave Sediments

The cave passages are mostly covered by breakdown deposits, with large collapsed blocks along the bedding and fractures, as well as breakdown debris material. In the lower parts of the cave, especially in the South and East Passages, breakdown material is composed of thick flowstone deposits, which collapsed after removal of underlying clay deposits. Later, they were covered with coralloid speleothems. Dripstone speleothems, mostly inactive, are found in the both the lower parts and the Big Room where they are affected by cold temperatures in winter due to large entrance opening. Brown clay deposits are covering the lower parts of the cave and are difficult to observe, being mostly covered by flowstone speleothems or breakdown debris.

5.3.2.3 Speleogenesis

Based on the orientation and morphology of passages, as well as geological and geomorphological setting, Cave Vodna Peš is likely a remnant of the output part of a former cave system discharging toward Crna Reka Valley. The pattern of Cave Vodna Peš is similar to Čulejca Cave in a way that the passages are rising and joining in the downstream part. The primary phreatic and paragenetic morphology is largely modified and masked by later breakdown processes. Passages were developed mainly toward NE along the strike of strata, with NNE–SSW- and WNW–ESE-oriented fractures having minor primary importance with bigger influence to the later collapse evolution. Passages developed upwardly due to base-level rise, with the deposition of sediments in the lower parts and later abandonment with development of passage at higher elevation. Continuous deposition forced paragenetic development in the previously formed phreatic passages. After base-level lowering, in vadose settings, sediments were removed and flowstone was deposited. Continued lowering of base level further removed sediments and reused former phreatic passages, triggering collapse of bedrock and flowstone after removal of underlying sediments. Located high above the water table, the cave is now mostly affected by collapse processes, and small vadose percolation depositing dripstone and flowstone speleothems.

Cave Vodna Peš is now located high (~500 m) above riverbeds of present Crna Reka or Sušica River (Fig. 5.61). Its development was governed by base-level positions in Crna Reka Valley, which has later incised further by 500 m, down to the present position. Considering its location and the geomorphological and geological situation, the waters forming the cave were most likely coming from the upstream area of Sušica River.

The aggradation in Crna Reka Valley influencing upward cave development might be connected to Pliocene and Pleistocene deposition in paleo-Crna Reka Valley. Vertical distribution of the Pliocene deposits (Solnje Formation and up to Vitačevo Formation) is from ~250 m (in the riverbed of Crna Reka and below) up to 800 m in Sušica Valley and Blašnica Valley (Fig. 5.59). To the west (~3 km) of the cave, remnants of Pliocene deposits (Solnje Formation) are found up to 670 m elevation. In Blašnica Valley, Pliocene deposits grade upward into deposits of Mariovo Fm. (Early Pleistocene). Although this whole area was uplifted in Pleistocene, differential uplift in Crna Reka, Sušica, and lower part of Blašnica is unlikely, with them being part of the same Mariovo neotectonic block (Arsovski and Petkovski 1975).

Distribution of Pliocene deposits in Crna Reka, Sušica and Blašnica valleys, which are delineating Starec Mt. (Fig. 5.59), suggest that there was an incision of these valleys prior to Pliocene deposition. As was suggested on the case of Čulejca Cave, they might have been formed during the Messinian Salinity Crisis event and later filled with deposits due to Pliocene transgression. Later, Pleistocene incision eroded these sediments, at places developed superimposed valleys (as in the lower part of Blašnica), with remnants of these deposits still filling parts in riverbeds of Crna Reka, Sušica, and Blašnica rivers. The deep incision of Pre-Pliocene valleys has most likely also influenced karst evolution, with deep vadose development prior to Pliocene deposition and base-level rise that led to per ascensum speleogenesis in Cave Vodna Peš.

5.3.3 Temna Peštera–Mrežičko

Temna Peštera–Mrežičko is situated on the right side of Mrežička Reka valley, about 500 m upstream from Mrežičko Village (Fig. 5.63). The entrance is located at 600 m a.s.l., 15 m above the riverbed of Mrežička Reka (Fig. 5.64). It is named Temna Peštera–Mrežičko to differentiate it from the Temna Peštera–Dragožel in Kamenica Valley.

The cave is developed in Triassic limestones, part of a stack of thrust sheets with several structural levels of ophiolitic rocks (Robertson et al. 2012). The sheet of Triassic limestones in which Temna Peštera–Mrežičko is located, overthrusts Upper Cretaceous (Turonian) siliclastic rocks and is overthrust by Upper Jurassic

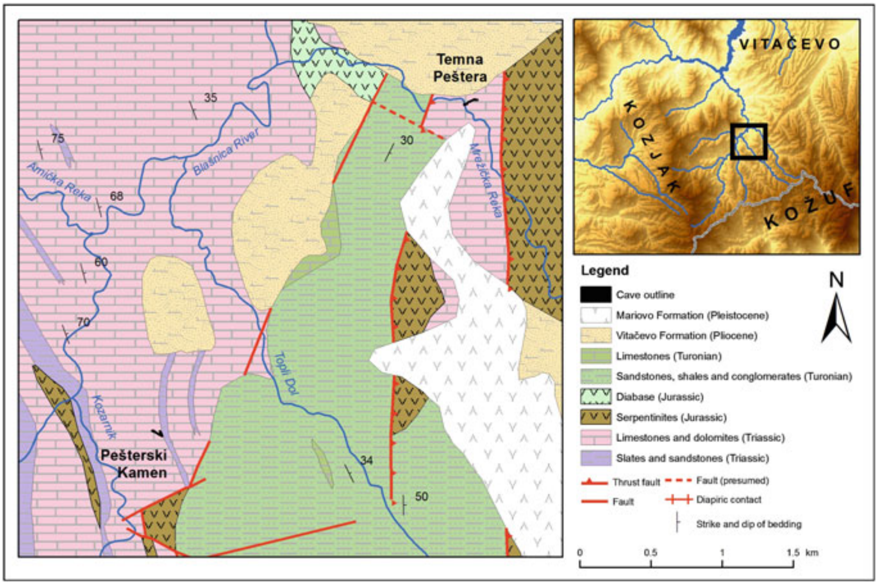


Fig. 5.63 Geological map of the area between Temna Peštera–Mrežičko and Pešterski Kamen caves, on the NW foothill of Kožuf Mt. Geological data modified after Dumurdžanov et al. (1976), Rakićević and Pendžerkovski (1970), Geološki Zavod–Skopje (unpublished)

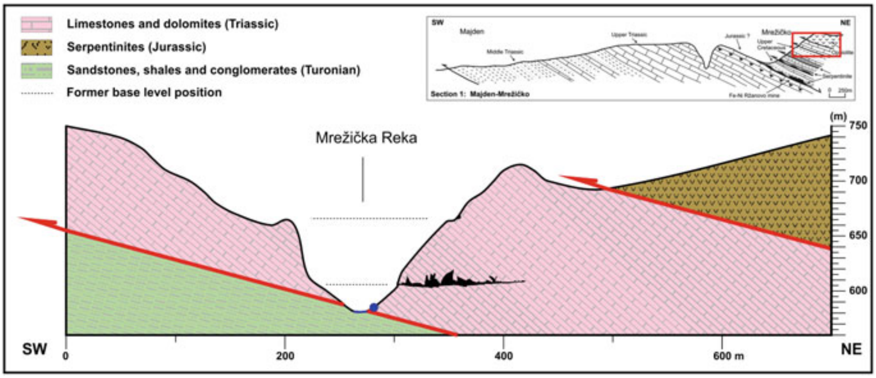


Fig. 5.64 Geological setting of Temna Peštera–Mrežičko in the valley of Mrežička Reka. Regional geological cross section after Robertson et al. (2012)

(Tithonian) ophiolite-related rocks (serpentinites, grabro). This pre-Cenozoic rocks are covered with pyroclastic deposits of Mariovo Formation, with source volcanoes located 4 km to the SE.

Mrežička Reka has cut through the Pleistocene pyroclastic rocks forming a deep valley, with gorge-like characteristic of the part developed in limestones. The limestones here are dipping by 40° to E–NE, with the valley floor exposing the contact with the Cretaceous rocks just below the cave (Fig. 5.64).

Some 60 m above the cave, on the gorge slope there are several small cave entrances with few meters long passages. They correspond to a former base-level position, with remnants of a terrace also seen on the left side of the valley.

In the riverbed below Temna Peštera–Mrežičko, there is a small spring close to the contact with the underlying impermeable rocks. In high water, an overflow 2 m above the spring is also active. Field measurements of water showed pH of 7.81, Electronic conductivity of 368 μS/cm and temperature of 8.5 °C.

5.3.3.1 Morphology

Temna Peštera–Mrežičko consists of a single horizontal passage with ENE general direction with meandering parts in plan view (Fig. 5.65). It is developed mostly along fractures with WSW–ENE to W–E direction.

Paragenetic morphologies are seen throughout the cave, with pendants, channels, flat ceilings, and alluvial notches (Fig. 5.66).

Paragenetic morphology is most evident in the upstream parts, where the passage has east direction, with ceiling channel seen above a floor filled with clay sediment, and pendants partly covered with clay sediments. Little downstream from this part, the passage has a clear flat ceiling. In the middle part of the cave, the passage is narrower and meandering in plan view, with several well-preserved alluvial notches

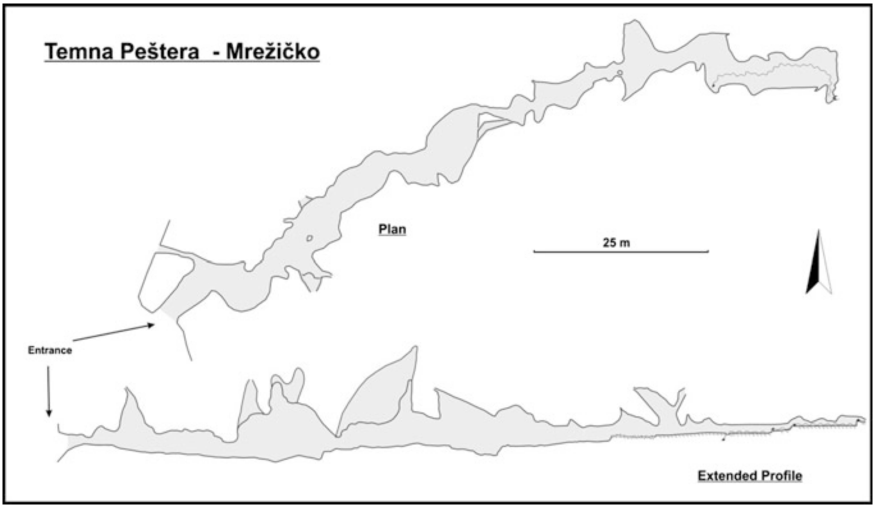


Fig. 5.65 Simplified map of Cave Temna Peštera–Mrežičko. For more detailed cave map, see Appendix

Fig. 5.66 Characteristic features of Temna Peštera–Mrežičko: **a** Breakdown-affected passage with debris and clay-filled floor; **b** Pyroclastic-derived cobbles; **c** Remnants of paragenetic notches in a breakdown-modified passage; **d** Paragenetic notches; **e** Small pockets with clay vermiculations; **f** Paragenetic pendants on contact with clay-filled floor. Photographs by M. Temovski

on the wall. There are at least 4 alluvial notches with the lowest being widest and best preserved. These paragenetic notches in the downstream part are preserved only at several places, due to breakdown processes. Above the meander, a ceiling channel is rising in the downstream direction. Below the lowest notch in the meander, a vadose canyon is incised with well-rounded pebbles and cobbles mostly composed of pyroclastic-derived agglomerates, filling the floor.

In the upstream part, sediments completely filled the passage, with dissolution producing flat ceiling, while in the middle part at same elevation, alluvial notches were produced with free surface water table, indicating phreatic development in the upstream part, and vadose development in the middle to downstream part, prior and during the paragenetic development.

The cave continues to the east above a rimstone dam with a clay-filled passage along which a small vadose stream is flowing during high waters (spring and autumn). This stream continues downstream from this rimstone dam, through a series of small clay-filled rimstone pools, sinking in a small ponor where this east-directed passage part ends.

5.3.3.2 Cave Sediments

Brown clay, similar to clays in Vitačevo caves, is covering passage floors mostly in the upstream part. Clay deposits are also found filling floor and niches in a small-side passage above the main passage in the upstream part. In this passage cave, walls of pockets and cupolas are covered with clay vermiculations. In the upstream part, clay-to-silt deposits are filling rimstone pools. Above them, younger generation of flowstone crust is deposited.

Volcanic clasts of pebble to cobble size are also seen filling passage floor in the middle to downstream part of the cave.

Breakdown deposits include collapsed limestone blocks and small breakdown debris, mostly found in the middle to downstream part of the cave.

Dripstone and flowstone speleothems are found at various places in the cave, mostly in the upstream part. In the upstream part, four rimstone dams are found with rimstone pools in between filled with clay deposits. Small intermittent vadose stream is flowing above them, with flowstone crust being deposited on clay before sinking in a small ponor.

5.3.3.3 Speleogenesis

Temna Peštera–Mrežičko is a water table cave, developed during a stable base level in Mrežička Reka. Sediment aggradation in the river triggered sediments deposition in the cave, which leads to rise of water table, and paragenetic cave development. Paragenetic morphology can be seen throughout the cave with upstream parts still filled with sediments. The evolution of this cave is connected with the base level lowering due to incision of Mrežička Reka. Above Temna Peštera–Mrežičko on the same side of the valley, there are small cave entrances with few meter long passages that are remnants of water table cave development during previous stable base level in the valley (Fig. 5.64). The present location of the water table is at the riverbed, where water discharges from a spring close to the contact with underlying impermeable clastic rocks. The clastic sediments in the cave indicate that the source of sediments is the pyroclastic rocks, which are covering large areas in the vicinity. Pliocene to Pleistocene volcanic activity in the Kožuf volcanoes, located less than 5 km to the SE produced huge amount of pyroclastic deposits, which in Upper Pliocene to Early Pleistocene completely covered this area. As the present fluvial incision is connected to the Pleistocene uplift, which is also partly responsible for draining of Central Macedonian and Mariovo Lakes, the incision of Mrežička Reka started first in Pleistocene deposits of Mariovo Formation, with earliest possible time for Temna Peštera–Mrežičko development in Early Pleistocene. Considering the allogenic sediments in the cave, the input area is probably in the upstream parts of Mrežička Reka.

5.3.4 Cave Pešterski Kamen

Cave Pešterski Kamen is located on the right side of Kozarnik River valley, on the NW foothill of Kožuf Mt., 3 km SW of Temna Peštera–Mrežičko with entrance located at 947 m elevation, just below the ridge that separates Kozarnik Valley with Topli Dol Valley (Fig. 5.63).

The cave is developed in Upper Triassic limestones, part of the carbonate (limestone and dolomite) formation of Rožden Horst, which are highly folded up to isocline folds. At the cave, the beds are dipping by 60–70° to the SW as a part of a SW wing of an NW–SE-oriented anticline. The Upper Triassic limestones overlie Middle Triassic siliclastic rocks, and to the east they are overthrust by Upper Cretaceous (Turonian) siliclastic rocks (Fig. 5.67).

5.3.4.1 Morphology

Cave Pešterski Kamen is more than 170-m-long cave with more than 60 m vertical development, consisting of three segments (Fig. 5.68): the upper part (Upper Passage, Upper Room), the lower part (Big Passage), and the middle part (Steep Passage, Clay Passage).

The lower part (Big Passage) and upper part (Upper Room, Upper Passage), are sub-horizontal and developed in strike (NW–SE) direction, with phreatic paragenetic morphology and sediment-filled floors.

They are connected by a steeply inclined passage (Steep Passage), developed in WNW–ESE direction between strike and dip direction of steeply (70°) dipping strata. It is a vadose passage, with the upper part covered by flowstone deposits and the lower part having paragenetic ceiling morphology with sediment-filled floor.

The morphology of the Big Passage is greatly masked by collapse processes, but the passage is developed along the strike with clay- and breakdown deposit-filled floors. Four small passages are seen joining in the ceiling from the SE, developed in

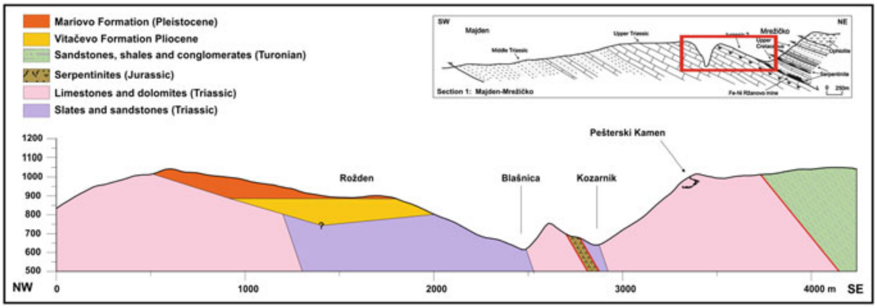


Fig. 5.67 Geological cross section showing Cave Pešterski Kamen Cave and its relationship with Kozarnik and Blašnica valleys, as well as Mariovo and Vitačevo Formations around Rožden. The regional geological cross section in *top right* is after Robertson et al. (2012)

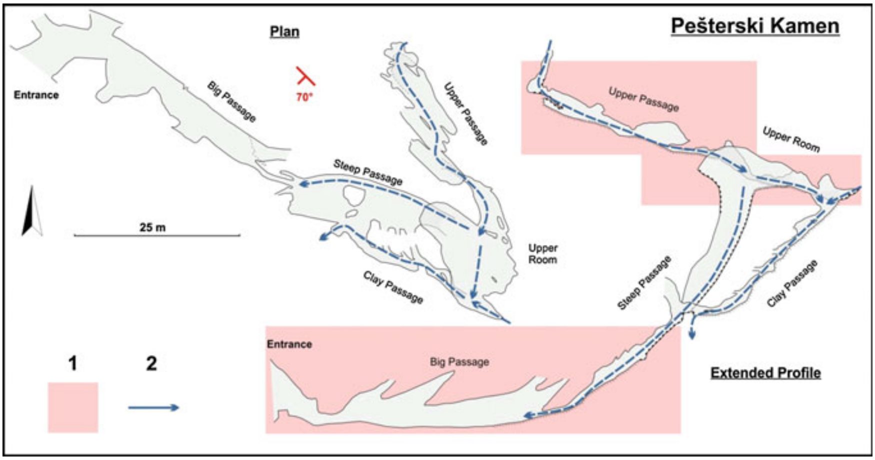


Fig. 5.68 Simplified map of Cave Pešterski Kamen with distribution of paragenetic morphologies in sub-horizontal paragenetic phreatic passages (*1*) and direction of later vadose passage development with excavation of sediments and deposition of speleothems (*2*). For more detailed cave map, see Appendix

similar direction as the Steep Passage, with paragenetic morphology and some remnant pockets of sediments. To the north of the Big Passage, just after the entrance of the cave, a passage of similar size continues, with the same direction as the Big Passage, filled with sediment and flowstone deposits. It is the normal continuation of the Big Passage, while the entrance is opened by slope retreat erosion.

The Upper Passage consists of four parallel passage parts strongly controlled by strike of steeply dipping strata, with paragenetic features such as ceiling channels and pendants. These passage parts are consecutively rising in elevation to the NE, indicating NE shift of strike-oriented phreatic passage development due to sediment deposition and paragenesis. The floors are filled with sand and clay deposits, once completely filling passages, later eroded and covered by flowstone speleothems.

The Upper Room is also developed along the strike, having clay-filled floor, and paragenetic ceiling features. To the SE, this passage is choked with sediments and flowstone deposits, while to the north, it is connected with the Upper Passage by vadose passage developed in coarser clastic deposits. From the southern part of the Upper Room, a small vadose passage (Clay Passage) is developed at the contact with and within clastic deposits, connecting with the Steep Passage at several locations, continuing to the west with a small vadose passage. Also a small vadose passage, which can be climbed to the surface, is joining the Upper Passage from north.

Paragenetic morphology is seen throughout the cave (especially in the lower and upper part) connected with fine to coarse-grained sediments, with coarser sediments located in the upper parts of the cave (Fig. 5.69). Paragenetic features such as ceiling channels and pendants on passage ceilings (in the lower and upper part) indicate upward cave development in phreatic settings.

5.3.4.2 Sediments

Fluvial sediments are found throughout the cave, previously filling most of the cave passages.

In the Upper Passage, orange to orange brown sands and clays are filling passage floor, covered by flowstone speleothems. Erosion of these sediments led to collapse of flowstone plaques. At places removal of sediments between successive layers of flowstone left multiple levels of false floors.

Below the flowstone deposits, beside sand and clay, well cemented breccias can be seen (e.g., passage connecting Upper Room and Upper Passage). Fragments are angular, indicating short traveling distances, and mostly composed of schists and sandstones, originating either from the Upper Cretaceous or Middle Triassic siliclastic formations.

Based on the location of the cave and distribution of deposits of Mariovo and Vitačevo Formation in the vicinity, macroscopically visible pyroclastic-derived sediments (as in Temna Peštera–Mrežičko and Vitačevo caves) were expected to be found in the coarser deposits where fragments of sizes up to 10 cm can be seen (as in the connection between the Upper Room and Upper Passage); nevertheless, such sediments were not found, although contribution from pyroclastic rocks to the fine-grained sediments is still possible.

Speleothem deposits can be seen throughout the cave, but mostly in the upper and middle part. In the upper part, flowstone deposits cover clay, sand, and breccia sediments and are also covered by younger flowstone and dripstone speleothems. Thick flowstone deposits can be seen also in the Upper Room continuing down to the Steep Passage. Coralloid speleothems are also covering walls and ceiling in the upper part of the cave.

Fig. 5.69 Characteristic features of Cave Pešterski Kamen: **a** View of the Big Passage toward the entrance; **b** View of the connection between the Big Passage and the Steep Passage, with strong bedding influence on paragenetic morphology; **c** The Upper Room with clay-filled floor and paragenetic ceiling morphology; **d** Vadose passage development in previously deposited cave sediments (Upper Passage); **e** False floor flowstone speleothems after removal of sediments (Upper Passage); **f** Eroded sand and clay sediments and breakdown of overlying flowstone deposits (Upper Passage). Photographs by M. Temovski and D. Nedanoski

5.3.4.3 Speleogenesis

Based on the passage morphology and pattern, small-scale paragenetic morphology and sediments present in the cave, we can separate three different speleogenetic phases.

Orientation and morphology of passages indicates passage formation by paragenesis due to base-level rise, which led to sediment deposition and upward paragenetic development in phreatic settings. Paragenetic morphology associated with clay and sand deposits can be seen on the walls and ceiling of the Big Passage and lower part of Steep Meander, as well as in the upper part in Upper Room and Upper Passage where continuous sediment deposition and phreatic paragenesis led to gradual shift of development of consecutive strike (NW–SE)-oriented paragenetic passages to the NE.

Prior to the base-level rise and paragenetic development, the cave was likely developed in vadose to epiphreatic environment, with vadose passages developed along the steeply dipping limestones (e.g., Steep Passage and small passages joining at the ceiling of Big Passage), leading to epiphreatic or phreatic passages (Big Passage) developed along strike in NW–SE direction.

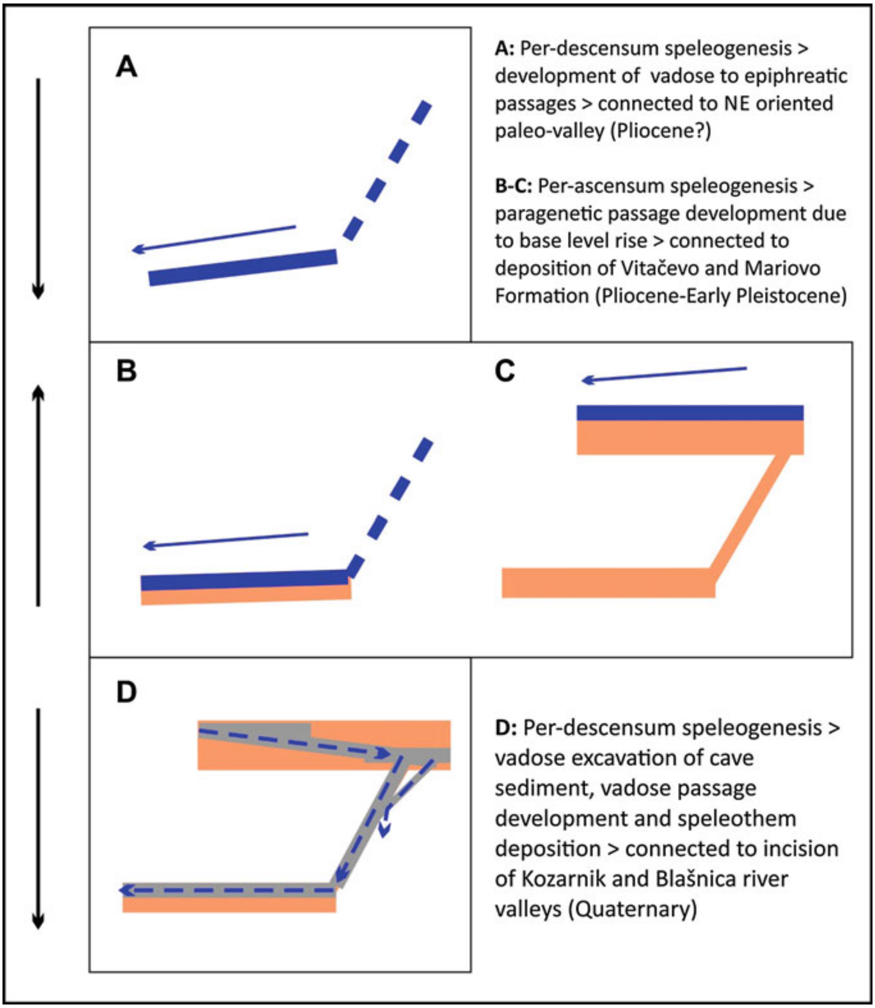
The recharge area was likely to the SE from the Upper Cretaceous siliclastic rocks, which also supplied the cave sediment material, as evident from the coarser clastic deposits filling passages between the Upper Room and Upper Passage.

The latest phase is connected with vadose excavation of sediments, vadose passage developments at contact with or within sediments and deposition of vadose speleothems at places in combination with redeposition of sediments. In the upper parts, this vadose development is directed in SE direction, with younger vadose passage connecting Upper Passage and Upper Room, then turning to the NW along the Steep Passage and the younger vadose Clay Passage, which exits in the southern wall of the cave. The general direction of flow is in NW direction, likely connected with incision of Kozarnik and/or Blašnica river valleys.

Water was likely coming from the Upper Cretaceous siliclastic formation and sinking in the Upper Triassic limestones, developing vadose passages along the dip, and epiphreatic to phreatic passages along the strike of steeply dipping strata in NW direction. Rise in base level, likely connected to deposition of Vitačevo and Mariovo Formation deposits in Rožden area to the north filling paleovalleys, led to paragenetic development and shift of passage development in upper level due to paragenesis in phreatic settings. Remnants of Pliocene Vitačevo deposits can be seen to the north of the cave up to elevation of 900 m, while to the west between Rožden and Arničko villages, they are rising up to 1150 m (Figs. 5.63 and 5.67). They are followed by Early Pleistocene deposits of Mariovo Formation, which covered most of the area between Kožuf and Kozjak Mt. Pleistocene incision removed most of the Tikveš Basin deposits, uncovering the underlying pre-Cenozoic rocks. The karst system during this phase may have contributed to the deposition of travertine layers in Vitačevo Formation with two notable travertine layers near Rožden to the north, found at 820–830 m and 860–870 m and the lower part (Big Passage) of the cave located at 950 m. No clear terraces at the elevation of lower part and upper part of Cave Pešterski Kamen are found in the Pliocene and Pleistocene deposits to the north, though.

Kozarnik and Blašnica river valleys are cutting first in the Mariovo and Vitačevo Formations and then in the older Triassic rocks, which indicates their formation in Quaternary. They incised to more than 300 m below the cave, starting vadose excavation of sediments and development of small vadose passages at the contact with or within cave sediments, as well as flowstone deposition. This younger fluvial drainage after Pleistocene incision likely cut allogenic input in the cave leading to mostly autogenic vadose flow.

Considering the registered speleogenetic phases and geomorphological and geological evolution of the area, the cave development is likely connected first to Pliocene per descensum speleogenesis toward a NE-oriented paleovalley, then Pliocene–Pleistocene per ascensum speleogenesis connected with Pliocene and Pleistocene deposition (Vitačevo and Mariovo Formations) in lacustrine to fluvial settings filling paleovalleys, and later vadose per descensum evolution due to Pleistocene incision and development of younger superimposed fluvial valley network (Fig. 5.70).



A: Per-descensum speleogenesis > development of vadose to epiphreatic passages > connected to NE oriented paleo-valley (Pliocene?)

B-C: Per-ascensum speleogenesis > paragenetic passage development due to base level rise > connected to deposition of Vitačevo and Mariovo Formation (Pliocene-Early Pleistocene)

D: Per-descensum speleogenesis > vadose excavation of cave sediment, vadose passage development and speleothem deposition > connected to incision of Kozarnik and Blašnica river valleys (Quaternary)

Fig. 5.70 Schematic representation of the interpreted evolution of Cave Pešterski Kamen

5.3.5 *Other Caves*

Other caves reported from this area have not been studied, mostly due to the inaccessibility of the area, or due to inability to locate them. They have been reported by cavers from PSD Orle from Kavadarci, with some of them mapped as a part of a military project in the 1970s, registering caves for possible war use. This includes Gališka Peštera, Vodena Peštera, Marina and Radina Dupka, Manastirska Peštera, Kaštanik, Kalina Dupka, Markova Crkva, Boševa Peštera, Ratovica, and Stankova Peštera. Mostly they are quite small caves, although some (Gališka Peštera) have some significant length. Most of them are developed in Triassic limestones, Ratovica is in Turonian limestone, and Marina and Radina Dupka are in Senonian limestones of the Galište–Arničko graben.

5.4 Discussion

Most of the karst terrains in the studied area have "normal" epigenic karst development, receiving allogenic or autogenic recharge from the adjacent surface. As the oldest carbonate rock was exposed to meteoric waters for a long geological time (before Cenozoic), we can assume continuous karst development in the area, with some terminations due to transgression and burial. The present geomorphology in the area is mostly affected by the tectonic and geomorphological evolution since Neogene, as part of the South Balkan extensional system; consequently, this has played major role in controlling karst development.

The major controls on the epigenic speleogenesis in the area are the evolution of Crna Reka Valley (incision and aggradation), and the Pliocene–Pleistocene deposition in Tikveš and Mariovo Basins.

5.4.1 *Quaternary Valley Incision and Epigenic Cave Development*

Most of the present geomorphology in this area is a result of the erosion that followed the draining of Central Macedonian and Mariovo Lakes, as a result of the subsidence in the Aegean Sea, and general uplift in the Balkan Peninsula. The draining in Mariovo Lake started between 1.8 and 1.6 Ma (see Sect. 4.1.1 Provalata Cave), while the draining of Central Macedonian Lake was as late as Middle Pleistocene (Dumurdžanov et al. 2004). The draining of the lakes has started the incision of Quaternary Crna Reka, and its tributaries, which first incised in the deposits of Mariovo and Tikveš Basin and then in the Pre-Neogene basement (Fig. 5.71). Between Mariovo and Tikveš Basin, Crna Reka also incised in Pliocene and Pleistocene deposits filling an older (Miocene) paleo-Crna Reka Valley. While the

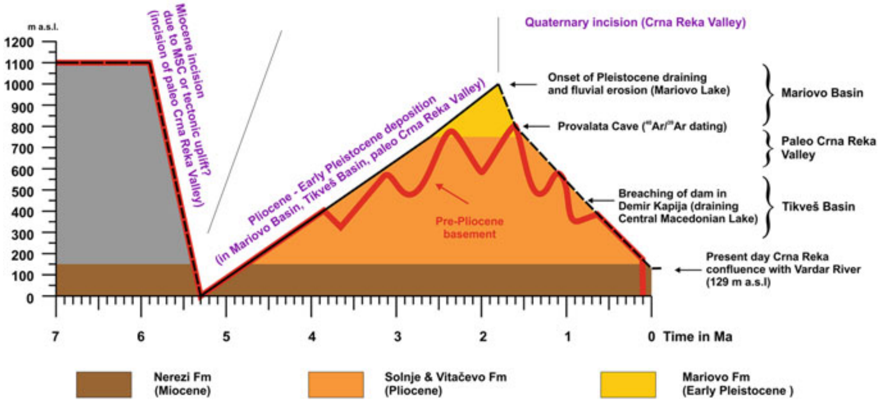


Fig. 5.71 Schematic reconstruction of Neogene–Quaternary evolution and events along Crna Reka Valley (Mariovo and Tikveš Basins)

higher karst areas were not covered by Neogene and Quaternary sediments and had continuous karst development, in the lower areas as in Crna Reka Valley, Mariovo, and Vitačevo, karst development was reactivated and governed by the incision of Crna Reka and its tributaries.

In Vitačevo Plateau, especially in the Upper Kamenica Valley where most of the karst areas are located, the evolution of karst was controlled by the rate of incision of Kamenica River (Fig. 5.72) and the retreat of the pyroclastic caprock of Mariovo and Vitačevo Formations of Tikveš Basin (Fig. 5.74b). The output of this karst system is at Zelen Izvor locality, at the contact of Upper Cretaceous (Turonian) limestones and underlying flysch rocks. As the rocks here are folded in a NW plunging anticline (Kamenica Anticline), the position of the spring was controlled by both of the incision of Kamenica River (vertical control) and the contact of limestones and flysch (horizontal control). The three caves found here are phreatic to water table

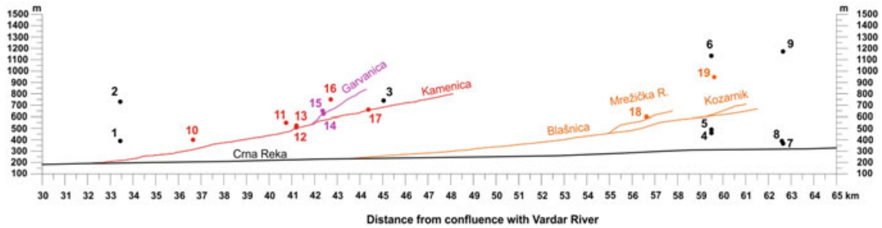


Fig. 5.72 Plot showing elevations of caves against long profiles of Crna Reka Valley and its major tributaries. Crna Reka (*black*): *1* Čulejca Cave, *2* Lekovita Voda, *3* Vodna Peš, *4* Dupkite 1, *5* Dupkite 2, *6* Pešti Cave, *7* Podot 1, *8* Podot 2, *9* Živovska Propast; Kamenica River (*red*): *10* Budimirica Cave, *11* Temna Peštera–Dragožel; *12* Zelen Izvor, *13* Nad Zelen Izvor, *14* Garnikovska Propast, *15* Mala Peštera, *16* Dragoželska Propast, *17* Aramiska Peštera; Blašnica (*orange*): *18* Temna Peštera–Mrežičko, and *19* Cave Pešterski Kamen

caves, and their development is connected to stable base-level position. The present location of the spring cave Zelen Izvor is little higher (5 m) above the riverbed of Kamenica River, due to collapse of the valley slope, while Nad Zelen Izvor and Temna Peštera correspond to river terraces at 530 and 550 m (Fig. 5.25).

In the upstream part, allogenic input to the karst system is found in the main Kamenica Valley (Aramiska Peštera) and in the right-hand tributary Garvanica (Garnikovska Propast). Both caves are ponor caves, with small perennial streams, developing in vadose to epiphreatic environment. The evolution of the caves is connected to the incision of the valleys and erosion of the overlying pyroclastic deposits, and upstream shift of the ponors. High sediment load in the caves forced paragenetic development, with passage levels connected to the stable base-level positions and aggradations in Kamenica Valley, reflecting the situation from the output part in Zelen Izvor locality. Regional aggradation connected to the terrace at Zelen Izvor at 550 m is reflected with paragenetic passages found in both Aramiska Peštera and Garnikovska Propast (Fig. 5.73). Dragoželska Propast is another cave located in the upstream part. It is developed at the contact of two faults, the regional NW–SE-oriented Dragozel Fault, and WSW–ENE-oriented fault, with mostly vadose (shaft) morphology, and a large collapse room. Considering its location to the nearby paleovalley filled with Pliocene and Pleistocene deposits of Vitačevo and Mariovo Formations, parts of the cave (connected to the Dragozel Fault) may have formed before Pleistocene, governed by the paleovalley evolution. Flowstone deposits from an unroofed cave found close to the present riverbed of Kamenica Valley can be also from a former phase of karstification, connected to the paleovalleys to the SE, or they can be formed in the same phase, when Kamenica Valley was at higher elevation, and were later cut by the incision in the valley. Thick flowstone deposits are found in both Aramiska Peštera and Garnikovska Propast 40 m and deeper below the present riverbeds of Kamenica and Garvanica rivers.

In the downstream part of Kamenica River, Budimirica Cave is developed in the limestone block situated between Kamenica and Crna Reka valleys. While the cave may have formed prior to the Kamenica River incision, it has a paragenetic development connected to aggradation in Kamenica Valley, corresponding with a terrace at 390 m, which likely corresponds with the terrace at 550 m at Zelen Izvor locality (same relative elevation above present Kamenica River), representing regional aggradation in Kamenica Valley (Fig. 5.73).

The sediments in Budimirica Cave connected with this aggradation are covering flowstone deposits with Late Pleistocene age (83 Ka), which places this aggradation and cave development as younger than 83 Ka. As a result of a stable base-level position after this aggradation, water table caves developed in the output positions (Budimirica Cave, Temna Peštera–Mrežičko) with Aramiska Peštera and Garnikovska Propast developing epiphreatic sub-horizontal passages connected to the base-level position. The Lower Passages in Aramiska Peštera and Garnikovska Propast, as well as Nad Zelen Izvor and Zelen Izvor developed after incision of Kamenica River, connected to periods of stable base level and are younger than 83 Ka.

Pleistocene incision of valleys also influenced evolution of caves in the SE parts of Kozjak Mountain and the NW parts of Kožuf Mountain. Temna Peštera–

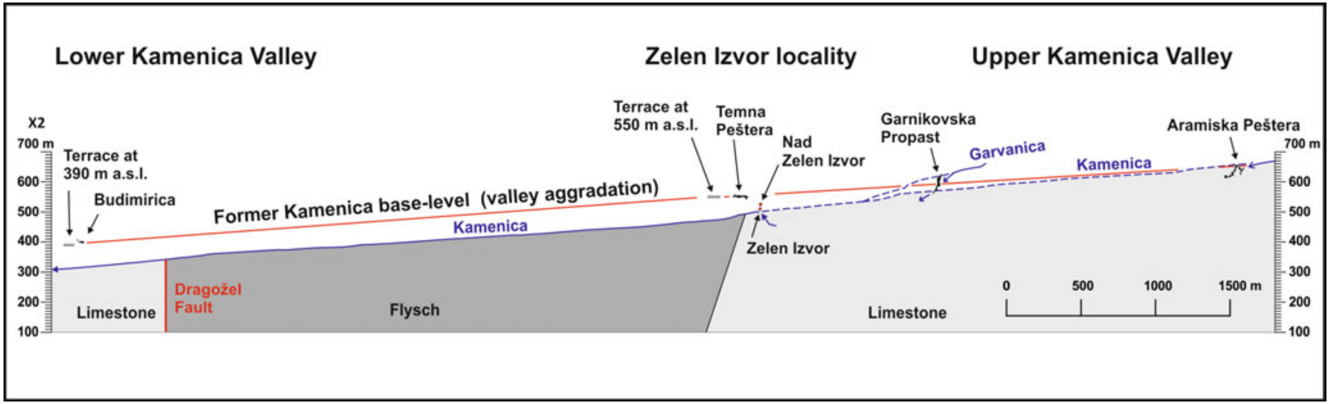


Fig. 5.73 Location of caves along Kamenica Valley and correlation of former Kamenica base level to caves (Temna Peštera–Dragožel, Budimirica Cave) and paragenetic passages (Aramiska Peštera, Garnikovska Propast)

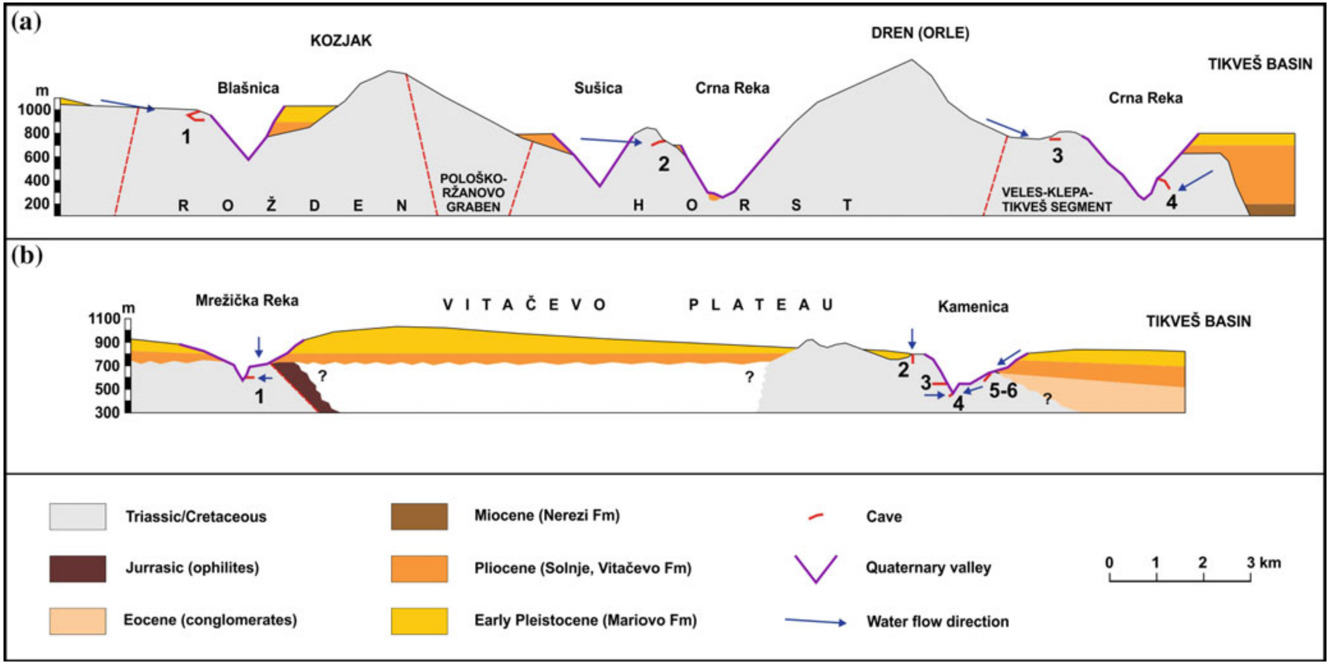


Fig. 5.74 Simplified cross section showing cave relationships to Pliocene–Early Pleistocene deposits and Quaternary valleys. **a** Caves with development connected to Pliocene–Early Pleistocene deposition (*1* Pešterski Kamen Cave, *2* Vodna Peš Cave, *3* Lekovita Voda Cave, *4* Čulejca Cave); **b** Caves developed below Pliocene–Early Pleistocene deposits, connected to incision of Quaternary valleys (*1* Temna Peštera–Mrežičko, *2* Dragoželska Propast, *3* Temna Peštera–Dragoželj, *4* Zelen Izvor and Nad Zelen Izvor, *5* Garnikovska Propast and Aramiska Peštera)

Mrežičko is another example (Fig. 5.74b) of the evolution of the cave system as a result of the Pleistocene evolution of river valleys (valley of Mrežička Reka). The present spring is located in the riverbed, at the contact with underlying flysch rocks, while Temna Peštera–Mrežičko, a horizontal cave, is located 15 m above, with small cave entrances also found 60 m higher. The cave elevations correspond to former stable base levels, with paragenetic morphologies in Temna Peštera–Mrežičko (markant alluvial notches, flat ceiling, channels, etc.) indicating aggradation in the valley.

Continuous cave evolution is evident for the Živovska Propast, a network shaft developed along a set of NNW–SSE to WSW–ENE fractures, considering its location high above the highest elevations of Pliocene and Pleistocene deposits (Figs. 5.50 and 5.54).

In the main valley of Crna Reka, epigenic cave development is found at Podot locality, connected to the output system of Gugjakovo Springs. Numerous cave entrances in travertine are choked due to collapse, two of which lead to Podot 1 and Podot 2 caves, having a fracture guided network passages with passage levels corresponding to former river position (Figs. 5.48 and 5.54). The travertine deposits found in this area, as well as at higher elevation, are most likely connected to the former positions of the springs, with karst waters supplying high calcium carbonate content. The water in the springs is most likely originating from the Precambrian and Cambrian marble formations which are continuing to the north (Fig. 5.49), although contribution from the Turonian limestones is also possible. Considering the location of a thermal spring in Karši Podot Cave, in the opposite terrace of Karši Podot, and little higher temperature of the Gugjakovo Springs, there is probably mixing with thermal waters converging at the lowest output position of the Precambrian and Cambrian marbles in Crna Reka Valley.

5.4.2 Cave Development Connected to Pliocene–Early Pleistocene Deposition in Mariovo and Tikveš Basin

At higher elevations in Crna Reka Valley are located Pešti Cave, Pešterski Kamen, Vodna Peš, Cave Lekovita Voda, and Čulejca Cave, which development is most likely older than the Pleistocene incision of Crna Reka, and/or correspond either to the Pliocene and/or Early Pleistocene deposition in Mariovo and Tikveš Basin (Fig. 5.74a).

Čulejca Cave, Cave Vodna Peš, and Cave Pešterski Kamen have rising phreatic passages connected with sediment deposition and paragenetic development and/or are located in higher elevations, while Cave Lekovita Voda is sub-horizontal phreatic cave with paragenetically developed passage due to sediment deposition and is located above Quaternary Crna Reka Valley. Their location correlates with distribution of Pliocene–Early Pleistocene deposits in Tikveš Basin and paleo-Crna Reka Valley, with only Čulejca Cave located below 400 m elevation and is likely older than the others. Deposits of Vitačevo Formation are found up to elevation of

750 m in Vitačevo Plateau, and filling paleovalleys to the west up to 800 m in Sušica Valley and 1150 m in Rožden area (Kozjak Mountain), with Mariovo Formation sediments starting from 750 m in the northern parts of Vitačevo, up to more than 1000 m elevation to the south close to the Kožuf volcanic centers. Quaternary incision led to per descensum speleogenesis in these caves, mainly with removal of sediments and deposition of speleothems, as well as development of small vadose passages (e.g., Cave Pešterski Kamen).

5.4.3 Possible Influence of Messinian Salinity Crisis on Epigenic Cave Development

The morphological interpretation and cave deposits in Čulejca Cave, as well as the correlation with the surrounding geological and geomorphological setting, indicate formation of cave passages by rising waters due to aggradation in the surface depressions (Tikveš Basin, paleo-Crna Reka Valley), likely as a result of the Pliocene deposition of Vitačevo Formation (Fig. 5.75). In Late Pliocene and Early Pleistocene, this area was completely covered with deposits of Vitačevo and Mariovo Formations, which ultimately closed the karst systems in Vitačevo Plateau. After the draining of Central Macedonian Lake (as late as Middle Pleistocene; Dumurdžanov et al. 2004), incision of Crna Reka influenced per descensum development in Čulejca Cave, with deposition of thick pool and flowstone speleothems corresponding to stable base-level positions, and later their dissolution and deposition of fluvial sediments as a result of aggradation.

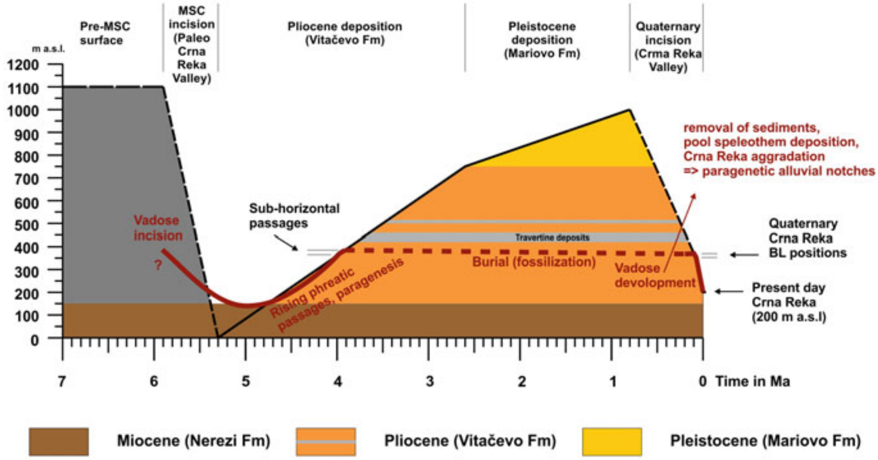


Fig. 5.75 Timeline of events (incision and deposition) in Crna Reka Valley (Tikveš Basin) and supposed timing of Čulejca Cave evolution connected to base-level changes. Miocene incision connected to the Messinian Salinity Crisis (MSC) or tectonic uplift

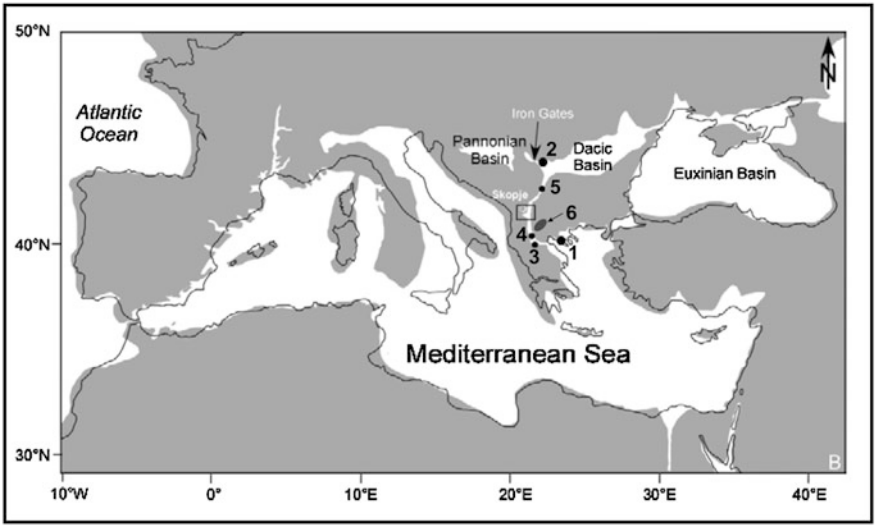


Fig. 5.76 Early Pliocene paleogeography of the Mediterranean and Eastern Paratethys with the proposed marine gateway between the Aegean Sea and Dacic Basin and location of lower part of Crna Reka river basin (*6*). Localities: *1* Trilophos, *2* Gilbert-type fan delta of Turnu Severin, *3* Prosilio, *4* Ptolemais, and *5* Niš (modified from Clauzon et al. 2008)

Per ascensum phase of cave development in Čulejca Cave connected to base-level rise by Pliocene deposition would indicate previous per descensum phase of karstification. Considering the proposed marine gateway connecting Dacic Basin (Eastern Paratethys) to the Aegean Sea (Fig. 5.76) prior and after the Messinian Salinity Crisis (MSC) in the Mediterranean, based on the discovery of Pliocene Gilbert-type fan delta (the postponed signature of the MSC) in Dračevo, near Skopje (Clauzon et al. 2008), as well as near Thessaloniki (Greece) and Niš (Serbia), the lowering of base level can be due to entrenchment of valleys due to desiccation of the Mediterranean Sea during the MSC in Upper Miocene. Pliocene deposits of Vitačevo and/or Solnje Formations are filling paleovalleys on Vitačevo Plateau (Fig. 5.4), Kozjak Mountain (Sušica and Blašnica valleys), and in Crna Reka Valley where Pliocene deposits can be found along the valley between Tikveš Basin, with Quaternary Crna Reka developed partly in Pliocene deposits (e.g., confluence of Blašnica River to Crna Reka, Fig. 5.59).

Other caves which might also correlate with MSC-influenced karst evolution include Vodna Peš, Cave Lekovita Voda, and Cave Pešterski Kamen. They are all located at higher elevations in Crna Reka and Blašnica valleys (Fig. 5.74a), with Cave Pešterski Kamen located at higher elevation than the others, most likely due to Kozjak Mountain having higher uplift rate as part of the Mariovo neotectonic block (Arsovski and Petkovski 1975) during the general uplifting in Pleistocene.

5.4.4 *Geological and Geomorphological Controls on Epigenic Cave Development*

Main controls on epigenic cave development are the Pliocene and Pleistocene sediment deposition in Tikveš and Mariovo Basins, and the incision of Crna Reka and its tributaries in Miocene and Pleistocene (Fig. 5.71). The Pliocene deposition of Vitačevo Formation in Tikveš Basin influenced per ascensum development of Čulejca Cave, Vodna Peš, and Pešterski Kamen, continuing with covering of karst areas by lacustrine deposits and later deposits of Mariovo Formation, resulting in closing of karst systems in lower areas (below 1000 m). The upper parts, which were not covered by the basin deposits, remained active throughout the Pliocene and Pleistocene, supplying carbonate content for the lacustrine to paludal travertine deposits in Vitačevo and Mariovo Formations in both Tikveš and Mariovo Basins.

Incision of Crna Reka drainage system was and still is the main controlling factor in cave development by lowering of the base level of karst terrains and removal of overlying caprock deposits covering karst. The influence of caprock retreat is most evident in Vitačevo Plateau, especially in the Upper Kamenica Karst where removal of overlying pyroclastic deposits led to increase of karst surface and upstream shift of ponors in Kamenica and Garvanica valleys (Figs. 5.73 and 5.74b). Deposits of Vitačevo and Mariovo Formation have played important part in cave development also by supplying the sediment material which after accumulation in cave passages (connected to either local or regional aggradation in river valleys) forced paragenetic development.

In most of the studied caves, clastic cave deposits are composed of clay, silt and sand, as well as gravel, cobble and boulder size deposits originating from the pyroclastic rocks of Mariovo and/or Vitačevo Formation (Table 5.11). This is especially evident in caves located in Kamenica Valley. Siliclastic rocks of Upper Cretaceous age were source of clastic cave deposits in Pešti Cave, while in Pešterski Kamen, Lekovita, and Budimirica caves, the sediments were originating from both (Upper Cretaceous and/or Middle Triassic) siliclastic and (Pliocene-Pleistocene) pyroclastic rocks. The source of clastic rocks correlates well with location of caves and distribution of non-carbonate rocks (Fig. 5.77). In karst areas which were covered by deposits of Vitačevo and Mariovo Formation (e.g., Vitačevo caves, Temna Peštera–Mrežičko), or cave development is connected to deposition of these formations (Čulejca Cave, Vodna Peš), pyroclastic rocks are the source of cave sediments.

In karst areas shielded from these deposits (e.g., along paleo-Crna Reka Valley), caves are either lacking clastic cave sediments (e.g., caves in Podot locality, Živovska Propast), or they originate from the Upper Cretaceous siliclastic rocks (e.g., Pešti Cave). Caves located on the border of Tikveš Basin deposits are having mixture of both pyroclastic- and older siliclastic-derived sediments (e.g., Lekovita Voda, Pešterski Kamen). Paleokarst deposits in Čulejca Cave are also likely originating from the Upper Cretaceous siliclastic rocks.

Most of the studied epigenic caves are phreatic caves, located in the output (and throughput) part of the karst system they are/were draining (Table 5.12). Some are

Table 5.11 Clastic cave sediments found in epigenic caves and their source

Cave	Description of clastic cave sediments	Source of clastic cave sediments (based on macroscopic observations, mineral composition, and geological setting)		
		Pyroclastic rocks (Mariovo and/or Vitačevo Fm)	Sandstones, shales, and conglomerates (Cretaceous, Triassic)	No clastic cave sediments
Aramiska Peštera	Pale brown clay, brown sand, gravel, cobble, and rounded boulders	▨		
Dragoželska Propast	Dark brown clay, cobbles	▨		
Garnikovska Propast	Brown to gray brown clay and silt, sand, gravel, cobble, and rounded boulders	▨		
Mala Peštera	Sand, gravel, cobble	▨		
Temna Peštera –Dragožel	Brown silt, dark brown clay, gravel	▨		
Zelen Izvor	Clay, sand	▨		
Nad Zelen Izvor	Sand	▨		
Budimirica	Yellow sand, silt and gravel, brown clay	▨	▨	
Čulejca	Brown clay, yellow clay, yellow paleokarst deposits, sand, gravel	▨	Paleokarst	
Lekovita Voda	Yellow clay, sand, and gravel	?	▨	
Vodna Peš	Brown clay	▨		
Pešterski Kamen	Orange brown sand and clay, gravel	▨	▨	
Temna Peštera–Mrežičko	Brown clay, gravel, cobble	▨		
Pešti	Red brown clay		▨	
Živovska Propast	/			▨
Podot 1	/			▨
Podot 2	/			▨

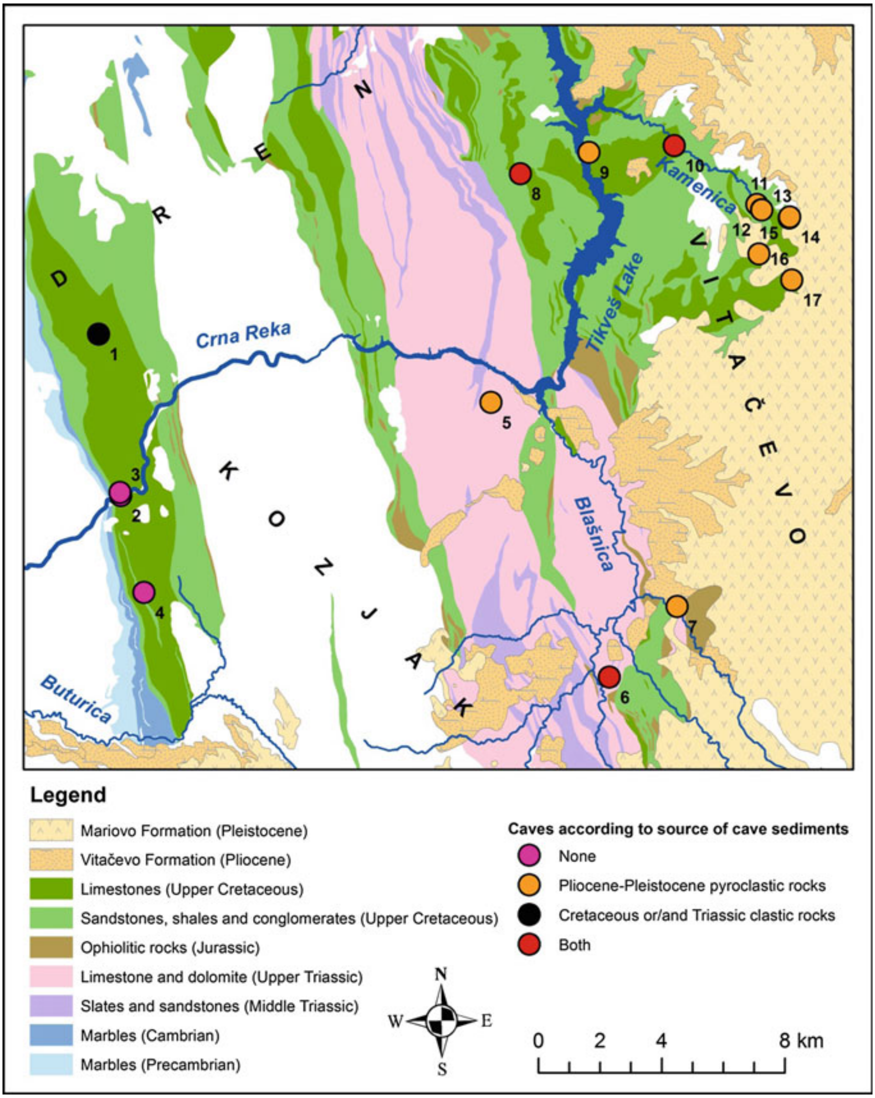


Fig. 5.77 Map of epigenic caves by source of clastic cave sediments. *1* Pešti Cave, *2* Podot 1, *3* Podot 2, *4* Živovska Propast, *5* Vodna Peš, *6* Pešterski Kamen, *7* Temna Peštera–Mrežičko, *8* Lekovita Voda, *9* Čulejca Cave, *10* Budimirica Cave, *11* Temna Peštera–Dragožel, *12* Zelen Izvor, *13* Nad Zelen Izvor, *14* Garnikovska Propast, *15* Mala Peštera, *16* Dragoželska Propast, and *17* Aramiska Peštera

having sub-horizontal phreatic passages connected to base-level position (Lekovita Voda, Budimirica, Podot 1, and Podot 2), with others having rising phreatic passages, connected to base-level rise (Čulejca Cave, Vodna Peš, Pešterski Kamen, Zelen Izvor, Nad Zelen Izvor). Temna Peštera–Mrežičko and Temna Peštera–

Table 5.12 Epigenic cave types, their position within the karst system, and type of recharge

Cave	Cave type				Karst system function			Recharge type		
								Allogenic		
	Shaft	Vadose canyon to epiphreatic tube	Phreatic cave	Water table cave	Input	Throughput	Output	Diffuse (caprock)	Ponor	Autogenic
Živovska Propast	▨				▨					▨
Dragoželska Propast	▨				▨			▨		
Aramiska Peštera		▨			▨				▨	
Garnikovska Propast		▨			▨				▨	
Mala Peštera		▨			▨				▨	
Pešti		▨				▨			?	▨
Lekovita Voda			▨			▨			▨	
Pešterski Kamen			▨			▨	?		▨	
Budimirica			▨			?	▨	?	▨	
Zelen Izvor			▨				▨	▨	▨	▨
Nad Zelen Izvor			▨				▨	▨	▨	▨
Podot 1			▨				▨			▨
Podot 2			▨				▨			▨
Čulejca			▨				▨		▨	▨
Vodna Peš			▨				▨		▨	▨
Temna Peštera–Dragožel				▨			▨	▨	▨	▨
Temna Peštera–Mrežičko				▨			▨	?	▨	?

Dragožel are output water table caves controlled by base-level position. Input caves are either shafts developed along the faults and prominent fractures (Živovska Propast, Dragoželska Propast) or vadose canyons leading to epiphreatic tube passages (Aramiska Peštera, Garnikovska Propast, Mala Peštera, and Pešti Cave).

Most of the caves are having allogenic or mixed allogenic/autogenic recharge (Table 5.12). Allogenic recharge in most of the karst areas is focused (ponors), although in Upper Kamenica Karst, diffuse allogenic recharge from pyroclastic caprock is also contributing to cave development, where caprock sediments are thinner due to surface erosion (e.g., Dragoželska Propast). Only autogenic recharge is characteristic for higher karst areas, which were not covered by Pliocene/Pleistocene deposits.

Base-level position given by Crna Reka Valley and its tributaries is the main boundary control on epigenic karst development. Incision in Crna Reka Valley led to lowering of water table and adjusting of passage development (vadose incision leading to epiphreatic and phreatic passages) near the new water table position. Aggradations in Crna Reka Valley and its tributaries on the other hand led to rise of water table, deposition of sediments and paragenetic development of rising phreatic passages, or development of alluvial notches in water table caves. The effect of one major Late Pleistocene aggradation in Kamenica River is seen in Budimirica Cave and Temna Peštera–Dragožel, corresponding with fluvial terrace (550 m a.s.l. at Zelen Izvor locality, 390 m a.s.l. near Budimirica Cave), which is also evidenced with paragenetic passage development in the input parts of Upper Kamenica Karst in Aramiska Peštera and Garnikovska Propast (Fig. 5.73).

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Chapter 6
Characteristics of Karst Surface

The main characteristic of the karst surface in the study area is lack of dolines and larger karst surface forms, and the presence of mostly fluviokarst surface morphology.

In karst rocks, the absence of dolines, which are generally considered as the diagnostic karst landform, does not mean that karst is not developed (Ford and Williams 2007). The studied caves presented in the previous chapters clearly indicated that karst was/is functioning in these terrains beside the lack of typical karst surface morphology found.

Although there are some differences between different karst areas and lithologies, generally karst surface in the area shares similar characteristics. The main morphological features seen on karst surface are the fluvial valleys of Crna Reka and its largest tributaries Buturica, Blašnica, and Kamenica rivers coming from the right side and Drenovica River from the left side. All of these rivers are allogenic rivers coming from non-karstic areas, and cutting through karst areas forming through valleys (Fig. 6.1).

Crna Reka has the biggest discharge and represents the regional base-level guiding the incision of the tributary rivers as well as karst development. Crna Reka Valley is cutting through karst terrains in three segments separated by non-karstic rocks: (1) in the eastern edge of the Pelagonian Massif, cutting through the stacked series of dolomitic and calcitic marbles (Precambrian and Cambrian) and limestones (Senonian) separated by clastic rocks (Senonian); (2) then in the Triassic carbonate series (limestones and dolomites) of the Rožden horst; and (3) last in the Turonian limestones of Vitačevo Plateau. In the first two segments, the valley is much deeper (up to 1000 m), comparing to the third segment cutting through the Vitačevo Plateau. As was discussed before, the evolution of the Crna Reka Valley is connected to two main phases of incision, one in Pleistocene following the draining of Mariovo and central Macedonian Lake, and the other in Miocene before the Pliocene deposition.

Considering the distribution of Pliocene deposits along the valley, the valley was already deeply incised during the Miocene incision, with the later Pleistocene development eroding the Pliocene deposits, and at places further incising the valley. This has had a major influence on karst development with fast lowering of the water table and development of thick vadose zone. Although its discharge varies

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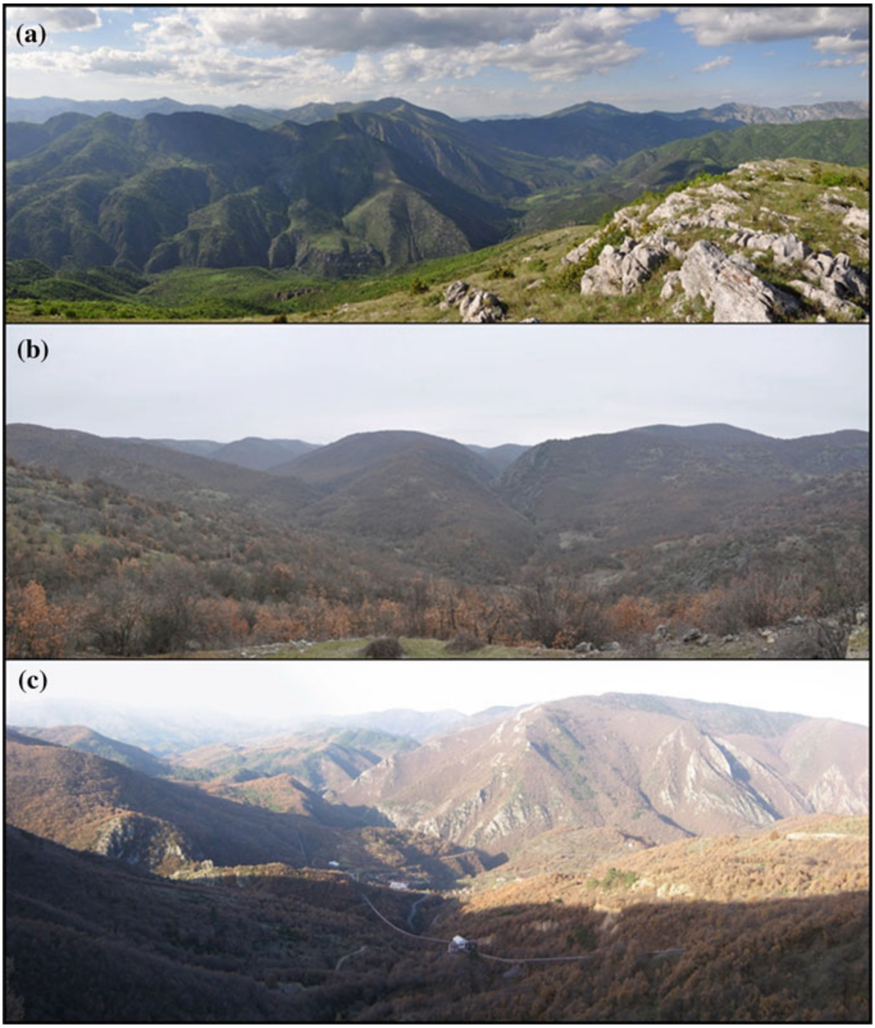

Fig. 6.1 The allogenic through valleys of: **a** Crna Reka in the western part between Vrpsko and Gugjakovo villages. **b** Kamenica River in the upper part at the confluence of Gaber (*left*) and Crkvište (*right*) rivers. **c** Blašnica River at the confluence with Mrežička Reka. Photographs by M. Temovski

significantly between wet and dry season, Crna Reka is a perennial allogenic river, which combined with the small difference in elevation between the input and output boundaries of the karst terrains through which it flows, allows the continuous development of the through valley.

Its tributaries have similar characteristics, but with much more inclined longitudinal profiles which allow for bigger differences between upper and lower parts of the valleys in the karst areas, leading to losing water in cave systems. This is best seen

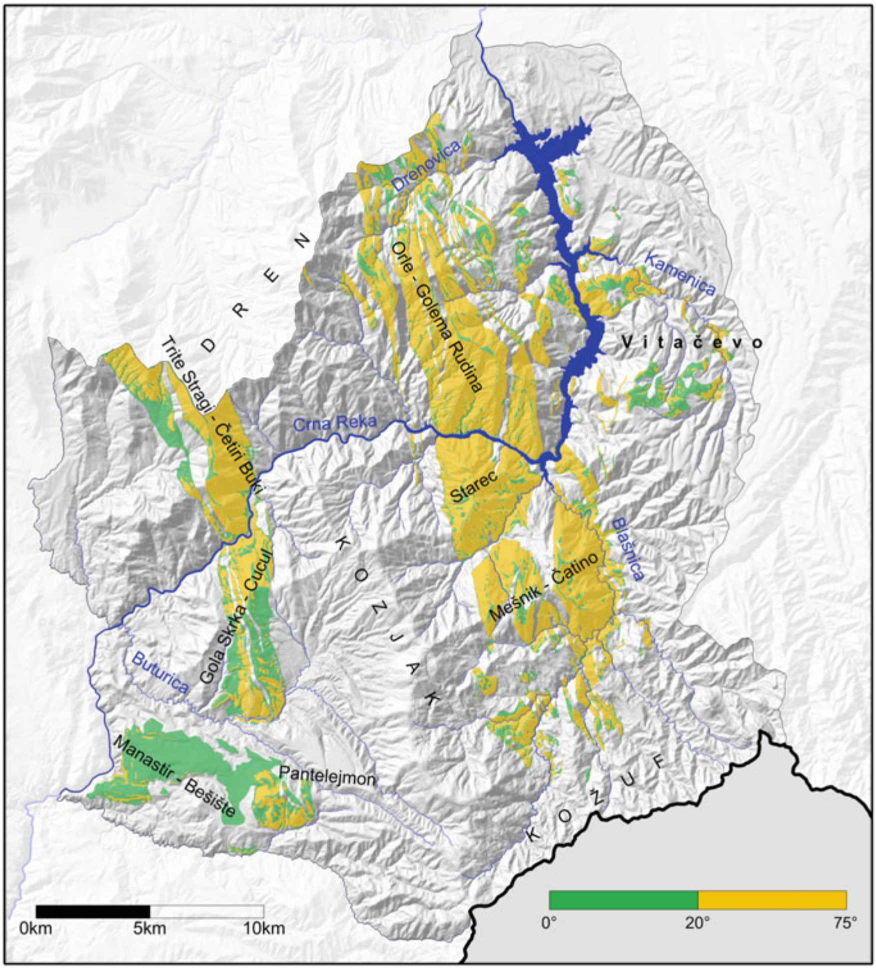

Fig. 6.2 Distribution of slopes in karst terrains

in Kamenica Valley, where Kamenica River flows on surface only in the wet period and after strong storms, while in the other periods the water is sinking in the upstream parts flowing underground to the output location in Zeleni Izvor at the contact with the underlying impermeable clastic rocks. Their development is connected with the main Crna Reka Valley serving as their base level.

The deep incision influenced development of steep slopes on valleys sides, where also smaller tributary valleys developed. They are quite steep dry valleys, active only during strong storms.

Thus, karst terrains have fluviokarst surface morphology consisting of dry valleys and deep allogenic valleys.

In the travertine deposits of Manastir–Bešište Plateau and in Crna Reka Valley, and in interfluves, especially on mountain ridges, the topographic slope is significantly lower. Dry valleys are not found here, with karst terrains having more leveled surfaces, although no dolines are found.

The low topographic slope in travertine deposits is connected to the low primary (sedimentary) slope, as these rocks were not later deformed.

In the mountain ridges, these semi-flat or flat areas are most likely remnants of former erosional surfaces, developed before the deep valley incision.

Although these areas are more or less horizontal, no dolines or bigger karst depressions are developed or developing in them. Although they share the same morphological characteristic (lack of dolines), the karst terrains on mountain ridges are developed in older karst rocks (Precambrian and Cambrian marbles, Triassic limestones and dolomites, and Senonian limestones), while the travertine deposits are part of the big Manastir–Bešište Plateau, or in smaller areas in Crna Reka Valley. Further, the older rocks have been subdued to karstification in a much longer period being also affected by the deep incision of valleys in Miocene, while the travertines are much younger (Pleistocene) and have been affected only by the base level lowering in Pleistocene.

Ford and Williams (2007) indicate three main factors preventing doline development: (1) very high vertical conductivity throughout the vadose zone; (2) spatially uniform and dense vertical permeability; and (3) steep (>20°) hillsides.

The main factor influencing the lack of dolines here are the steep slopes on valley sides. As Ford and Williams (2007) point out, on slopes higher than 20° the dominant epikarst hydraulic gradient is sub-parallel to the topographic slope, which will prevent development of depression in the epikarst water table, and focused flow and dissolution for development of dolines. On steep slopes, also mechanical

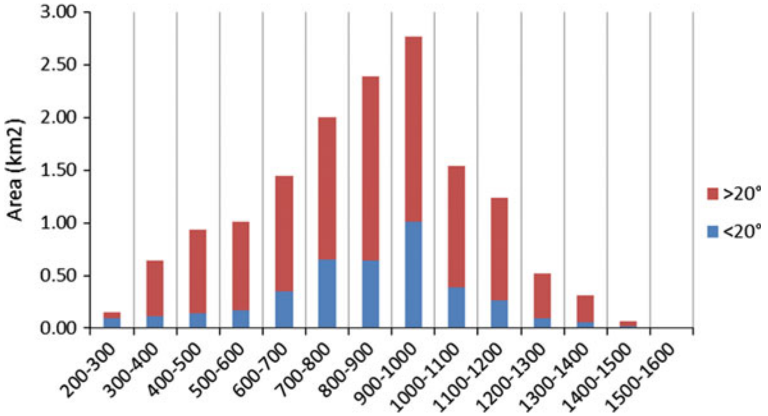

Fig. 6.3 Stacked distribution of areas with slopes smaller or bigger than 20° in elevation classes of 100 m

weathering can be more significant than chemical weathering, leading to mass movement (Stepišnik and Kosec 2011).

Morphometric analysis of terrain slope gave average slope value of 24.2° for karst rocks in the study area (Fig. 6.2). Differential analysis of terrain slope was done for different lithologies, and a distribution of slopes in 5° classes was compared against 100-m elevation classes (Fig. 6.3). Slopes of less than 20° cover 33 % of karst areas, with flat areas (<5°), mostly found in travertine deposits (69 %) (Fig. 6.4). In vertical distribution, most of the small slopes (<20°), and also flat areas (<5°), are located between 900 and 1000 elevation. This is due to the distribution of travertine deposits on Manastir–Bešište Plateau; mountain ridges in the western part between Melnica and Gugjakovo developed in (Precambrian and Cambrian) marbles and (Senonian) limestones; as well as the (Turonian) limestones in the highest parts of Vitačevo Plateau (Fig. 6.5). The small slopes in lower elevation classes are connected to the travertine deposits, while in the higher elevation classes (1000–1100, 1100–1200, 1200–1300, and 1300–1400) are attributed to the mountain ridges in the western part: developed mostly in (Senonian) limestone, and eastern part: developed in Triassic limestones and dolomites. Small slopes, mostly flat areas, are also found on travertine deposits in Crna Reka Valley. The highest slopes as expected are along the valley sides of Crna Reka and its tributaries.

On mountain ridges, the topographic slopes are much lower than on valley sides, which should allow development of dolines. The reason why dolines are not developing here may be the high conductivity in the epikarst due to thick well-developed vadose zone as a result of a long period of vadose development due to the incision of the valleys. Even if the Pliocene deposition filled the lower part of Crna Reka Valley, and some of the tributaries, the mountain ridges were not

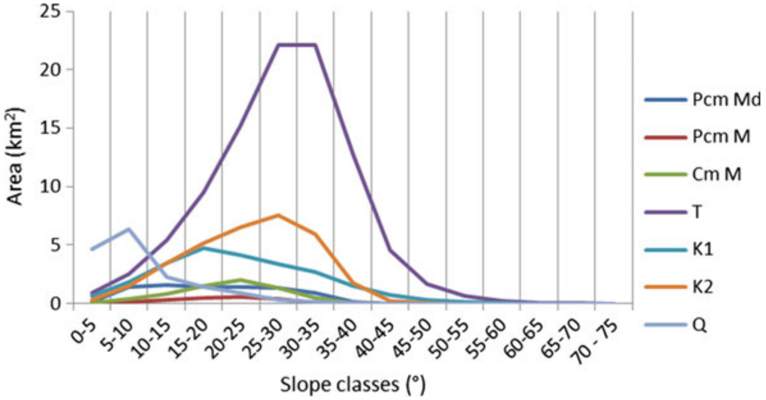

Fig. 6.4 Distribution of surface area of slope classes by different karst rocks: Pcm Md—dolomitic marbles (Precambrian); Pcm M—calcitic marbles (Precambrian); Cm M—calcitic marbles (Cambrian); T—limestones and dolomites (Triassic); K1—limestones (Turonian); K2—limestone (Senonian); Q—travertines (Pleistocene)

covered by sediments and maintained continuous vadose development. In Kamenica Valley, which developed in Pleistocene incising first in the Pliocene and Pleistocene deposits then in the older carbonate rocks, such thick vadose development was not present (although previous karstification phase was present), except maybe in the hilly area in the higher part of Vitačevo, where this may be the reason for lack of dolines.

In the large travertine deposits on Manastir–Bešište Plateau, which yields the largest flat areas, as small slopes were present since the exposure of the rocks after the draining of the Mariovo Lake (primary depositional low slopes), development of dolines would be expected. Nevertheless, this is not the case, with only (spatially) large and very shallow, hardly detectable, depressions developed on them. Although slopes are favorable for doline development, the reason for the lack of doline development may be the high primary porosity, which created high vertical conductivity in the vadose zone, which probably formed very fast with the incision of Buturica and Crna Reka valleys.

The main drainage in the travertines (although small) now is located at the contact with the underlying impermeable sediments, with the main spring located on the lowest point to the west in Crna Reka Valley in Manastir Village.

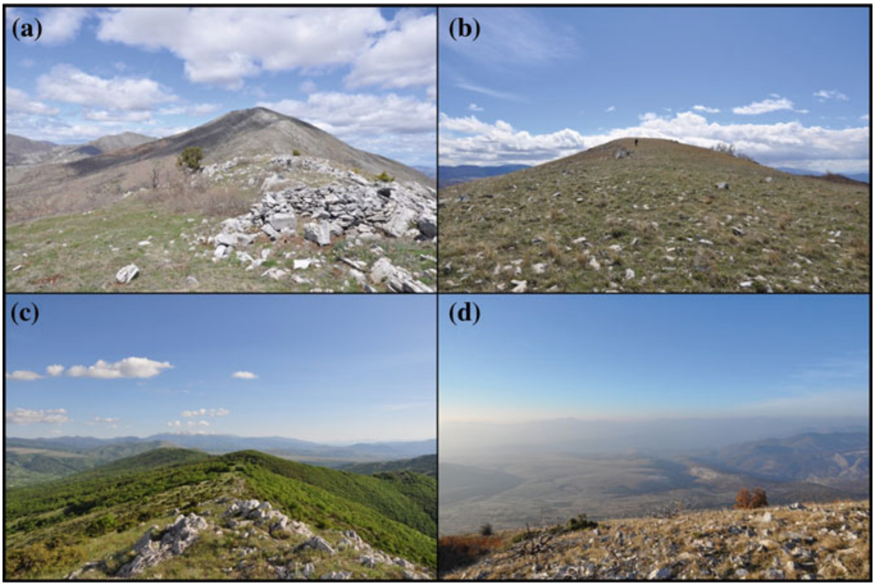

Fig. 6.5 Karst surface on low slope terrains: **a** View to the north of Trite Stragi–Četiri Buki mountain ridge. **b** View to the south of the same ridge on **a**. **c** View to the south of Gola Skrka–Cucul mountain ridge. **d** View to the northwest of Manastir–Bešište Plateau from Pantelejmon. Photographs by M. Temovski

Although karst depressions are lacking on the dominantly fluviokarstic surface morphology, small scale karst forms such as karren are developing. Some of them are merely surface sculpturing features, while others have also hydrological function in the epikarst system.

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Chapter 7
General Conclusions

Karst in the research area is characterized by fluviokarst surface morphology with developed underground karst. Karstification here has been active for quite long period, with the geological and geomorphological evolution of the area in Neogene and Quaternary having biggest influence on its intensity and distribution. Underground karst has been developed by epigenic speleogenesis receiving water recharge and CO_2 from the adjacent surface and also by hypogenic speleogenesis from deep circulating thermal waters with meteoric origin, with cave development due to cooling of CO_2 rich thermal waters, as well as by sulfuric acid dissolution and also ghost-rock weathering in dolomite and/or dolomitic marbles.

As the main geomorphological features represented in the terrain are result of the geological evolution in Neogene and Quaternary, connected to the South Balkan extensional system, karst evolution prior to these periods is difficult to determine, although karst rocks (with Precambrian, Cambrian, and Cretaceous age) have been exposed at least since the beginning of Cenozoic, some karst rocks (Precambrian) even earlier, and karst was most likely developing in them. All of the studied caves in the area have most likely formed in Quaternary and Pliocene.

The main controls on karst development in the area have been the evolution of the Crna Reka Valley as a base-level controlling factor; the evolution of the Tikveš and Mariovo basins, especially thickness and distribution of their deposits which controlled base-level position and karst exposure in the areas west and east of Kozjak Mountain; and the Kožuf–Kozjak volcanism, increasing the geothermal gradient as well as supplying most of the material for the basin deposits in Pliocene and Early Pleistocene.

M. Temovski, *Evolution of Karst in the Lower Part of Crna Reka River Basin*,
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7.1 Evolution of the Crna Reka Valley and Karst Development

The study area is cut by allogenic valleys of Crna Reka and its tributaries representing the erosional base-level position. Where these valleys cut through karst terrains, they represent the base level of the karst systems developed in them, and therefore, their position or evolution controls the evolution of the karst in the study area.

In the evolution of the valley network in Crna Reka basin, there are two main phases of valley incision, separated by a long period of aggradation and deposition of thick sediment sections connected to the basin deposits of Tikveš and Mariovo basins. The older phase of valley incision is predating the Pliocene deposition in Mariovo and Tikveš basins which also filled up these valleys and is likely of Miocene age. The most clear proof of this phase are the remnants of Pliocene deposits seen in the lowest parts of Crna Reka Valley between Mariovo and Tikveš basins, as well as the paleovalleys on Vitačevo Plateau filled with deposits of Vitačevo Formation (Pliocene). The main Crna Reka Valley during this incision phase was more than 1000 m deep. Pliocene transgression in Tikveš and Mariovo Basins also filled up these valleys. The latest phase of incision is connected to the general geomorphological evolution in the area due to the draining of the Macedonian Pliocene–Pleistocene lakes as a result of the subsidence in Aegean Sea where these rivers drain (as part of Vardar River system) and also the general uplift of the Balkan Peninsula in Quaternary.

These evolutions from incision of deep valleys, to their thick aggradation and later again incision, have had a great impact on karst development in the area. The river valleys represent the low surface topography and their position/elevation influenced both the epigenic cave development and the direction of hypogenic flow (hypogenic cave formation).

The karst development during the Miocene incision of Crna Reka is difficult to assess, with no clear proof found. Such deep incision in the karst terrains would have nevertheless lowered the base level and influenced development of thick vadose zone. Its indirect detection is based on karstification preceding the rising phreatic development in Čulejca Cave (which is attributed to the Pliocene deposition). While no definitive proof is presented for the karst underground, karst surface morphology is clearly influenced by this incision, developing fluviokarst surface morphology with deep allogenic through valleys.

The Pleistocene incision, which followed the draining of Mariovo and Central Macedonian lakes, reactivated the old valleys (mostly in Crna Reka), forming also new (superimposed) valleys cutting first in the Pliocene–Pleistocene (Tikveš and Mariovo basins) lacustrine to fluvial deposits, then in the basement karst rocks. It allowed removal of the basin deposits covering karst areas, and their reactivation, and/or development of new karst features. Most of the studied caves are connected with the Pleistocene evolution of the Crna Reka and its tributaries.

The best expressed example of the Pleistocene evolution of the karst with valley incision is in the Upper Kamenica Valley, where Kamenica River incision exposed karst rocks beneath the Pleistocene (Mariovo Formation) and Pliocene (Vitačevo Formation) deposits, and guided karst development with lowering of karst output position (Zelen Izvor, Nad Zelen Izvor, Temna Peštera–Dragožel), which also influenced lowering and shifting of cave development in the input position (Aramiska Peštera, Garnikovska Propast, Dragoželska Propast) while still developing its through valley due to allogenic recharge. In Mrežička Reka, tributary to Blašnica River, cave development is also connected with the Pleistocene incision of the allogenic through valley, with water table caves (Temna Peštera–Mrežičko) developing during stable base-level position and subsequent incision lowering cave development at lower position.

In Buturica Valley and in Podot locality in Crna Reka Valley, Pleistocene incision also guided hypogenic cave development. Incision of Buturica Valley, after the draining of Mariovo Lake, allowed removal of clay deposits in Provalata Cave, lowering of water table, and due to the introduction of H_2S, sulfuric acid speleogenesis. This second phase speleogenetic development in Provalata Cave was guided by the lowering of water table with valley incision, with cave development above water table by condensation corrosion. Incision of Buturica Valley also guided the evolution of the Melnička Peštera 1 and 2, which were developed in carbonate conglomerates at the water table close to the contact with underlying dolomitic marbles, most likely by thermal waters. In Podot locality, Crna Reka incision in the travertine and terrace deposits, allowed removal (by Crna Reka backflooding) of dolomitic alterite formed by ghost-rock weathering of Precambrian dolomitic marbles by rising thermal waters. This created Karši Podot Cave partly developed also in the terrace deposits (clastic and travertines) with low-temperature thermal waters still discharging.

Cave development in the travertine deposits on Podot terrace, opposite of Karši Podot Cave, was also guided by the evolution of the Crna Reka Valley, with the development of the two accessible caves (Podot 1 and Podot 2) connected to the former river positions, while further incision of Crna Reka lowered the spring (Gugjakovski Izvori) position close to the present riverbed.

Paragenesis played important role in cave evolution, creating paragenetic morphologies in both phreatic and vadose environments. The paragenetic development suggest aggradation in river valleys and is best expressed in the caves on Vitačevo Karst, connected to Kamenica River (Aramiska Peštera, Garnikovska Propast, Temna Peštera–Dragožel) and Crna Reka (Čulejca Cave, Vodna Peš), as well as in Blašnica River and its tributaries (Temna Peštera–Mrežičko, Pešterski Kamen). In Čulejca Cave, two different phases of paragenetic development can be separated, one connected with the development of rising phreatic passages (attributed to Pliocene deposition in Tikveš Basin), and the other connected dissolution of thick pool speleothem deposits and paragenetic notches (attributed to Pleistocene aggradation of Crna Reka).

The Pleistocene incision of river valleys also influenced the surface karst morphology. Allogenic rivers crossing the karst terrains developed through valleys, or reactivated the previously formed (and filled with Pliocene–Pleistocene deposits) valleys. This further influenced the fluviokarst surface development, with deep incision influencing steep slopes on karst terrains, and continuous development of vadose karst zone, preventing development of karst depressions.

7.2 Influence of Tikveš and Mariovo Basin Evolution on Karst Development

The influence of Tikveš and Mariovo Basin on karst evolution is mainly connected with the Pliocene and Pleistocene deposition. After the hiatus at the end of Miocene (Dumurdžanov et al. 2004), Pliocene deposition gradually filled both basins. In Tikveš Basin, Pliocene deposits spread further to the west in Kožuf area and also filled older valleys as well as the paleo-Crna Reka Valley between Mariovo and Tikveš basins. This resulted with rise of base level, influencing also karst terrains. The rising phreatic passages in Čulejca Cave and also the rising morphology in Vodna Peš and Cave Pešterski Kamen are likely connected to this deposition.

Filling of low topography (basin and valleys) continued in Pleistocene with deposition of Mariovo Formation in lacustrine to fluvial environment, composed of pyroclastic rocks and travertine deposits (Mariovo Basin). While the previous Pliocene deposits only partly covered karst terrains, Pleistocene deposits completely covered karst areas in lower elevations as in Vitačevo Plateau, in the foothill between Kožuf and Kozjak mountains and on the borders of Mariovo Basin. Previously formed caves were completely filled with clays derived from the pyroclastic rocks. This is most evident in Čulejca Cave, and especially in Provalata Cave where gray clays completely filled cave passages, and were later altered during the sulfuric acid speleogenesis connected with the Pleistocene incision of Buturica Valley. The Pleistocene deposits almost completely covered the Vitačevo karst, with only small areas of the highest hilly parts maybe lying above them. This completely closed the karst system on Vitačevo, until the removal of the caprock with the Pleistocene incision of Kamenica and Crna Reka. Only the upper parts of karst terrains (higher parts of river valleys, mountain ridges) remained above this deposits and retained continuous development throughout this periods.

While the Mariovo and Tikveš Basin deposition acted as prohibitor on karst development in the lower elevations, it also formed large younger carbonate deposits (carbonate conglomerates, travertines), in which karst started developing after the draining of the Pleistocene lakes.

7.3 Influence of Kožuf/Kozjak Volcanism on Karst Development

Kožuf (and Kozjak) volcanism is connected to the evolution of the South Balkan extensional system. The volcanic activity was dated at 6.5–1.8 Ma for Kožuf (Boev and Jelenković 2012), and 4.5–1.8 Ma for Kozjak (Kolios et al. 1980) volcanic complexes which are located at the southern borders of Tikveš and Mariovo basins.

The influence of volcanic evolution on karst development in the area is generally indirect and twofold.

As the volcanism was explosive, it produced high amount of volcaniclastic material which was deposited as part of Tikveš and Mariovo basin deposits. This speeds up the filling of the basins and closing of karst systems in lower elevations, with Vitačevo and Mariovo Formations in both basins consisting mostly of volcaniclastic material. These deposits also played important role in the later Pleistocene karst development in these areas, supplying most of the material of the clastic cave deposits.

The other influence of the volcanism is connected with the increase of geothermal gradient, as a result of which deep circulating meteoric karst waters were heated, producing hydrothermal hypogenic karst due to cooling of rising thermal waters. At places, other geochemical processes were also involved in the hydrothermal karstification, with increased mineralization and ore deposition in Allchar locality closely connected with the volcanic intrusions. In Provalata Cave, later introduction of H_2S in the hydrothermal karst system started sulfuric acid speleogenesis by condensation corrosion connected with water table lowering due to incision of Buturica River valley. In dolomitic marbles in Melnica and Podot localities, hydrothermal karstification increased porosity by ghost-rock weathering, with ghost-rock weathering in Triassic dolomites also playing a role in the evolution of the Allchar ore deposit.

7.4 Main Speleogenetic Mechanisms

As was demonstrated in the previous chapters, both epigenic and hypogenic cave development was present in the studied area. Epigenic speleogenesis was and is more widespread in the area, and formed caves in various settings and by several mechanisms. Hypogenic speleogenesis, while more localized, was also important in cave development yielding several different speleogenetic mechanisms.

Hydrothermal speleogenesis is the main hypogenic mechanism, connected to the increased geothermal gradient due to the Pliocene–Pleistocene Kožuf–Kozjak volcanic complex. While the cooling of carbonated thermal waters is the most widespread mechanism in the studied hypogenic caves, there was convergence with other processes/mechanisms connected to local geological or lithological control.

Sulfuric acid speleogenesis is determined in Provalata Cave as a second phase of cave development in previously formed cave due to cooling of thermal waters, and also is most likely an active process in the Kožuf area, with thermal springs discharging sulfate ions. While in Provalata Cave, the source of sulfuric acid might be connected to the Mariovo coal deposits, in Kožuf thermal karst, it is connected to the oxidation of sulfide minerals deposited previously in the same hydrothermal system, closely connected to the Kožuf volcanism, as seen in Allchar locality.

In the Precambrian dolomitic marbles between Melnica and Podot areas, ghost-rock weathering process is connected to the hydrothermal speleogenesis. Slow moving thermal waters increase porosity by selective dissolution, leaving in situ alterite residue, which if later introduced to a higher energy water flow will be removed and a phantom cave will develop. This process has been first described in Belgium and well studied in France in mostly epigenic environments, while here is connected to hypogenic dissolution by upward slowly moving thermal waters which provide the ghost-rock weathering and later surface erosion or backflooding of Crna Reka eroding the alterite residue.

The epigenic cave development is in phreatic to vadose conditions, strongly connected to base-level oscillations. Ponor caves are developed at the contact of impermeable cover and underlying karst rocks in Vitačevo, with water table caves developed in the output part of the same system, connected to base-level positions. Deep phreatic caves (now fossil) are connected to base-level rise, and per ascensum speleogenesis. Paragenesis played an important role in cave development in the area. Paragenetic modification, or cave passages development, is connected to base-level rise due to river and/or basin aggradation. It is seen in both phreatic and epiphreatic environments.

7.5 Draining of Mariovo Lake—Contribution to the Understanding of the Evolution of the Macedonian Neogene–Quaternary Lake System

The draining of the central Macedonian Lake in Pleistocene is connected to the subsidence in Aegean Sea, as well as to the general uplift of the Balkan Peninsula. This event is very important to understanding the geomorphological evolution in Macedonia, as it led to the onset of fluvial development and incision of valleys, shaping most of the present morphology in Macedonia, as well as controlling the base-level position of karst systems. Beside this, the timing of the draining of the central Macedonian Lake is still not precisely known. Dumurdžanov et al. (2004) suggest that the limestone dam in Demir Kapija was breached as late as Middle Pleistocene, and as this lake was the southern end-member of other lakes, such as

Mariovo Lake, Pelagonian Lake, Skopje Lake, and Polog Lake, controlled their evolution as well.

The sulfuric speleogenetic phase in Provalata Cave gives the possibility to constrain the timing of the draining of Mariovo Pleistocene Lake and with that to help understand the evolution of the draining of the lakes in Macedonia.

The two time markers which give a possible time range of the draining of Mariovo Lake are the topmost travertine deposits in Mariovo Basin, and the alunite/jarosite minerals formed in Provalata Cave. The travertine deposits belong to Mariovo Formation, which age was determined as Pleistocene, based on the pyroclastic deposits in the formation and the dated Kozjak/Kožuf volcanism (Kožuf 6.5–1.8 Ma, Boev and Jelenković 2012; Kozjak: 4.5–1.8 Ma, Kolios et al. 1980) which supplied the material. Tephra layers are found in the topmost 20-m-thick travertine deposit, therefore constraining the earliest possible time of Mariovo Lake draining after 1.8 Ma.

Alunite and jarosite are minerals found in the pale yellow deposit in Provalata Cave. Their formation is due to sulfuric acid alteration of the clay deposits filling the cave. Their formations is connected to the vadose zone, as the necessary conditions for their development in cave environment requires low pH sulfuric acid (Palmer 2007, 2013), and such pH levels can be achieved in droplets falling on clay deposits. The sampled alunite and jarosite, from the First Room in Provalata Cave, were dated using ^{40}Ar/^{39}Ar dating to 1.6 and 1.46 Ma, which indicates that the draining of Mariovo Lake occurred before this time, as it requires the incision of Buturica Valley to lower the water table in the cave. This puts the draining of Mariovo Lake, sometime between 1.8 and 1.6 Ma earlier than central Macedonian Lake, to which Mariovo Lake was likely an upstream continuation.

7.6 Some Considerations for Future Research

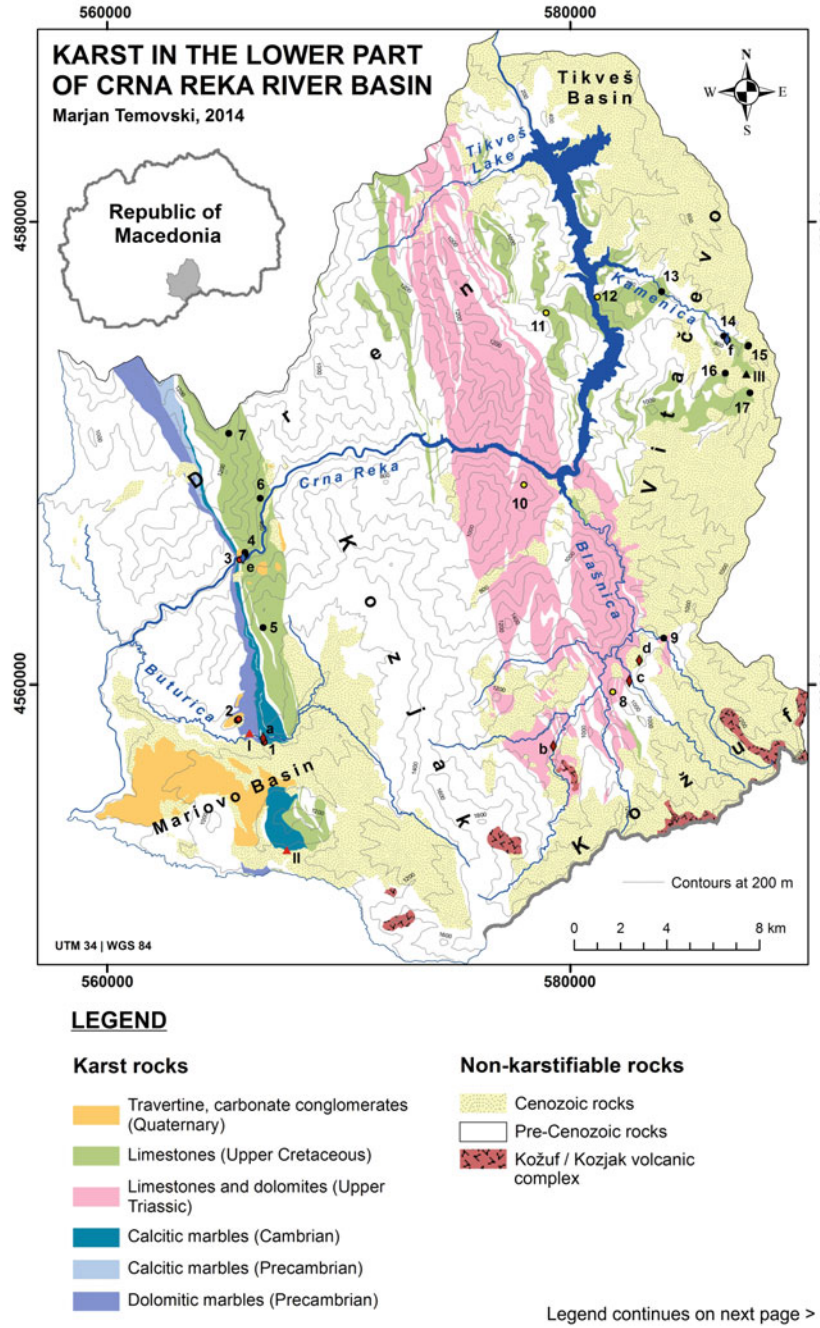
This work represents first attempt to systematically describe, study, and interpret karst development and evolution in the lower part of Crna Reka River Basin, and combined with the fact that this area is quite large, depopulated, and hardly accessible, it is reasonably expected that this work will raise more questions than answer. As a result of that, some considerations and recommendations for future research will be given.

Most of the studied caves are located in Vitačevo Plateau and along Crna Reka Valley and its main tributaries, leaving the Triassic limestones and dolomites on Dren Mountain (mainly Orle Mountain) and Kozjak Mountain as the least studied karst areas. Some caves are already known in these parts, and as these areas are the least accessible part of the river basin, future efforts should be made to document and study karst and caves in the Triassic carbonate sections.

Dating of caves has been done in only two studied caves: in Provalata Cave using $^{40}Ar/^{39}Ar$ method on speleogenetic alunite and jarosite, and in Budimirica Cave on clastic sediments using paleomagnetic method, with also preliminary $^{234}U/^{238}U$ dating on flowstone speleothems. They represent the first cave dating efforts in Republic of Macedonia. In all other caves, chronological interpretations were made based on speleogenetic evolution and correlation with geomorphological and geological evolution. Future dating of other caves will greatly increase the understanding of the rate of karst development and pinpoint some geomorphological markers especially connected to the Quaternary incision.

Considering the possibility of Messinian Salinity Crisis (MSC) influenced karst development as suggested in this study, expanding research to caves connected to Pliocene deposition in the neighboring basins to the north and south along the supposed marine gateway between the Aegean and Eastern Paratethys can be a reasonable step as such event would have regional influence on karst development.

Beside epigenic karst development, on which more work may be done in future, interesting subject may be more detail study of the hypogenic karst development in the area. In particular, interesting question remains the extent of ghost-rock weathering driven hypogenic karstification in the Precambrian dolomitic marbles between Melnica and Podot localities, and to which extent it influences karst development in these rocks, considering that no epigenic caves are found in the Precambrian dolomitic marbles. Another interesting question to be studied in future is the possibility of the coal deposit supplying sulfur for the sulfuric acid speleogenesis in Provalata Cave.



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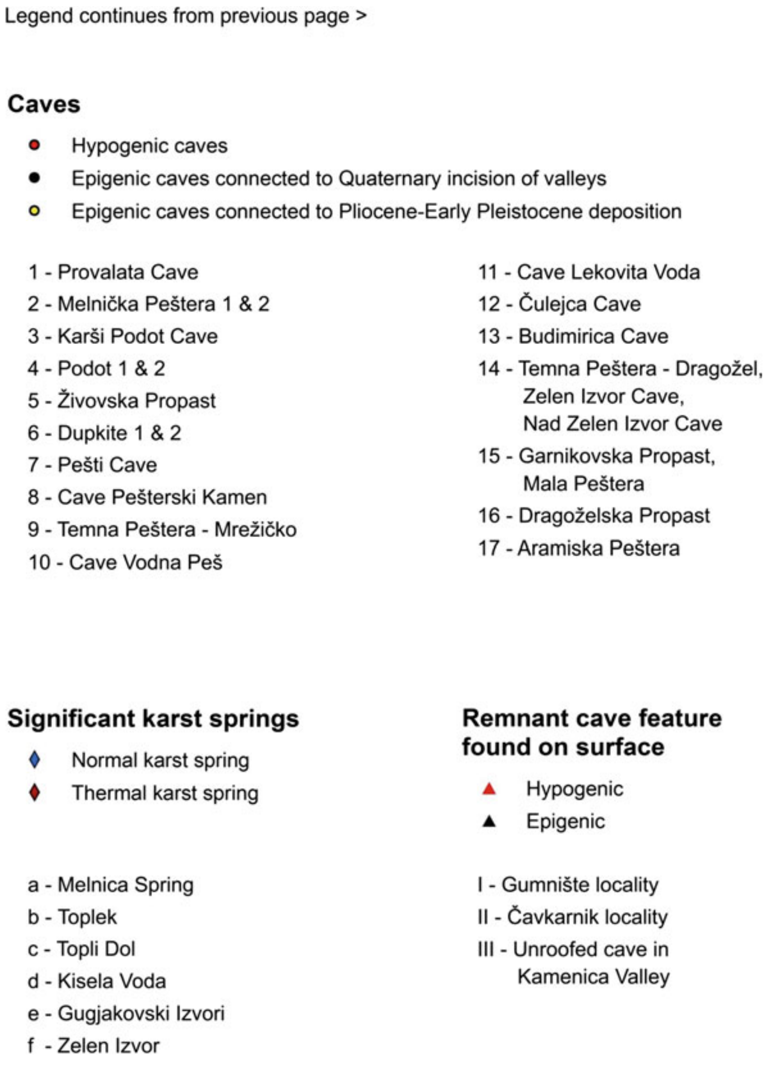

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Caves

- 🔴 Hypogenic caves
- ● Epigenic caves connected to Quaternary incision of valleys
- 🟡 Epigenic caves connected to Pliocene-Early Pleistocene deposition

1 - Provalata Cave
2 - Melnička Peštera 1 & 2
3 - Karši Podot Cave
4 - Podot 1 & 2
5 - Živovska Propast
6 - Dupkite 1 & 2
7 - Pešti Cave
8 - Cave Pešterski Kamen
9 - Temna Peštera - Mrežičko
10 - Cave Vodna Peš
11 - Cave Lekovita Voda
12 - Čulejca Cave
13 - Budimirica Cave
14 - Temna Peštera - Dragožel, Zelen Izvor Cave, Nad Zelen Izvor Cave
15 - Garnikovska Propast, Mala Peštera
16 - Dragoželska Propast
17 - Aramiska Peštera

Significant karst springs

- 🔷 Normal karst spring
- ♦ Thermal karst spring

a - Melnica Spring
b - Toplek
c - Topli Dol
d - Kisela Voda
e - Gugjakovski Izvori
f - Zelen Izvor

Remnant cave feature found on surface

- 🔺 Hypogenic
- ▲ Epigenic

I - Gumnište locality
II - Čavkarnik locality
III - Unroofed cave in Kamenica Valley

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Appendix A
Cave Maps

See Figs. A.1, A.2, A.3, A.4, A.5, A.6, A.7, A.8, A.9, A.10, A.11, A.12, A.13, A.14, A.15, A.16, A.17, A.18, A.19, A.20, A.21, A.22, A.23, A.24, A.25, A.26, A.27, A.28, A.29, A.30, A.31, A.32 and A.33.

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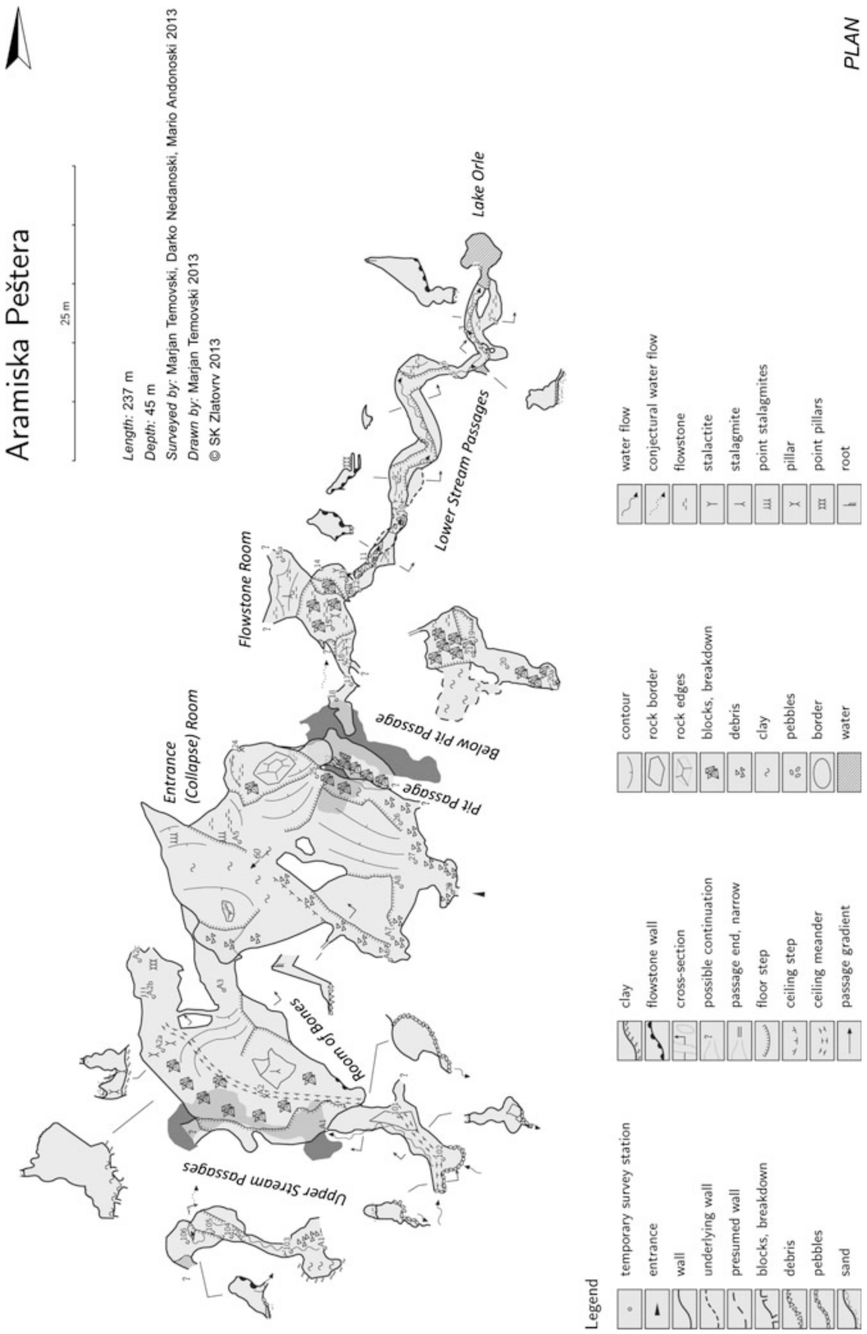


Fig. A.1 Aramiska Peštera—plan

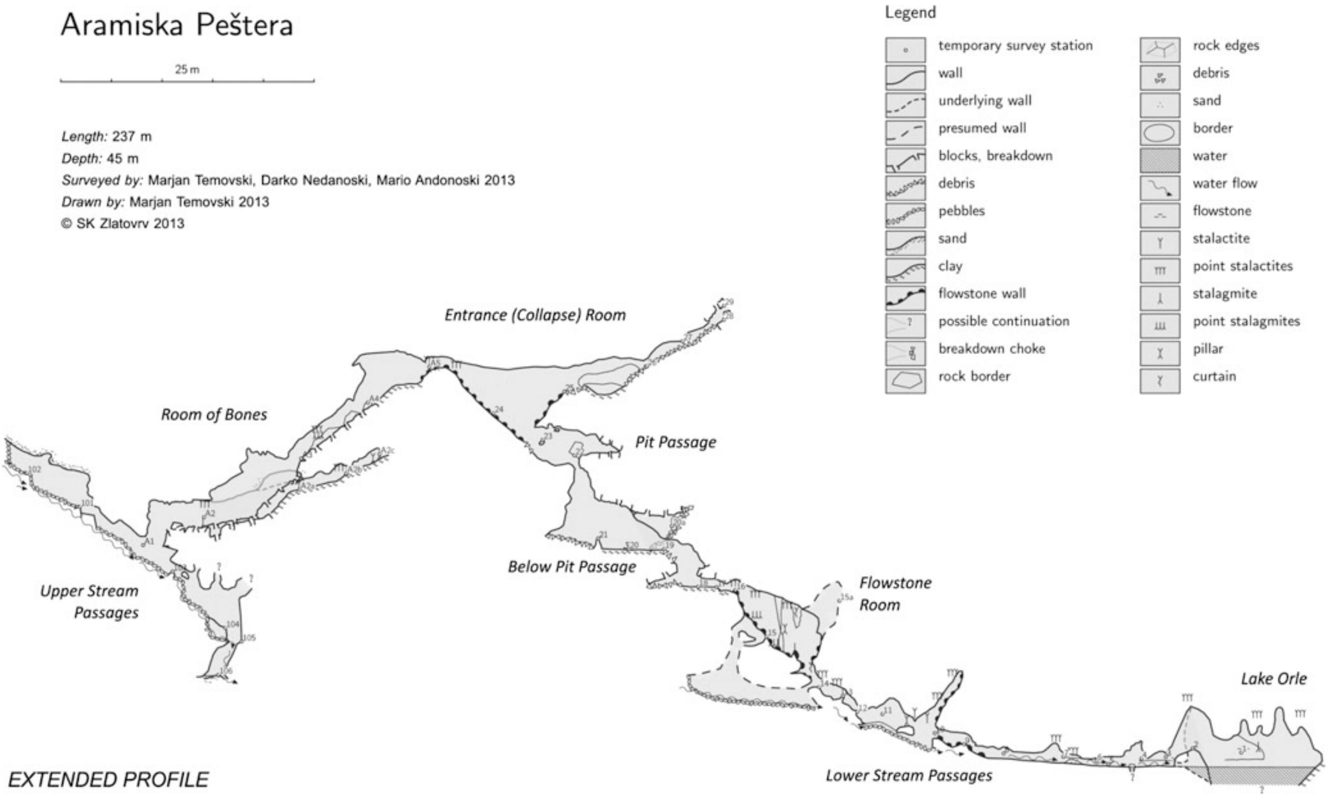


Fig. A.2 Aramiska Peštera—extended profile

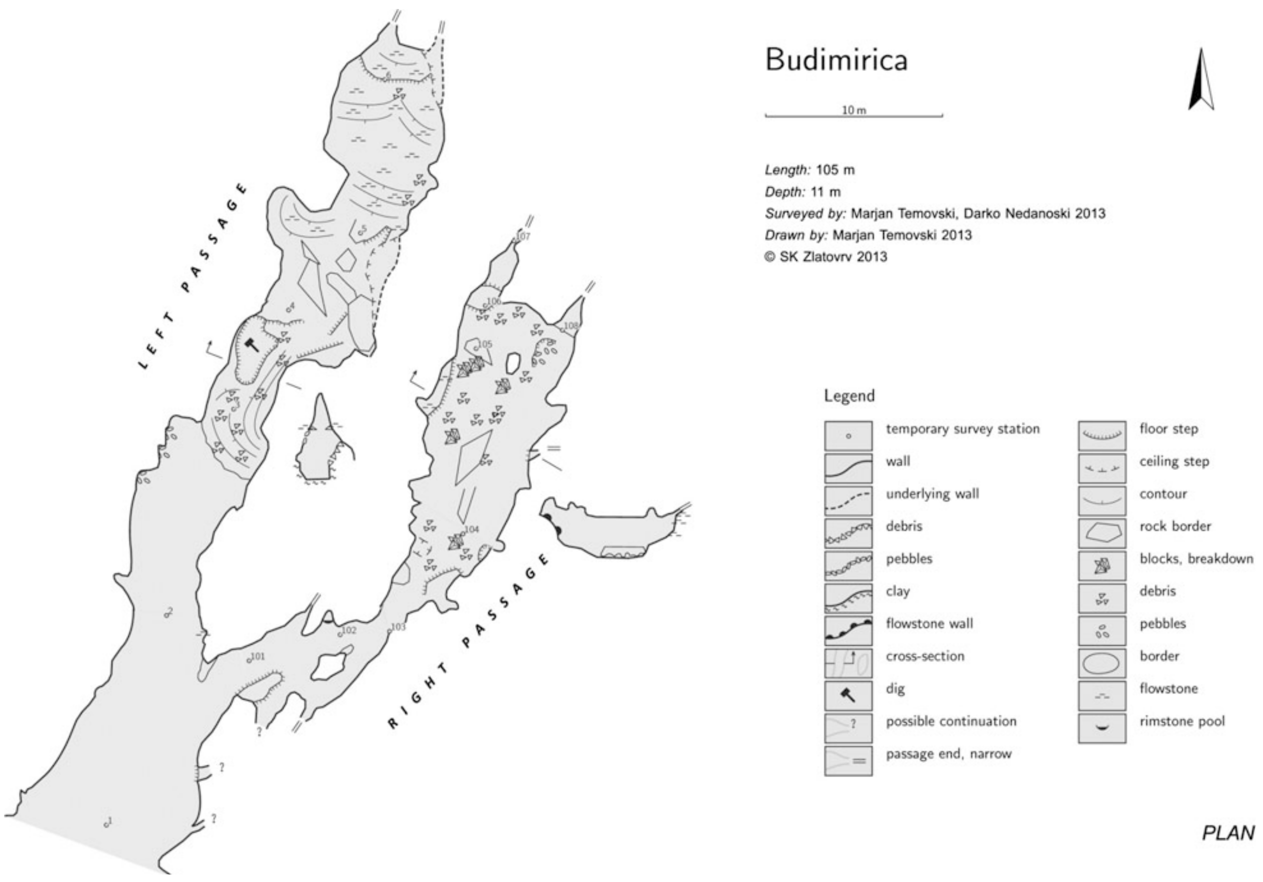


Fig. A.3 Budimirica Cave—plan

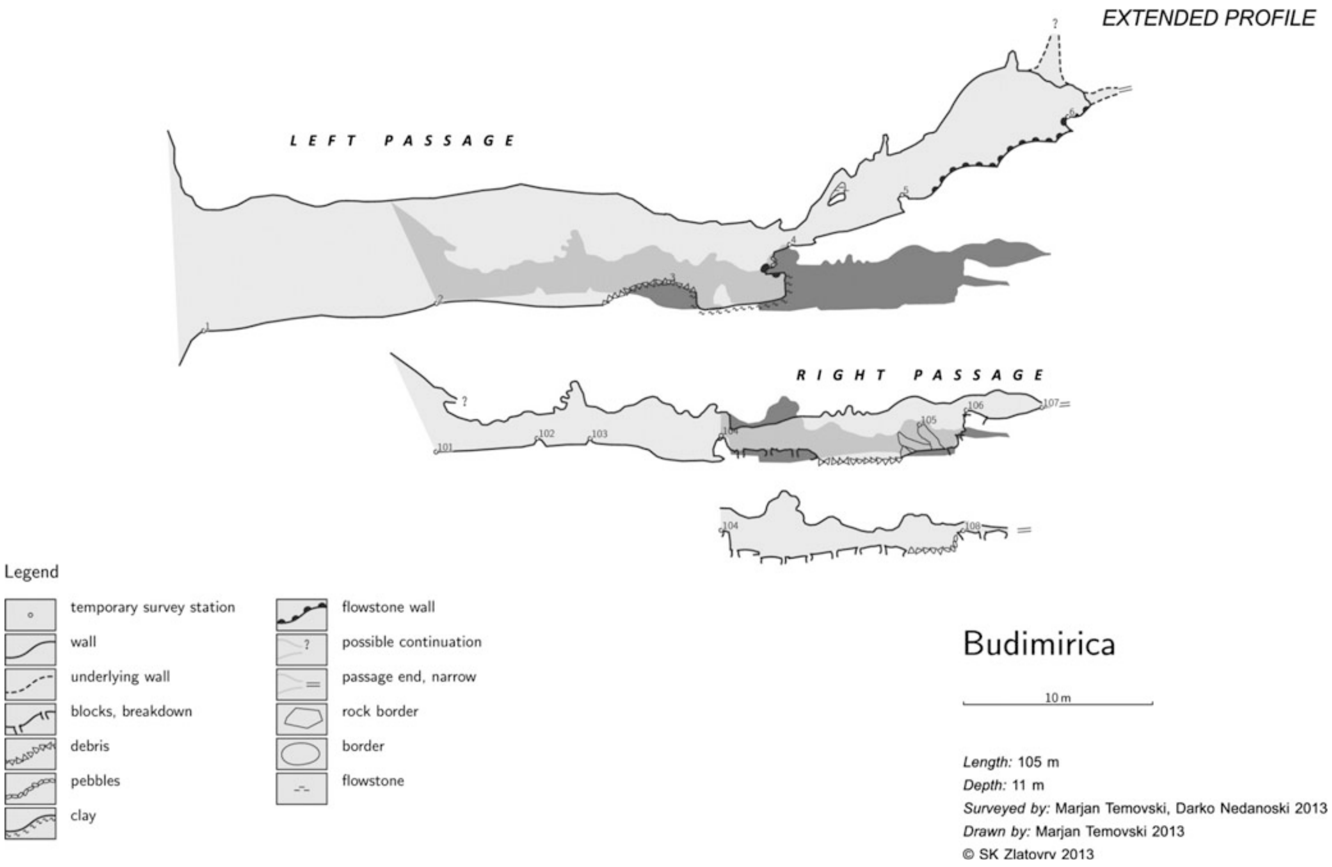


Fig. A.4 Budimirica Cave—extended profile

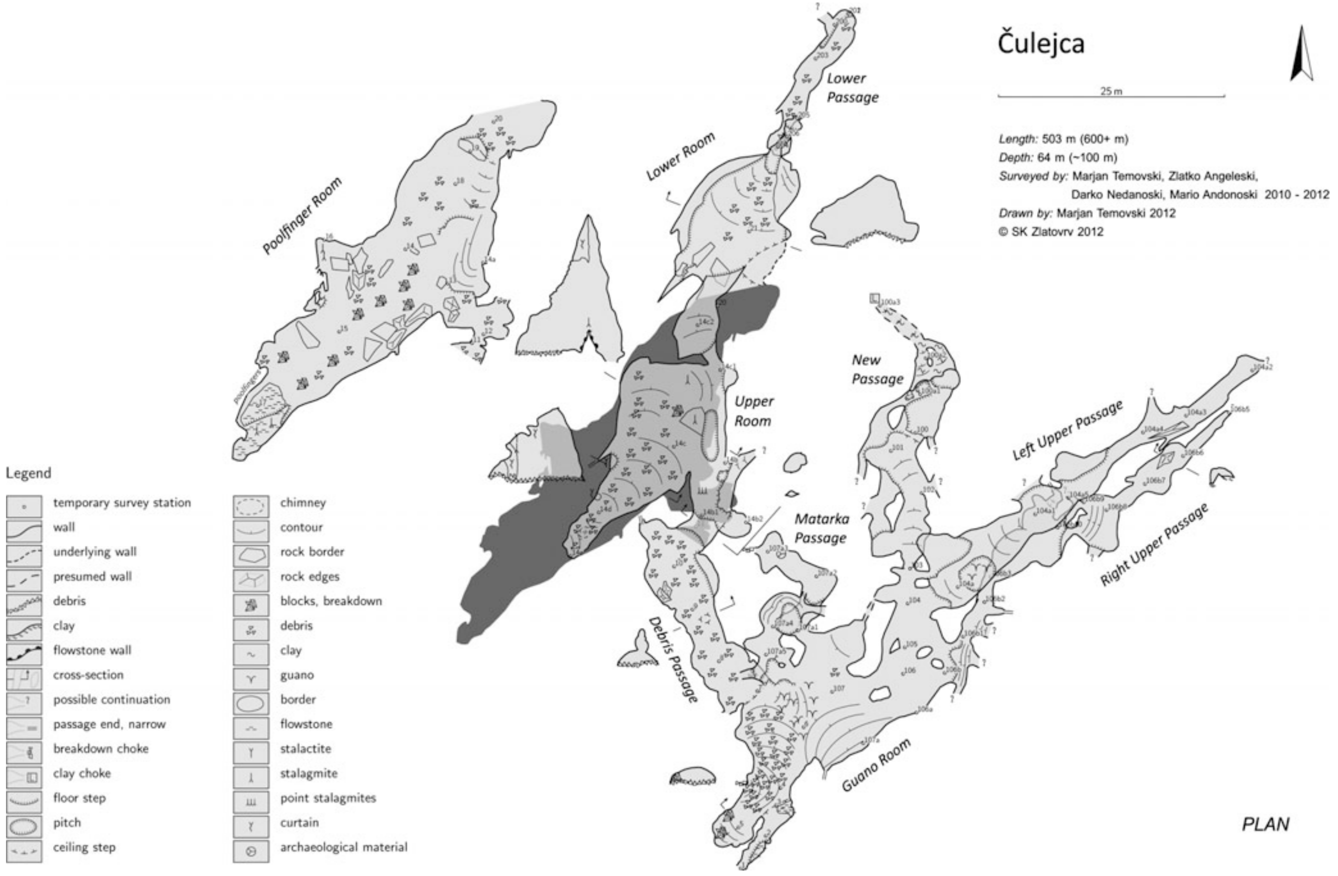


Fig. A.5 Čulejca Cave—plan

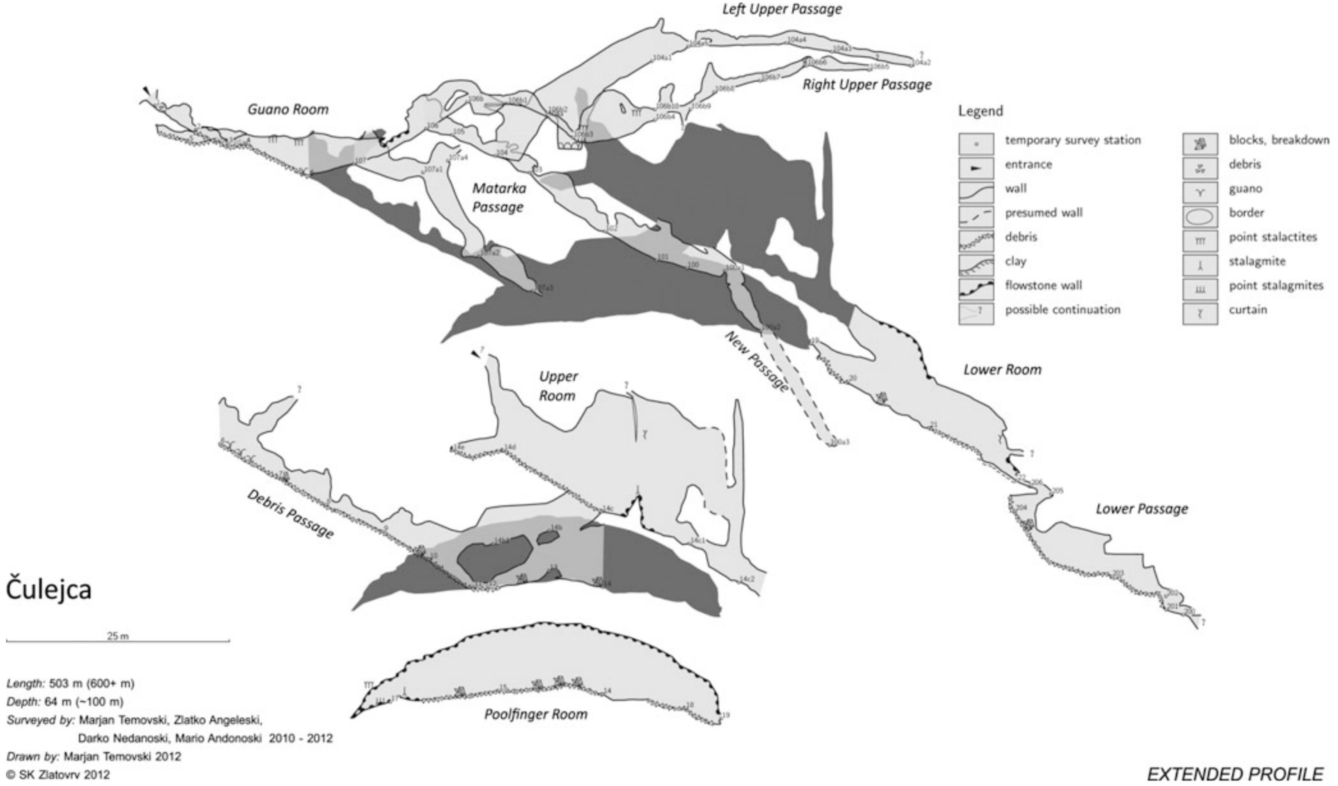


Fig. A.6 Čulejca Cave—extended profile

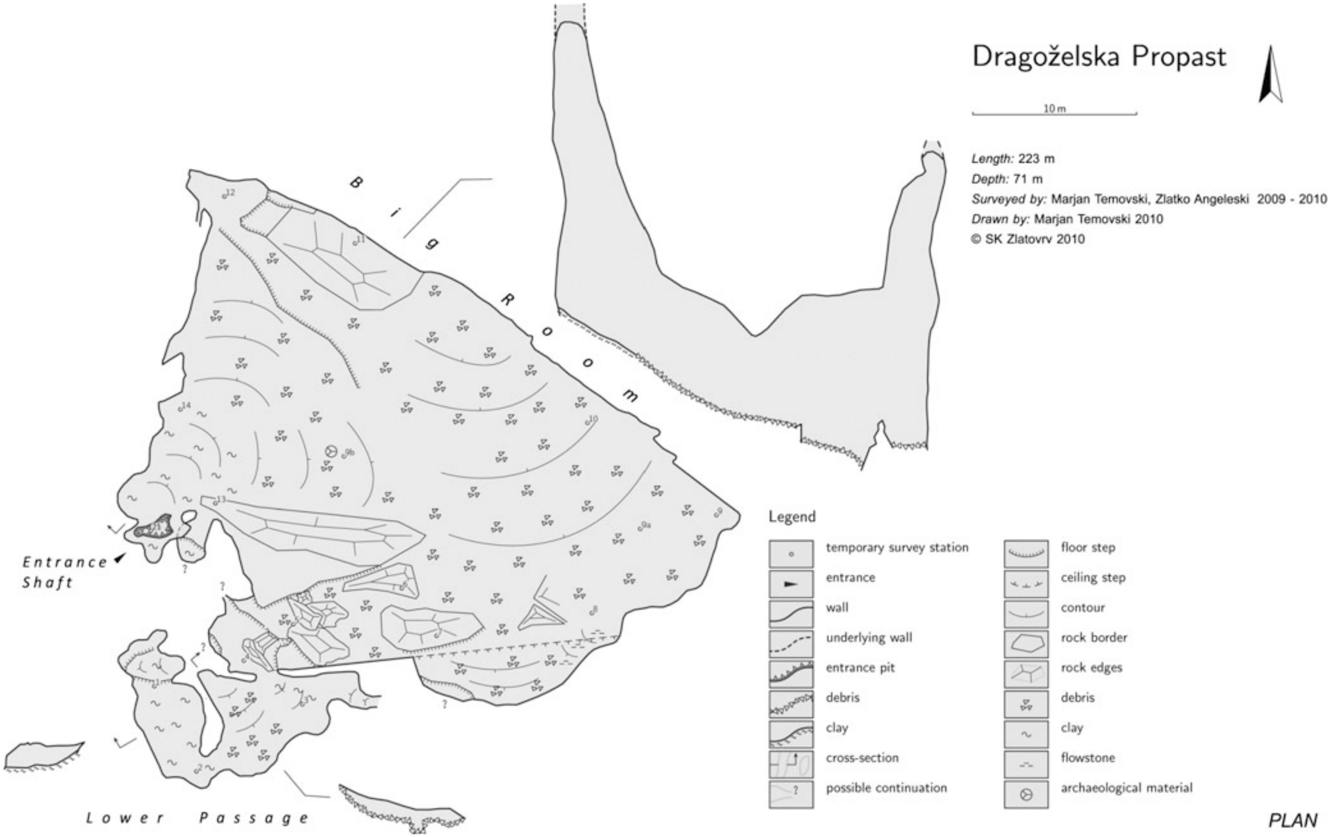


Fig. A.7 Dragoželska Propast—plan

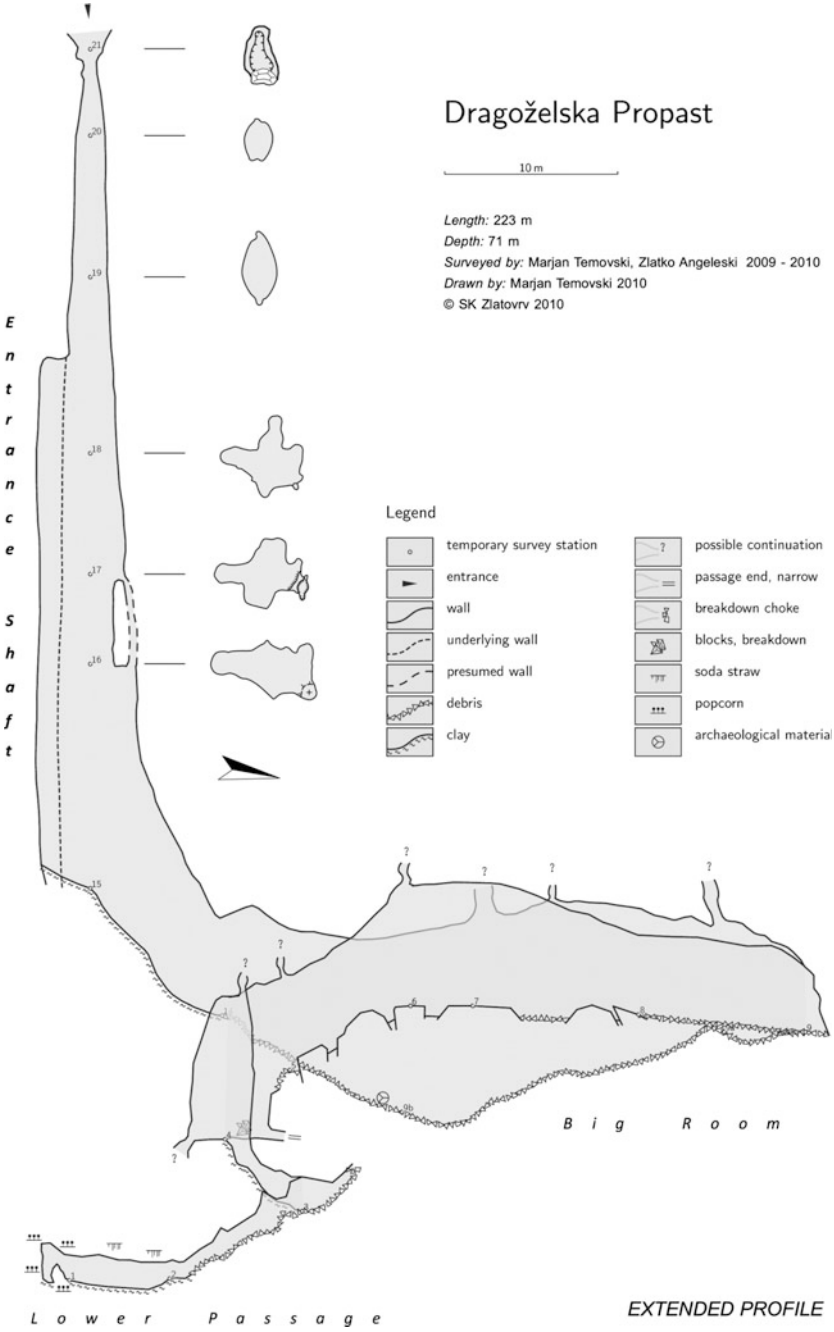


Fig. A.8 Dragoželska Propast—extended profile

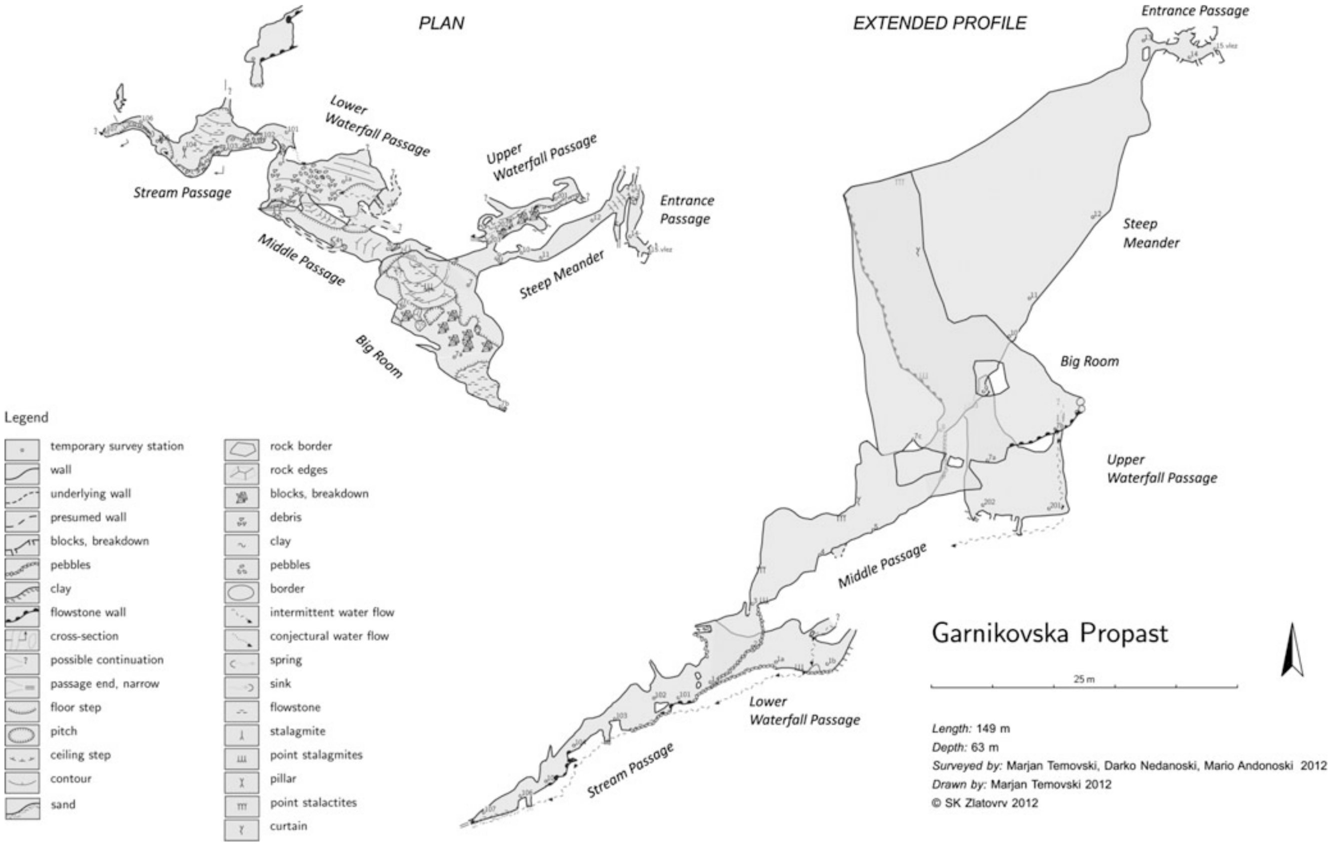


Fig. A.9 Garnikovska Propast—plan and extended profile

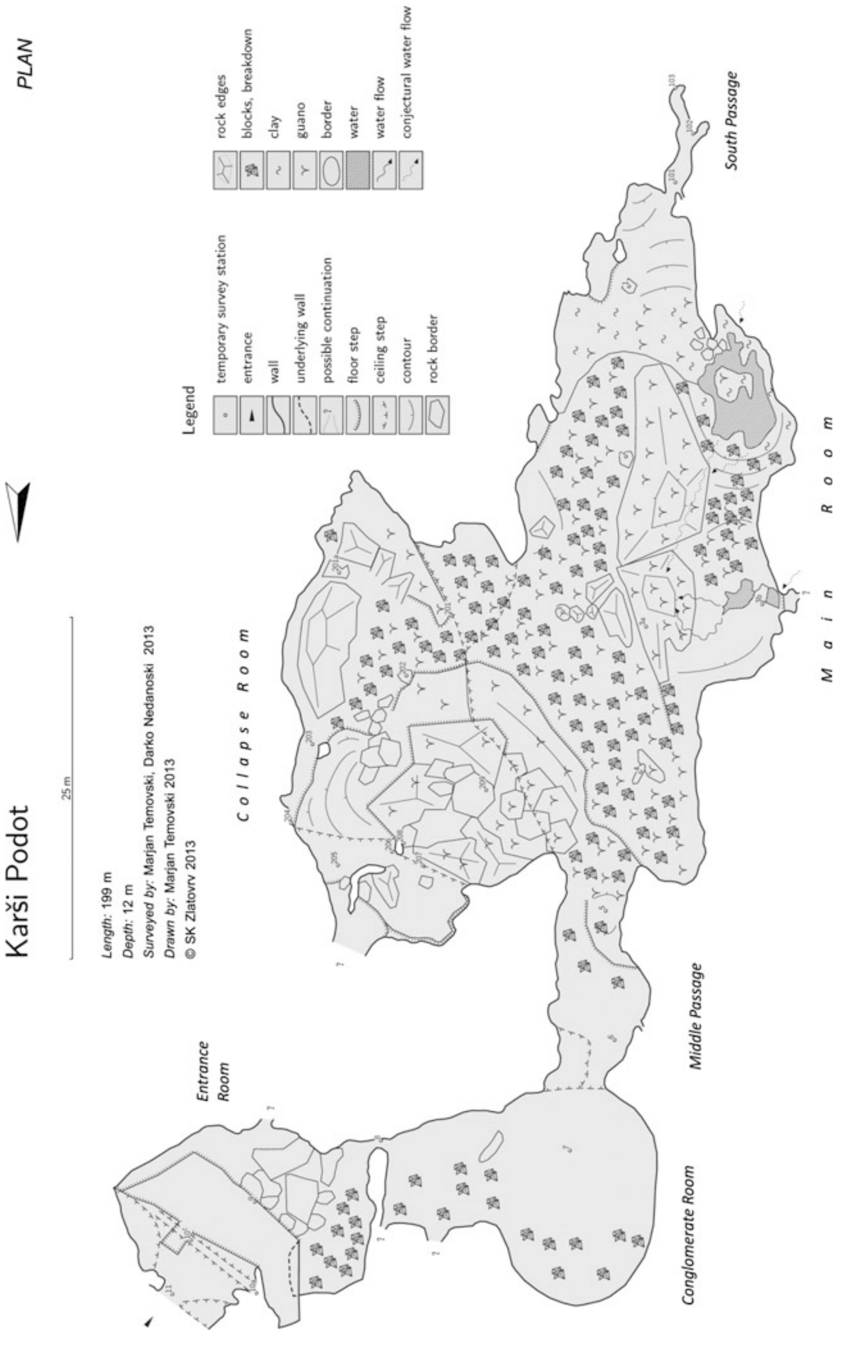


Fig. A.10 Karši Podot Cave—plan

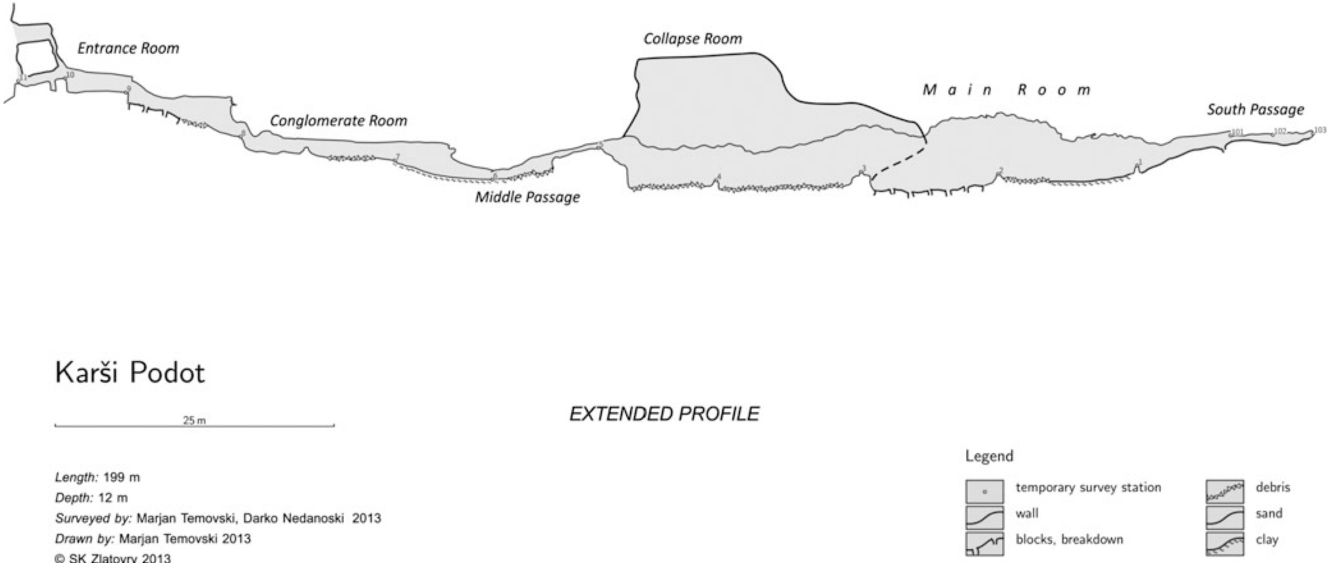


Fig. A.11 Karši Podot Cave—extended profile

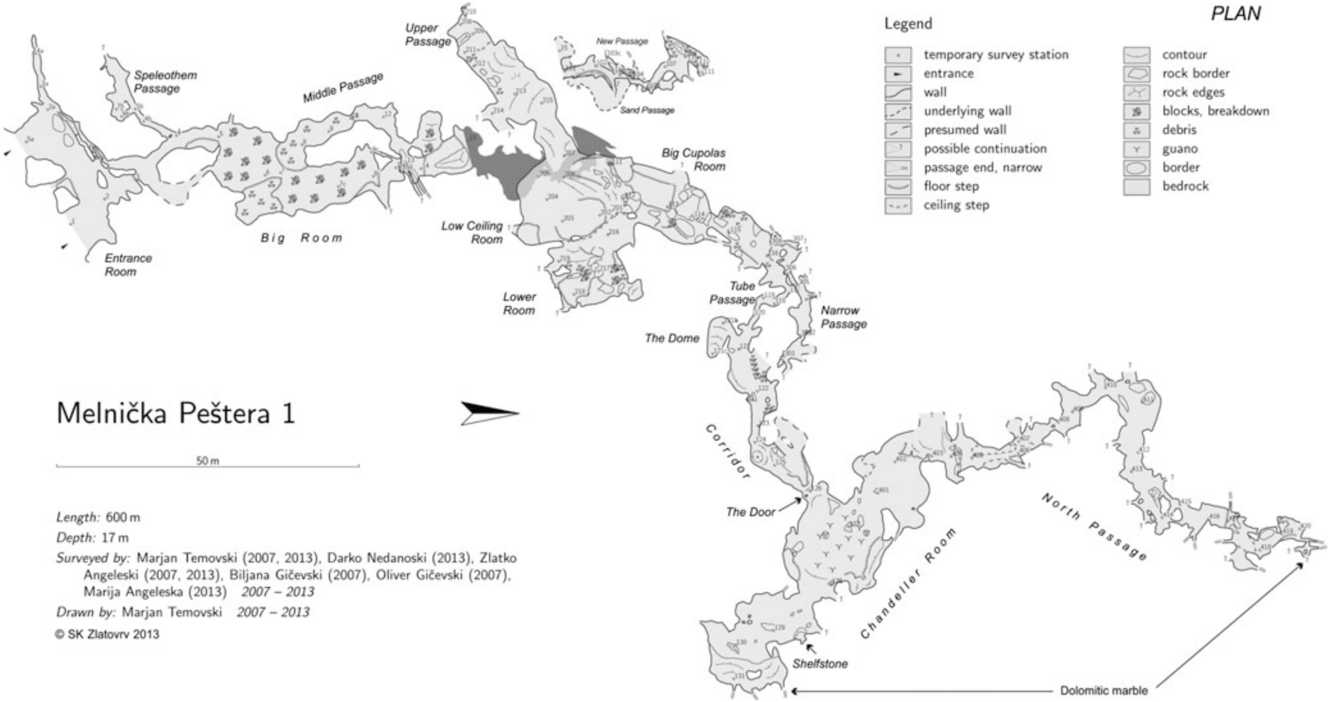


Fig. A.12 Melnička Peštera 1—plan

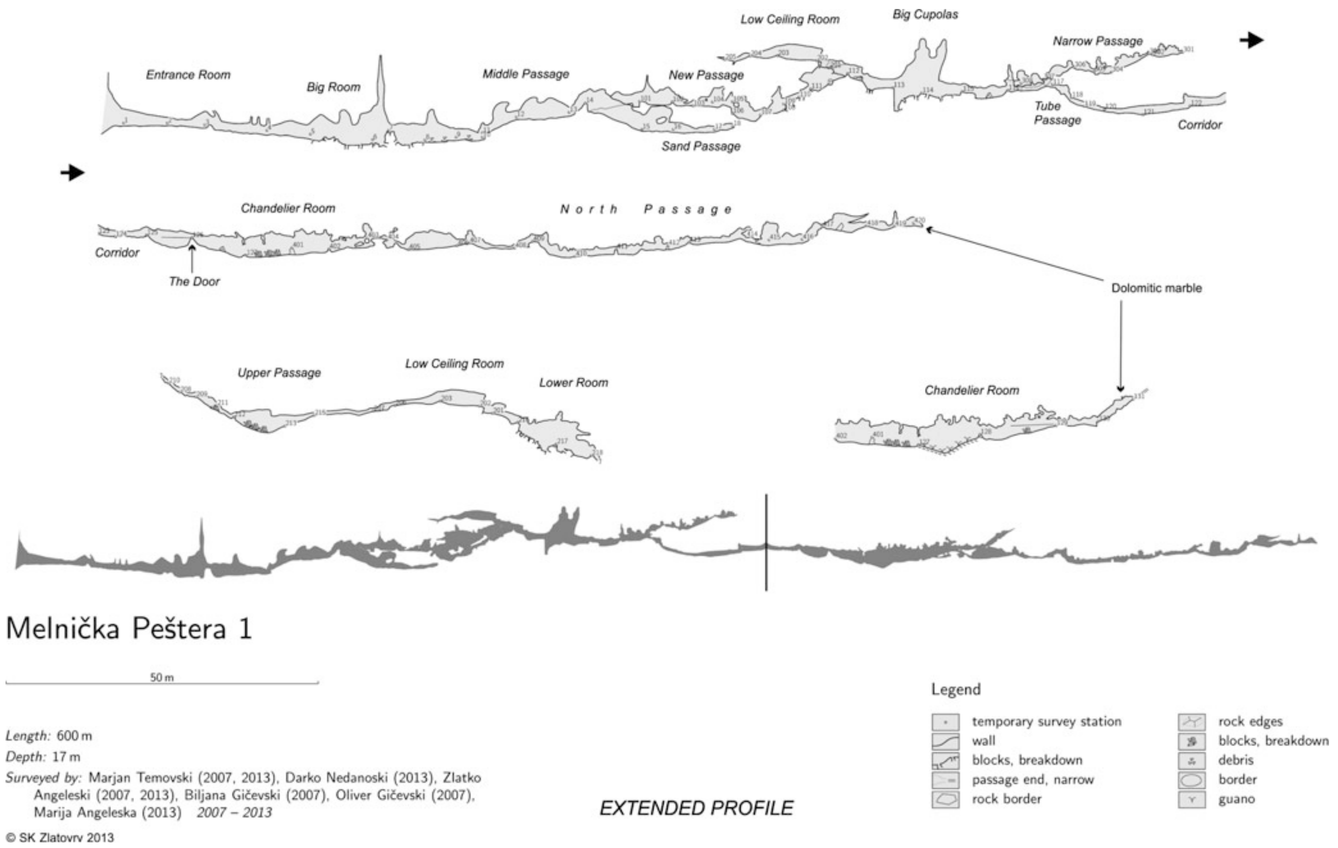


Fig. A.13 Melnička Peštera 1—extended profile

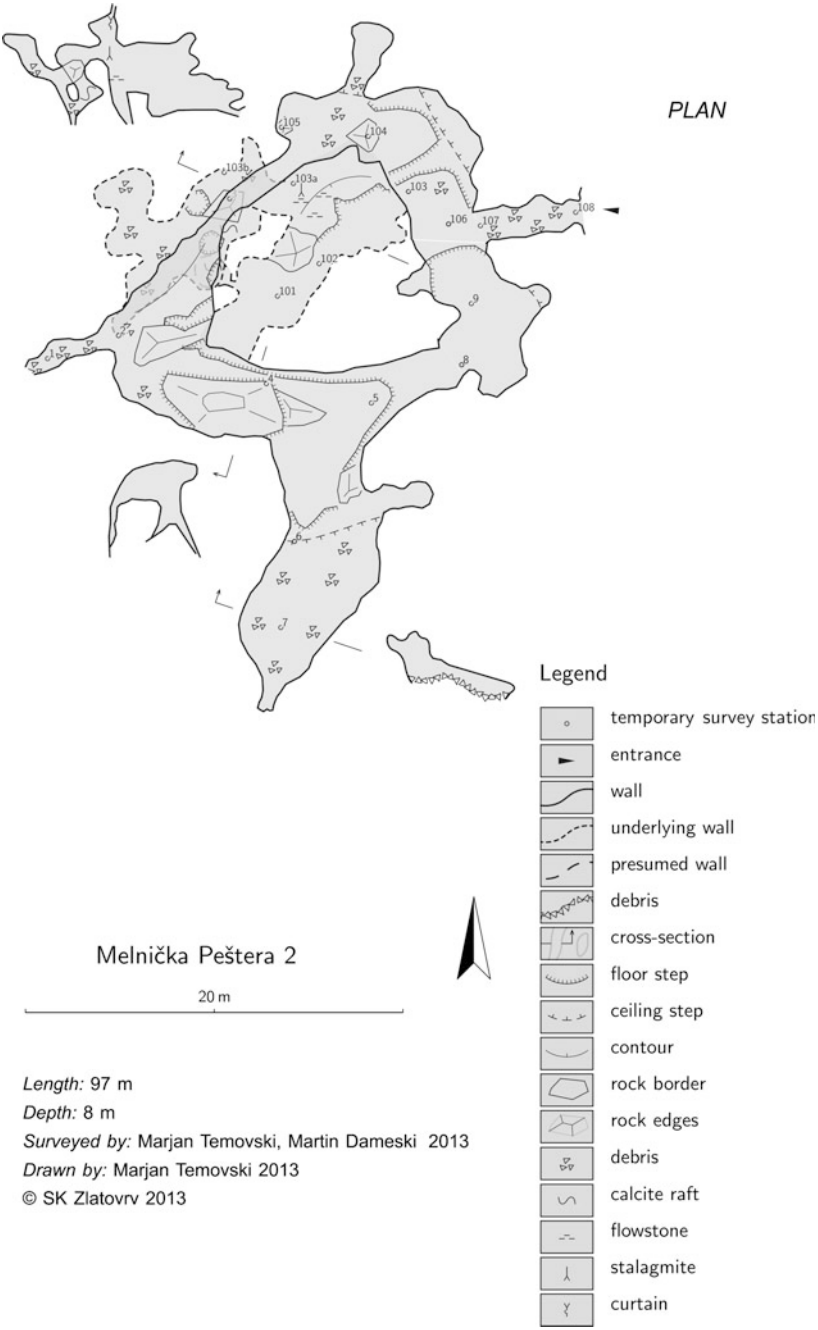


Fig. A.14 Melnička Peštera 2—plan

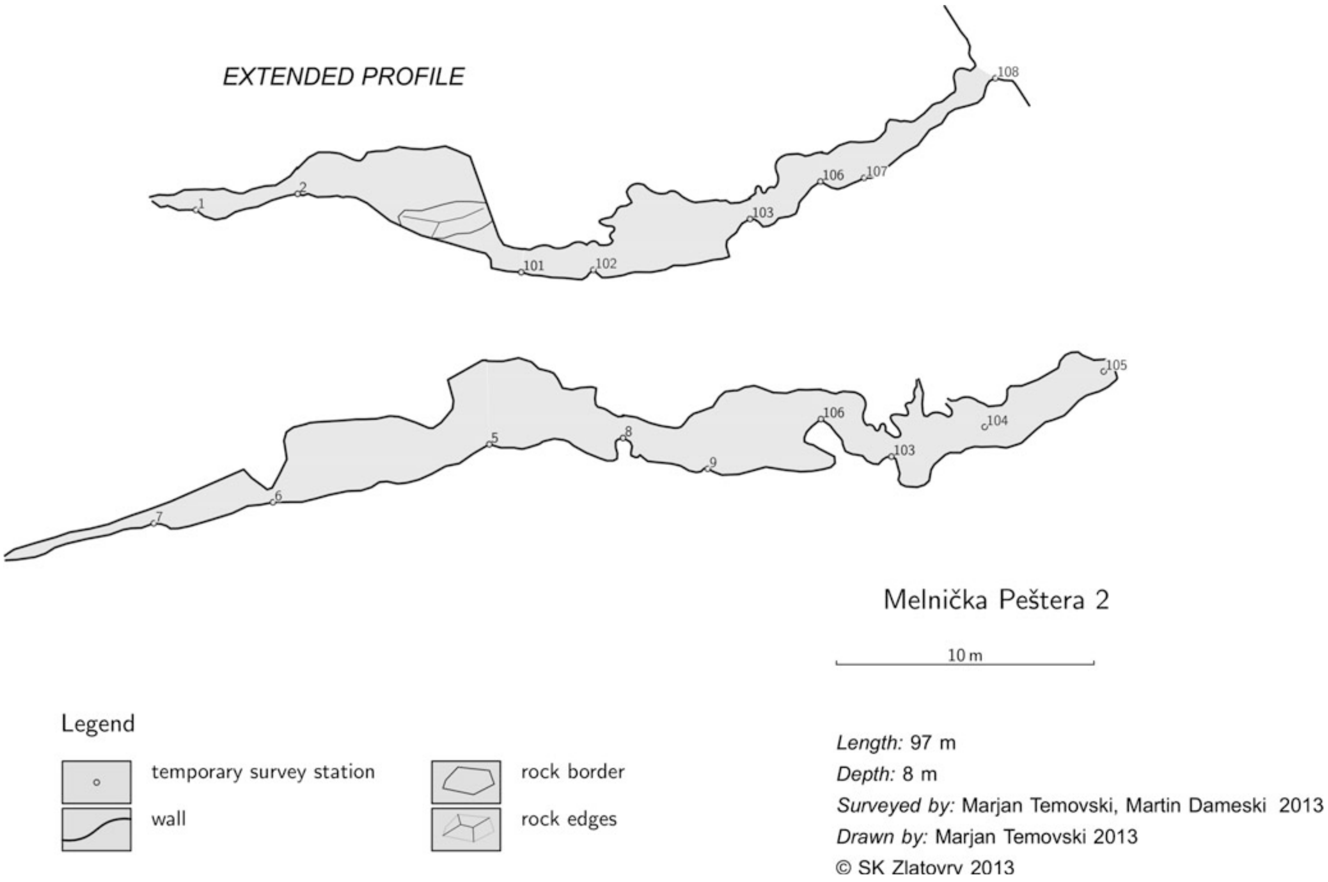


Fig. A.15 Melnička Peštera 2—extended profile

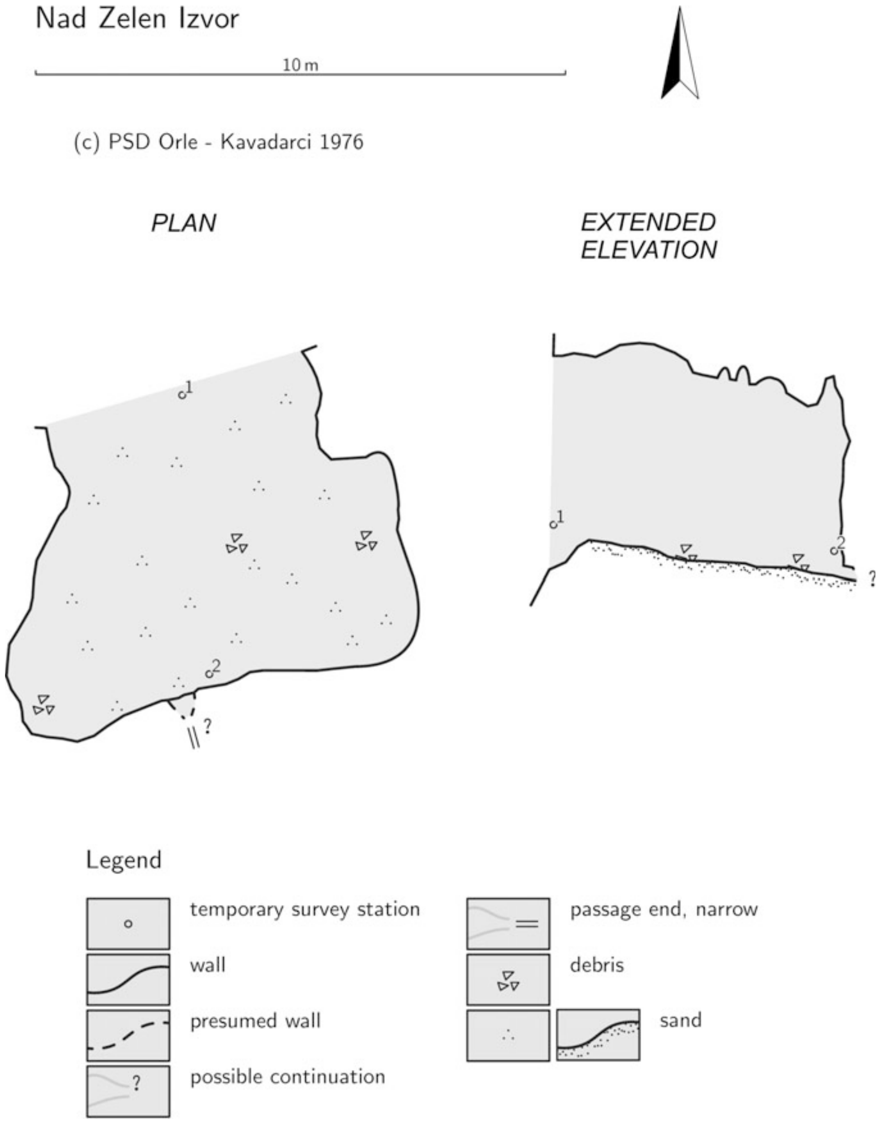


Fig. A.16 Nad Zelen Izvor—plan and extended profile

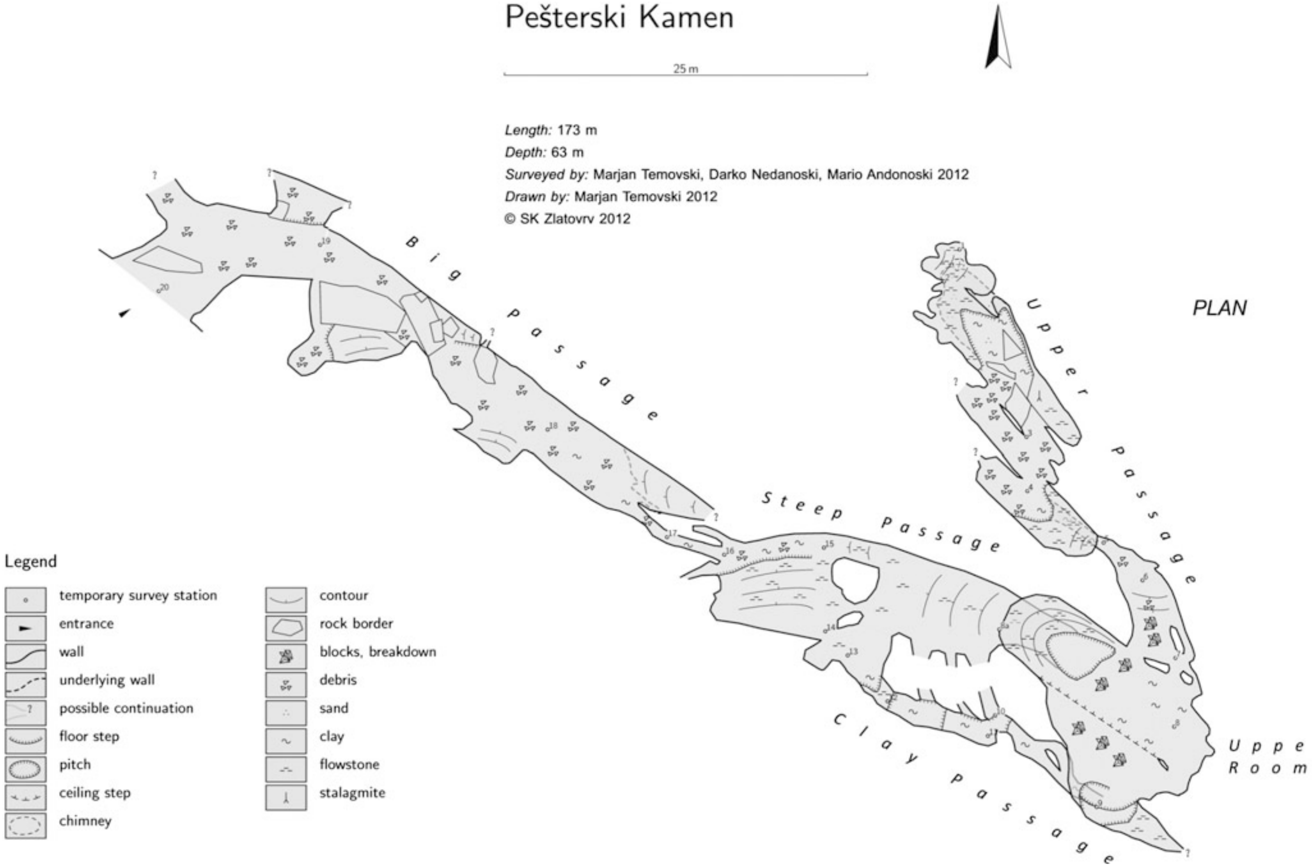


Fig. A.17 Pešterski Kamen—plan

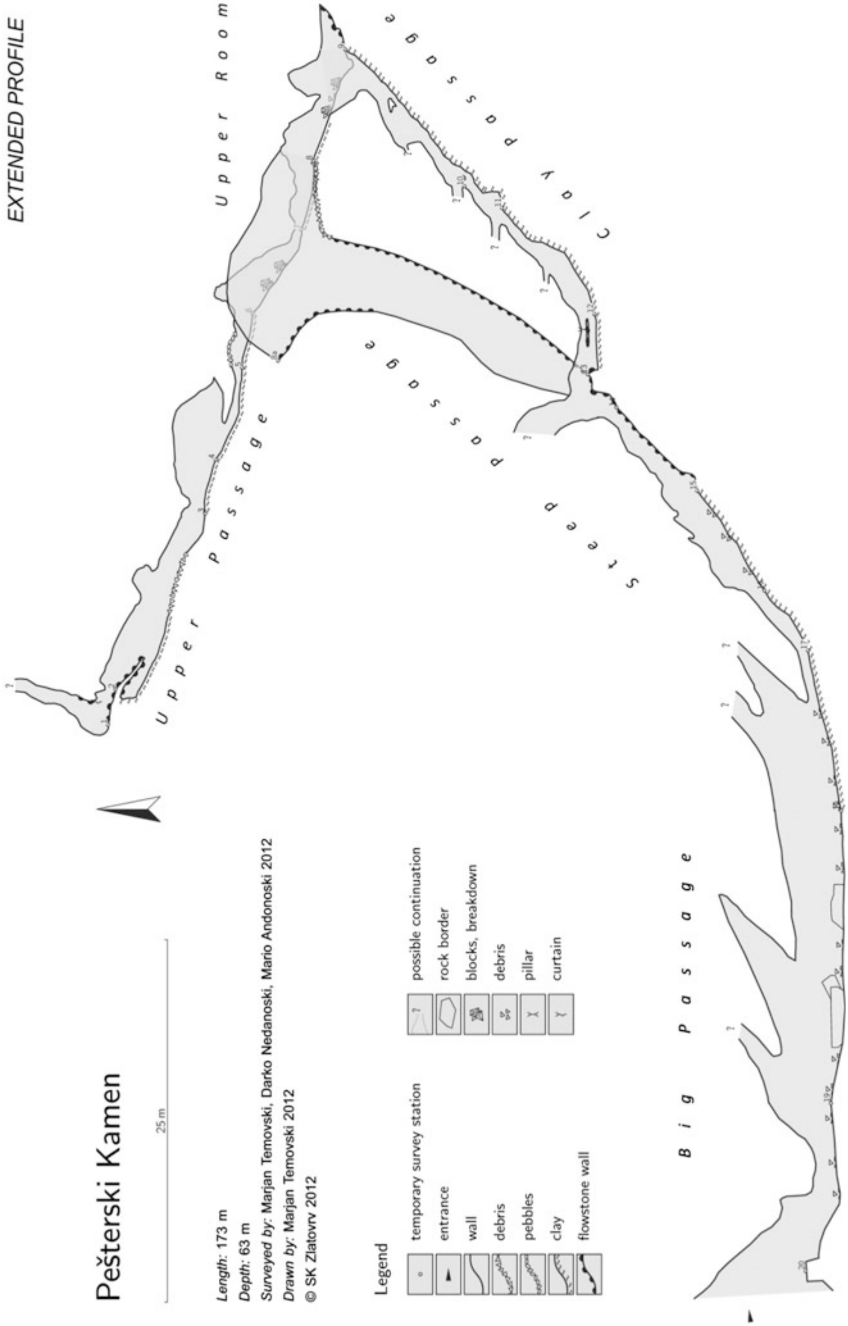


Fig. A.18 Pešterski Kamen—extended profile

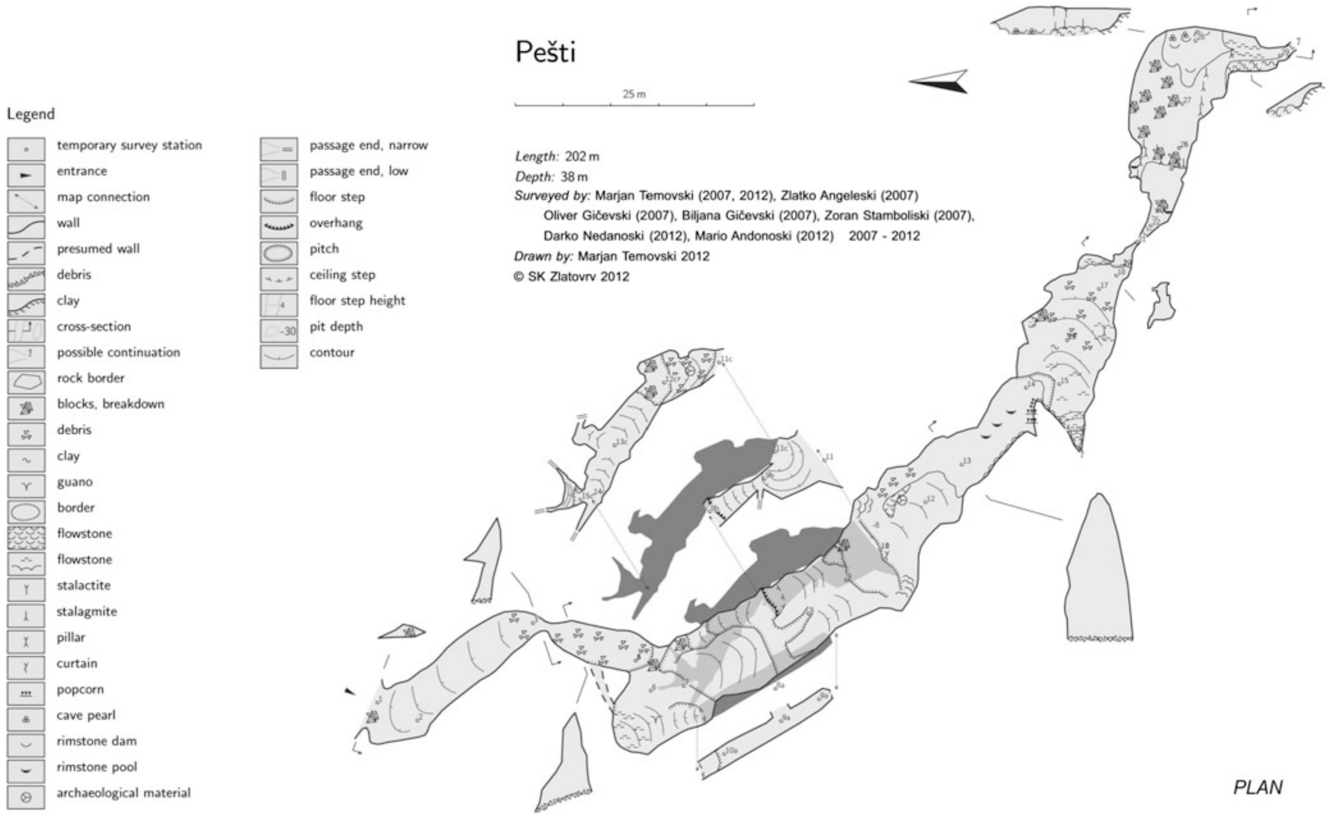


Fig. A.19 Pešti Cave—plan

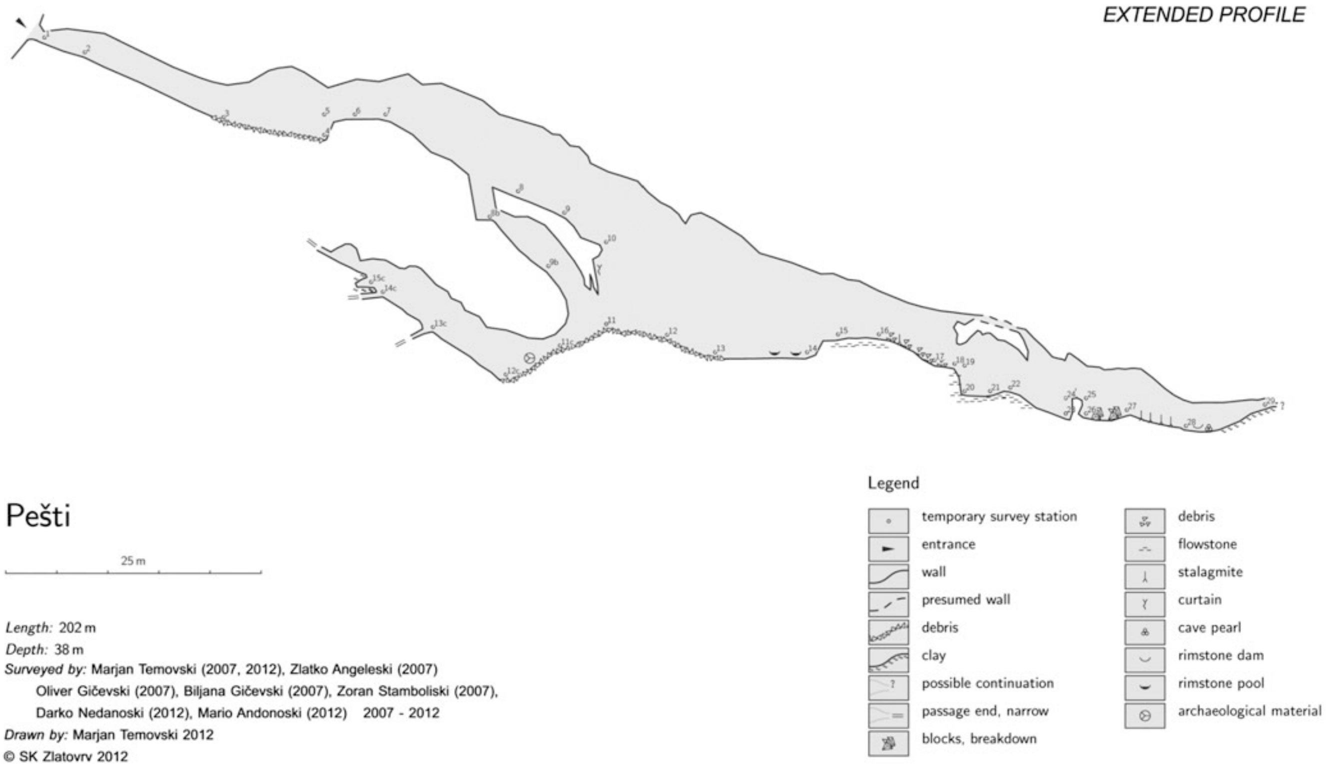


Fig. A.20 Pešti Cave—extended profile

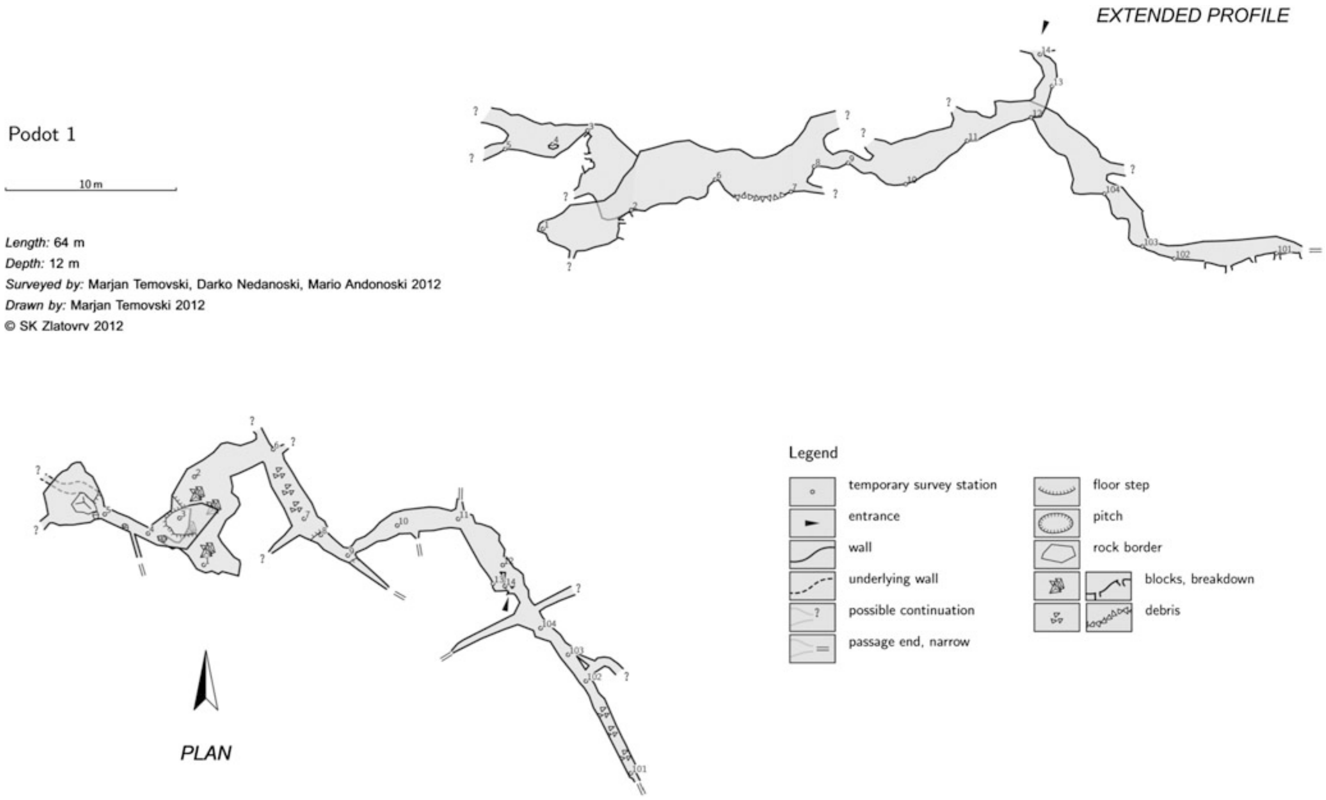


Fig. A.21 Podot 1—plan and extended profile

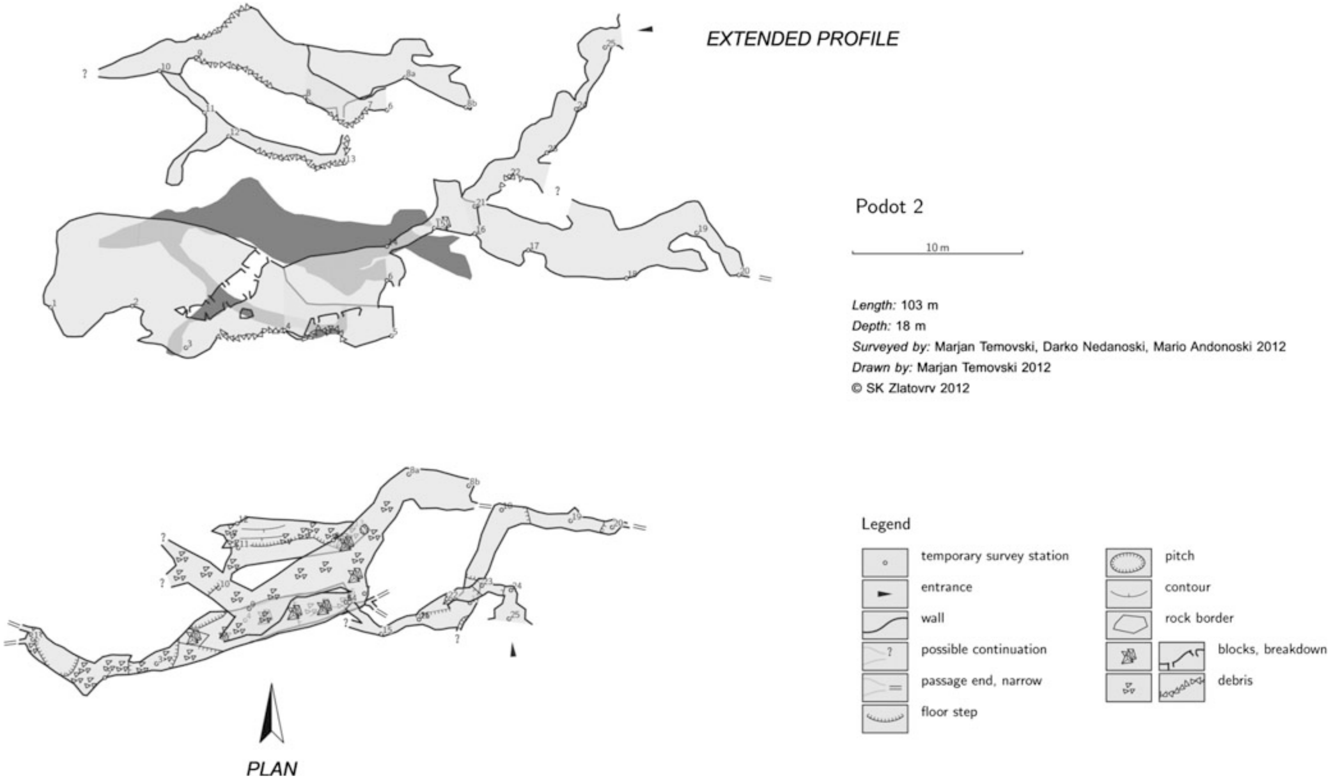


Fig. A.22 Podot 2—plan and extended profile

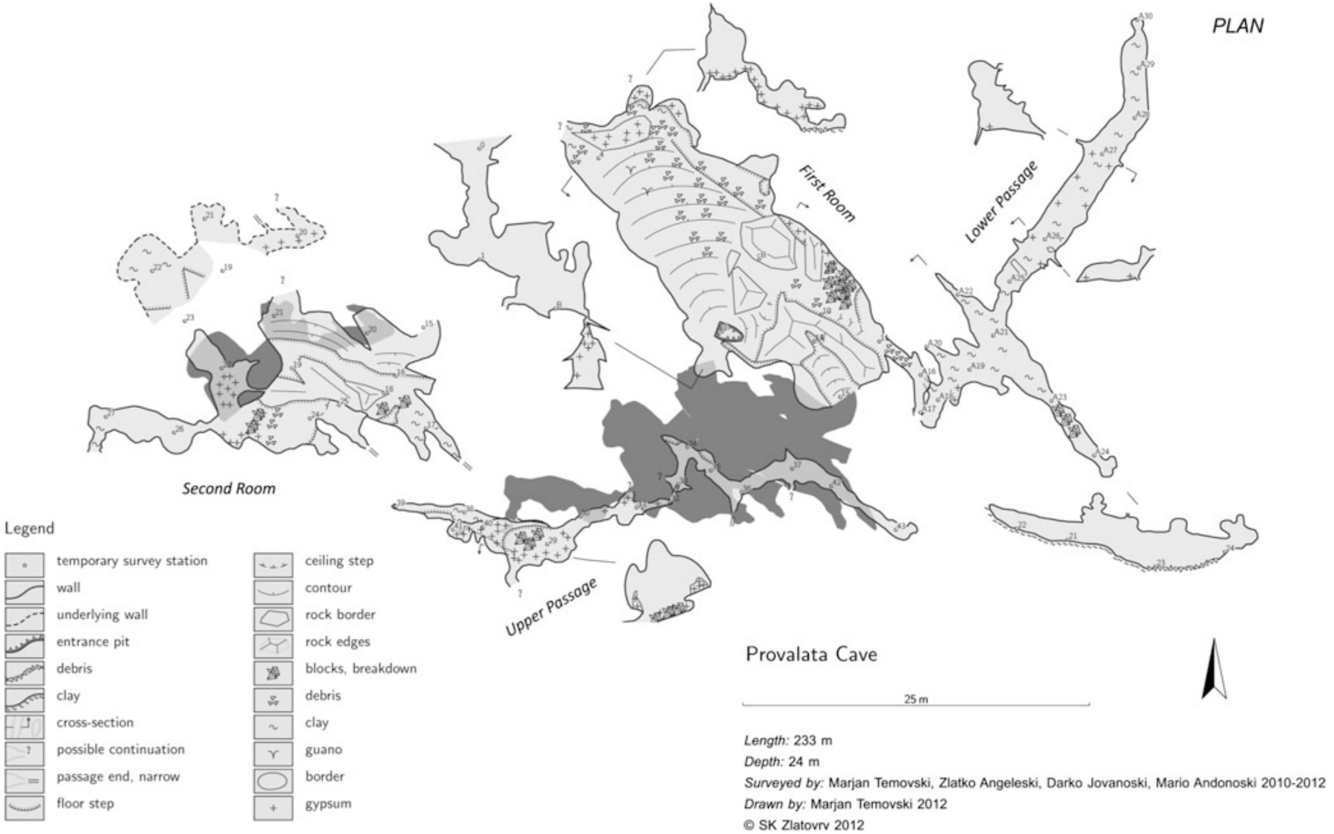


Fig. A.23 Provalata Cave—plan

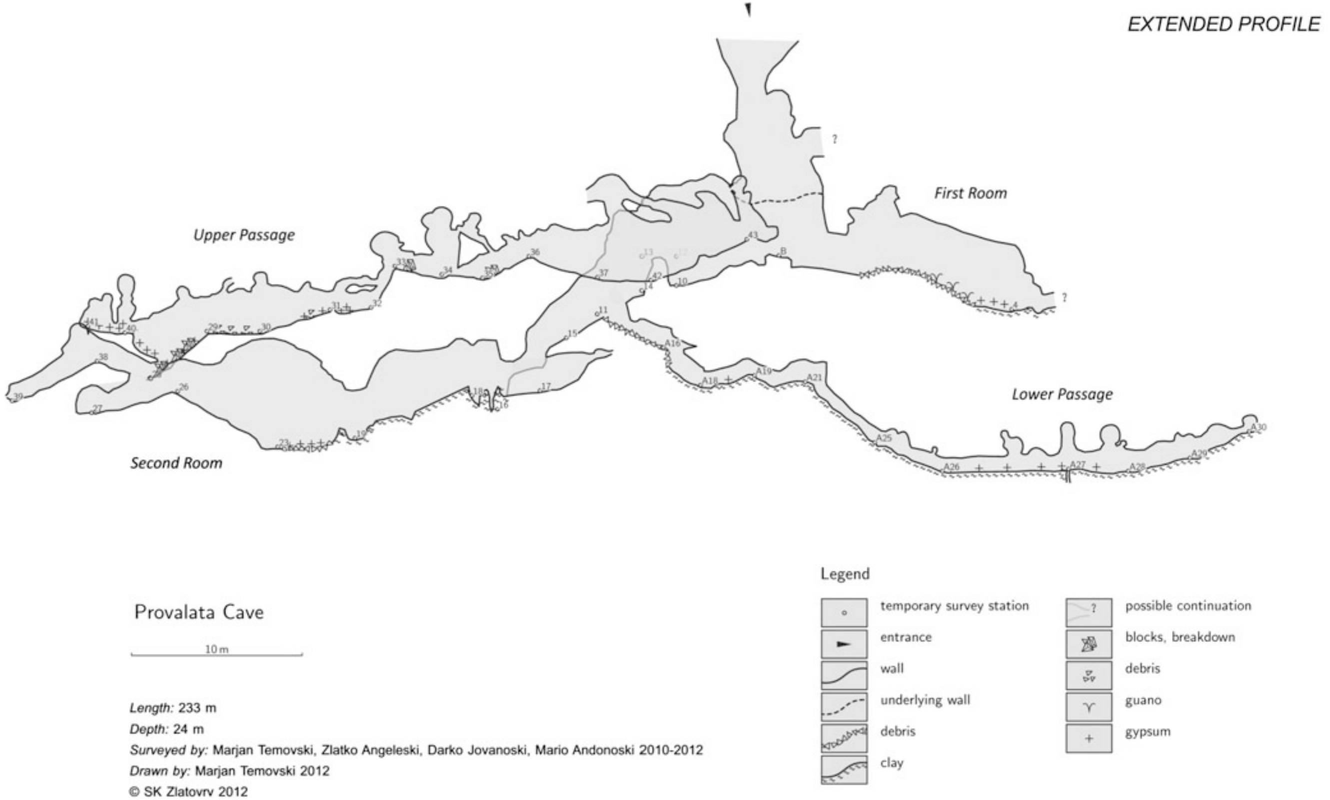


Fig. A.24 Provalata Cave—extended profile

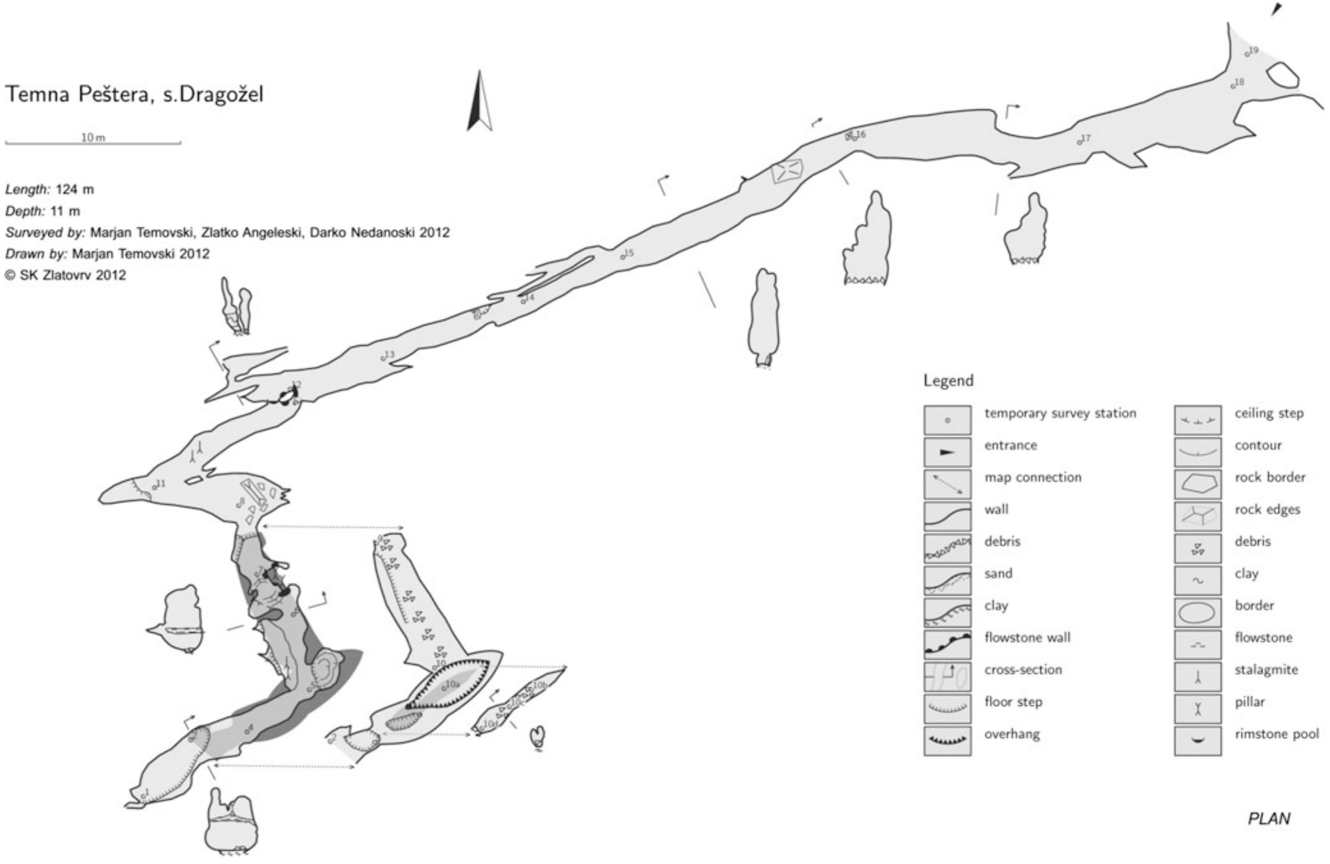


Fig. A.25 Temna Peštera–Dragožel—plan

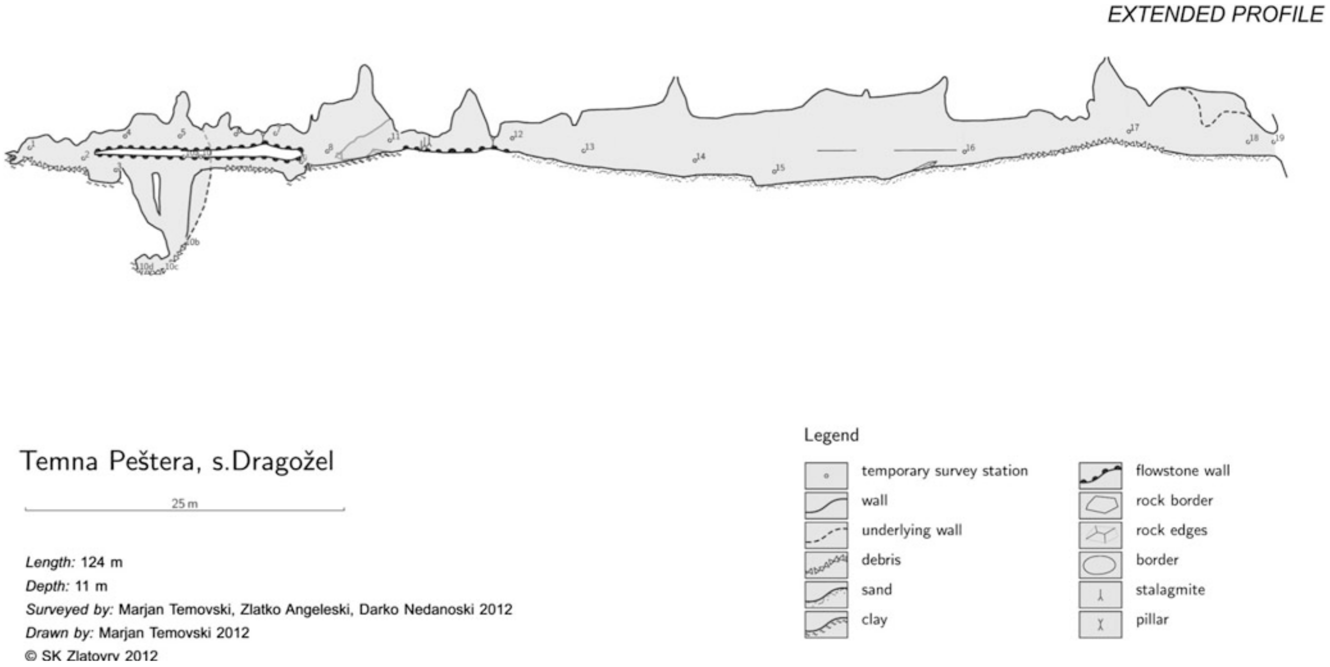


Fig. A.26 Temna Peštera–Dragožel—extended profile

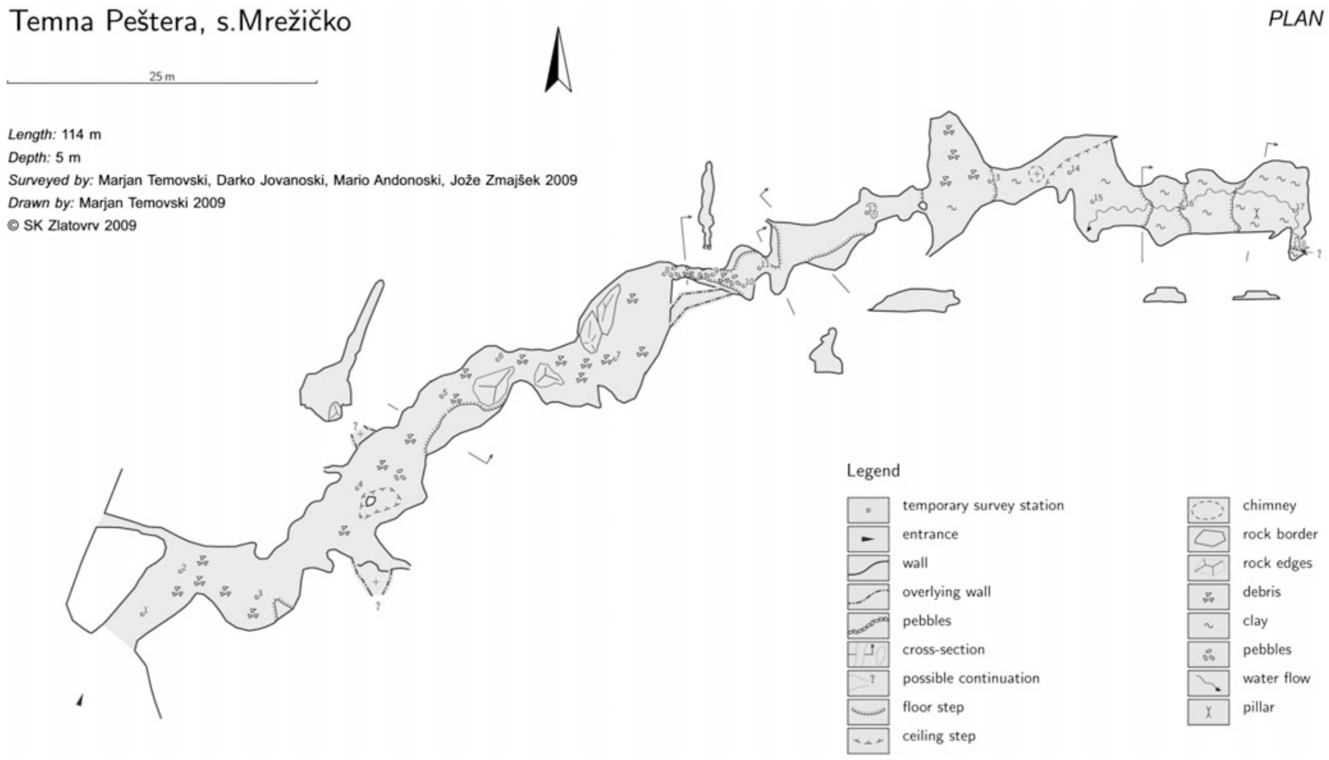


Fig. A.27 Temna Peštera–Mrežičko—plan

Fig. A.28 Temna Peštera–Mrežičko—extended profile

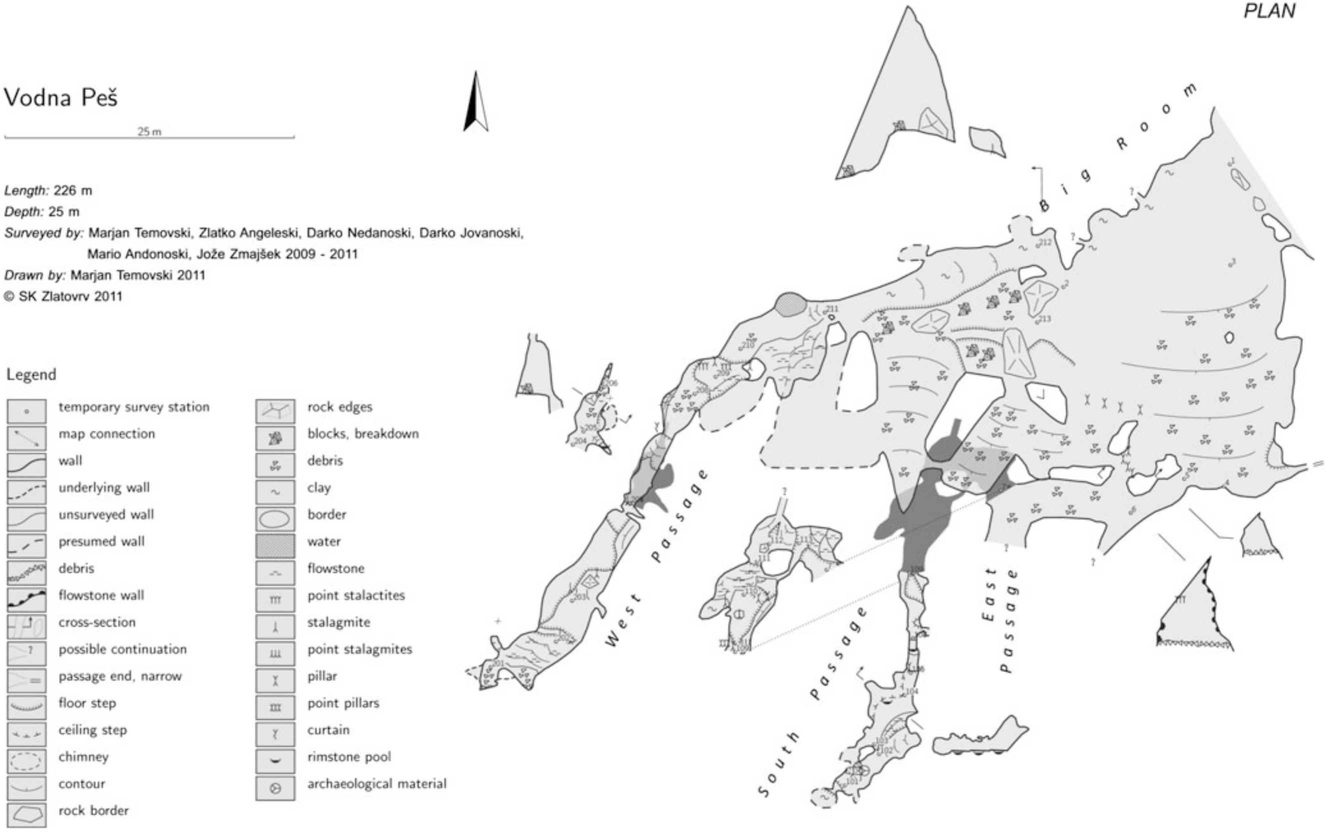


Fig. A.29 Vodna Peš—plan

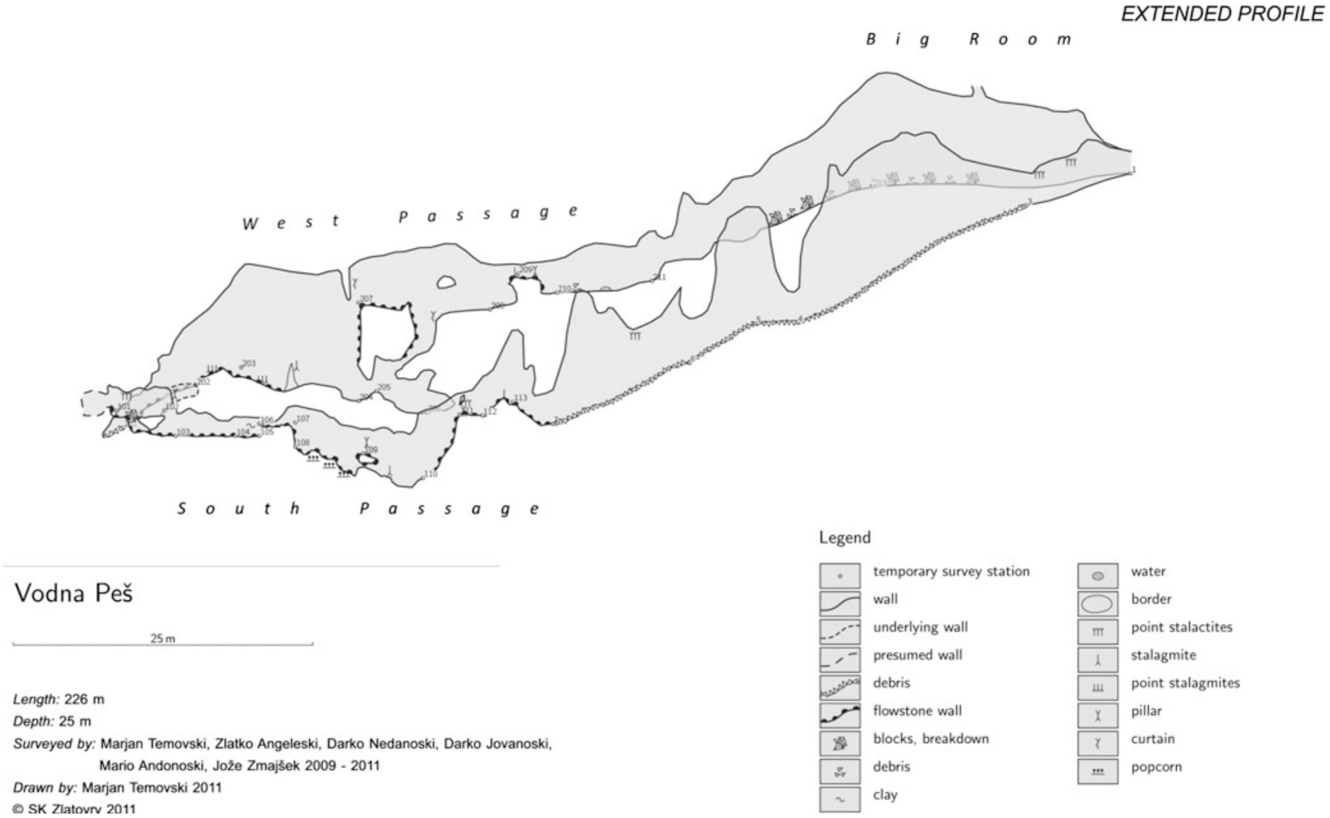


Fig. A.30 Vodna Peš—extended profile

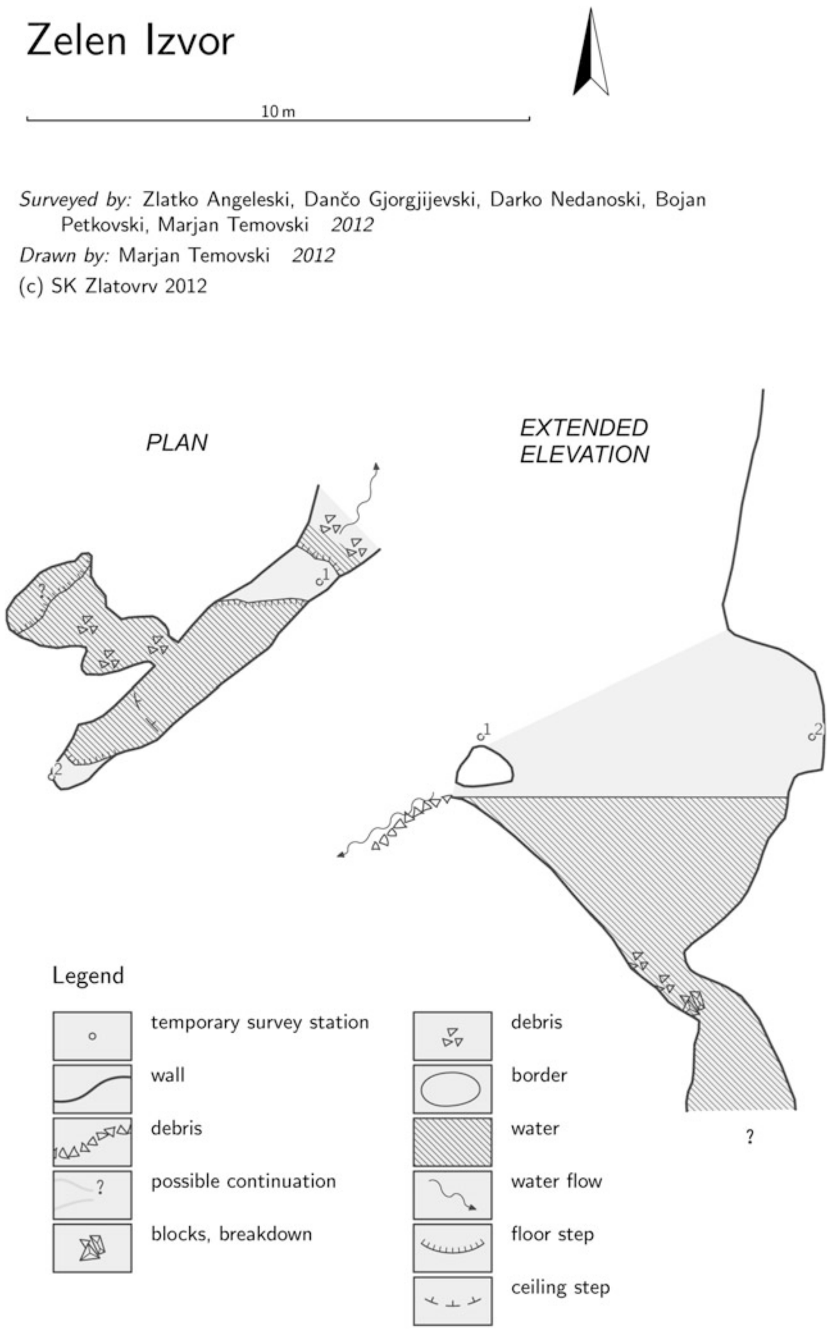


Fig. A.31 Zelen Izvor—plan and extended profile

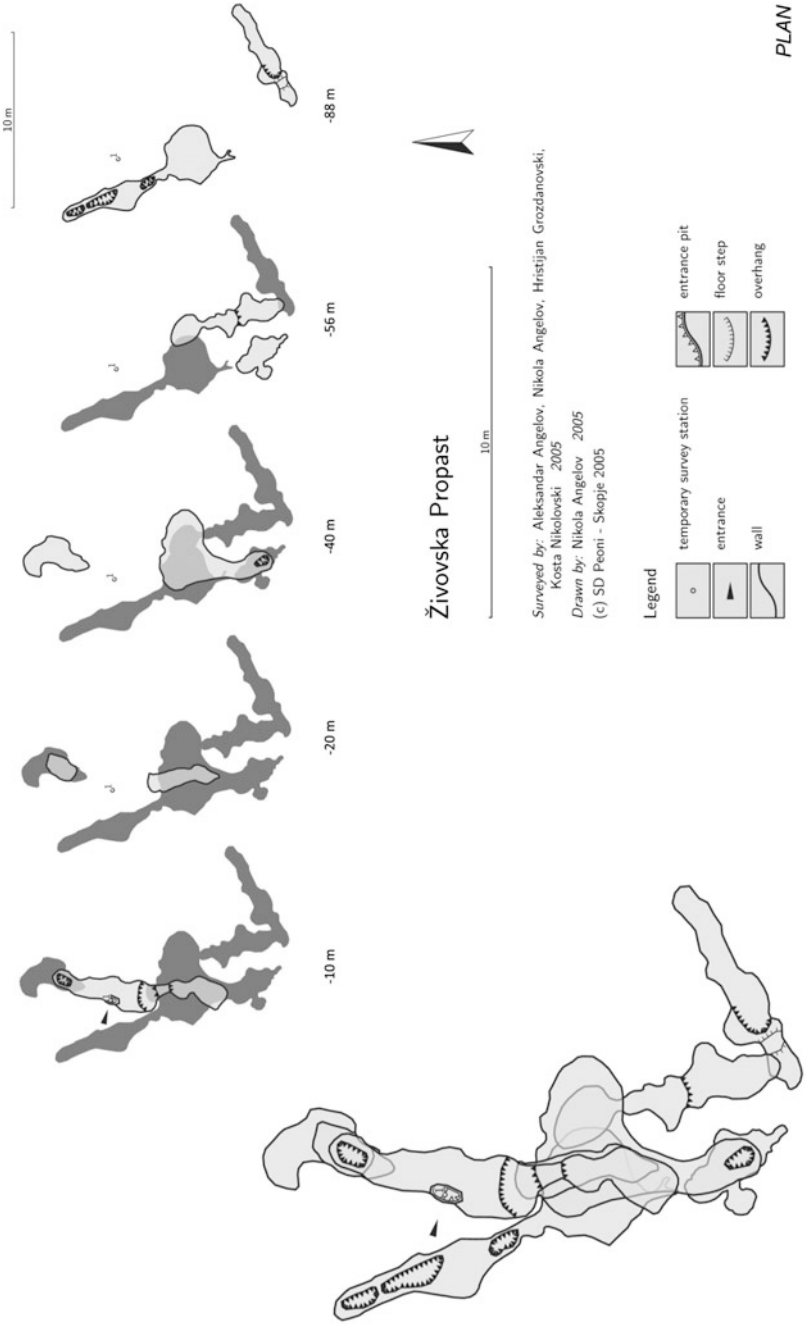


Fig. A.32 Živovska Propast—plan

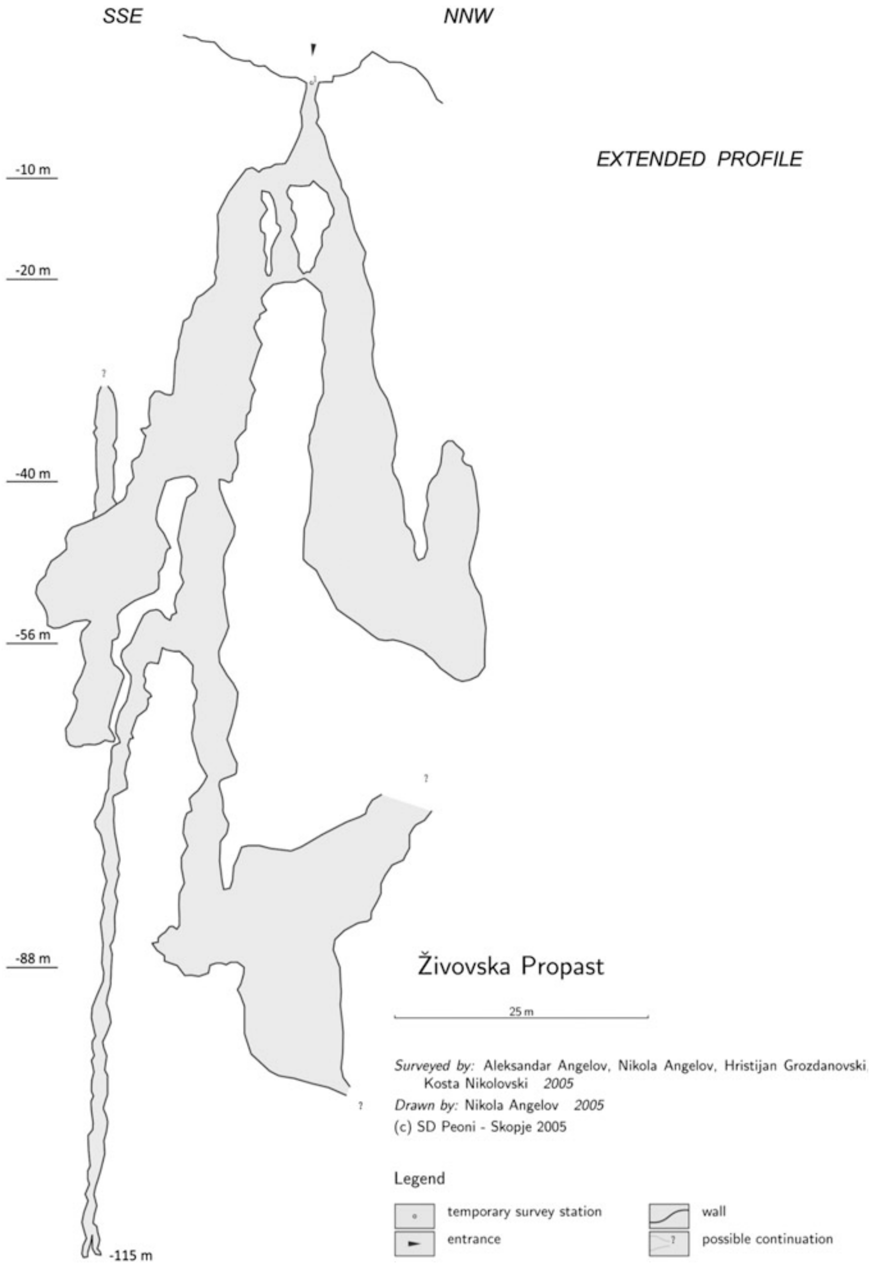


Fig. A.33 Živovska Propast—extended profile

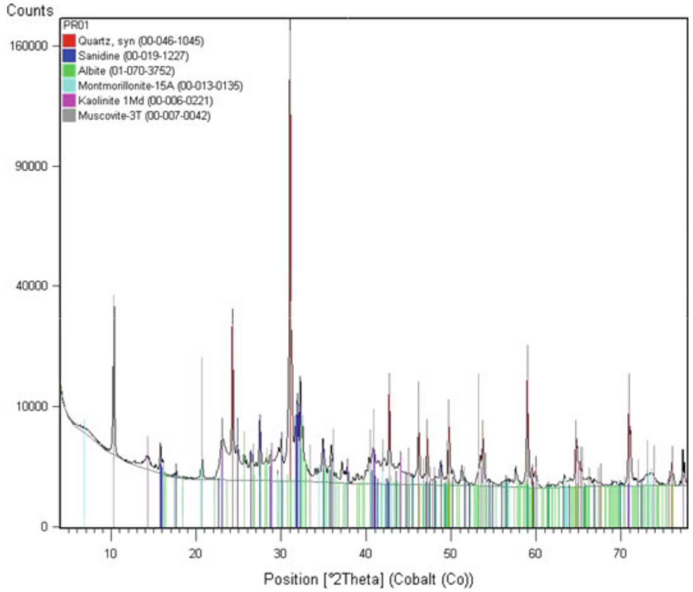
Appendix B
XRD Graphics of Sampled Sediments

List of sediment samples used for X-ray analysis

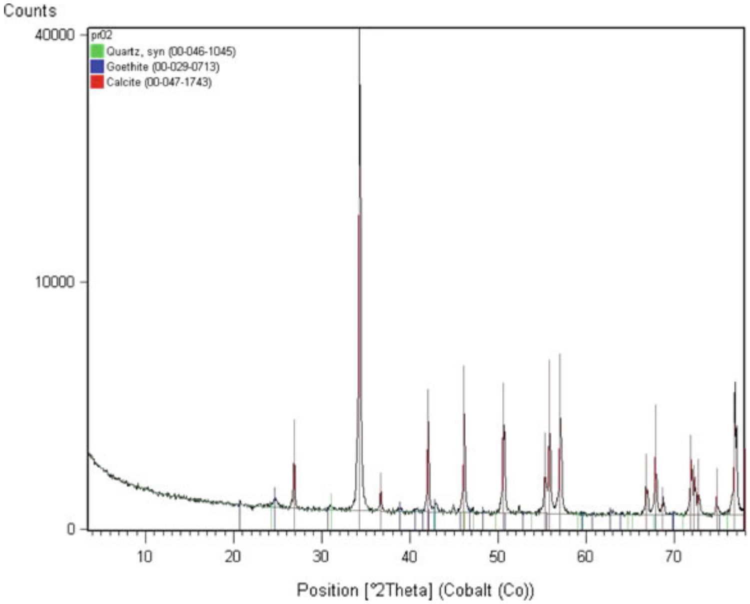
No.	Cave/locality	Sample	Sample code
1	Provalata Cave	Yellow-orange sand	PR01
2	Provalata Cave	Corroded yellow stained calcite crust	PR02
3	Provalata Cave	Gray clay	PR04
4	Provalata Cave	Gypsum crust	PR05
5	Provalata Cave	Pink clay	PR08
6	Provalata Cave	Corroded calcite crust	PR09
7	Provalata Cave	Pale yellow sand	PR10
8	Provalata Cave	Black corroded calcite crust	PR21
9	Provalata Cave	Red-colored calcite crust	PR23
10	Sadevite locality	Tuff	T01
11	Crveno Gumnište locality	Black crust	CGUM04
12	Karši Podot Cave	Red-brown clay	KP02
13	Karši Podot Cave	Brown silt	KP03
14	Karši Podot Cave	Brown sand	KP06
15	Pešti Cave	Red-brown clay	PES01
16	Aramiska Peštera	Pale brown clay	AR01
17	Aramiska Peštera	Sandy layer in sample AR01	AR02
18	Dragoželska Propast	Dark brown clay	DR01
19	Dragoželska Propast	Yellow layer in sample DR01	DR02
20	Budimirica Cave	Orange sandy clay	BUD01
21	Budimirica Cave	Orange sand	BUD02
22	Temna Peštera–Dragožel	Brown silt	TEM01
23	Temna Peštera–Dragožel	Brown clay	TEM02
24	Garnikovska Propast	Gray-brown silt	GAR01
25	Čuleca Cave	Reddish-brown clay	CH
26	Čulejca Cave	Paleokarst filling	CH02
27	Čulejca Cave	Paleokarst filling	CH03
28	Cave Lekovita Voda	Yellow clay	LEK01

M. Temovski, *Evolution of Karst in the Lower Part of Crna Reka River Basin*,
Springer Theses, DOI 10.1007/978-3-319-24547-8

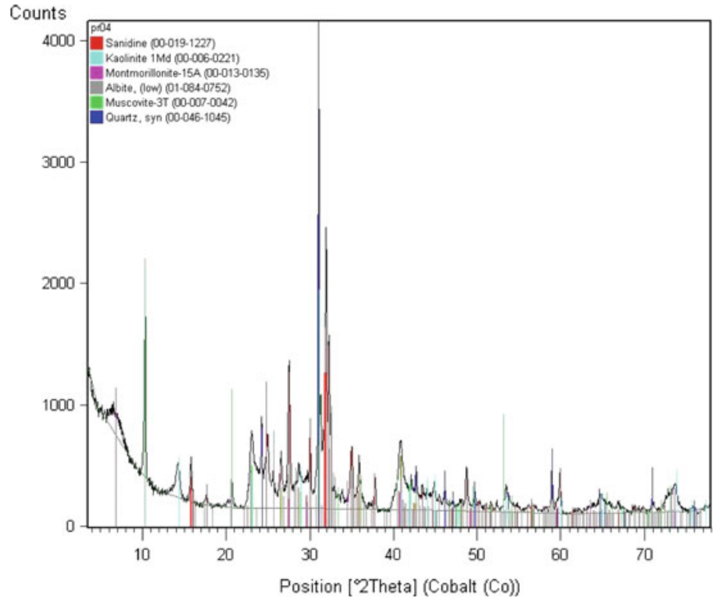
Cave	sample	location
Provalata	Yellow-orange sand (PR01)	from a ceiling channel between st.A21-A25 (Lower Passage)



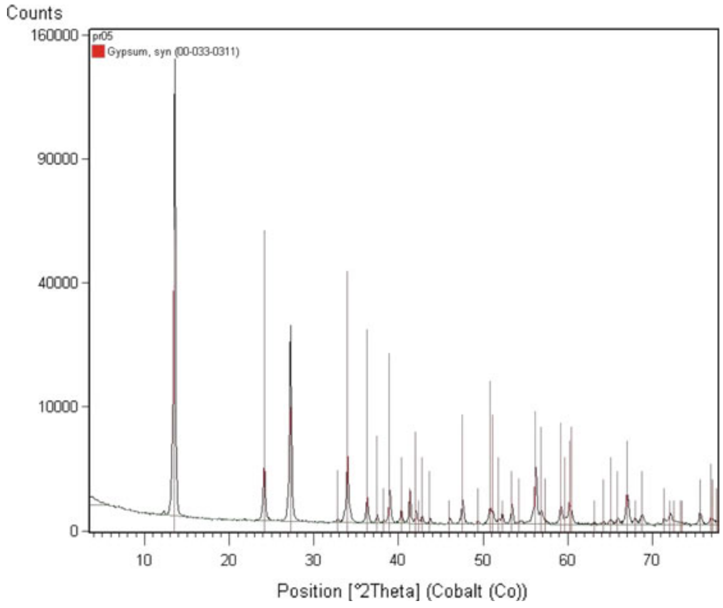
Cave	sample	location
Provalata	Corroded yellow stained calcite crust (PR02)	On a wall near st.A21 (Lower Passage)

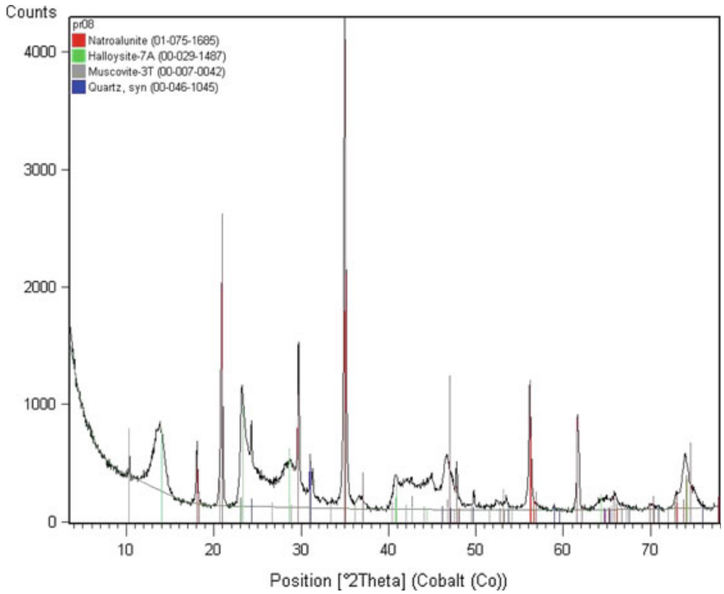


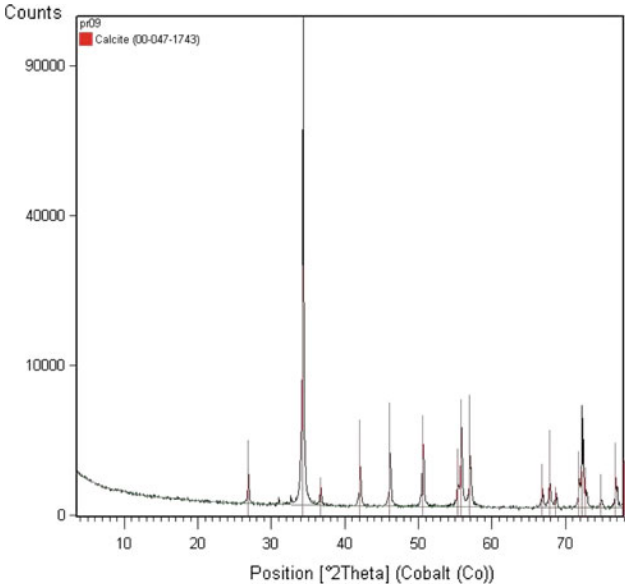
Cave	sample	location
Provalata	Grey clay (PR04)	From the floor at st.A21 (Lower Passage)

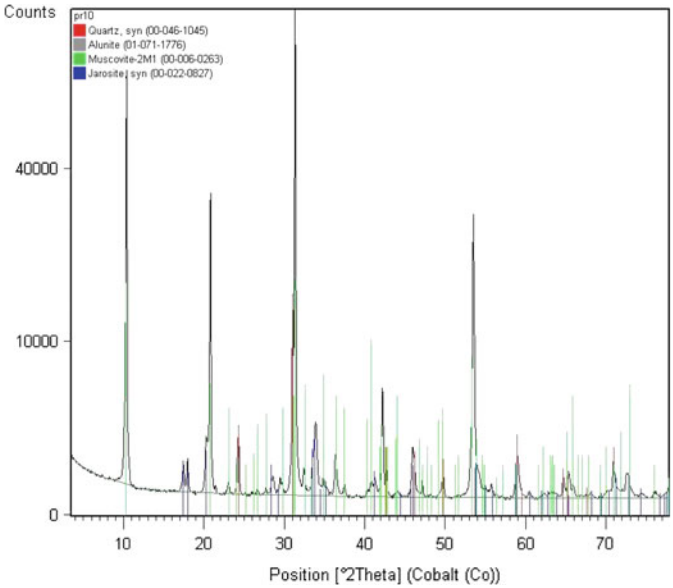


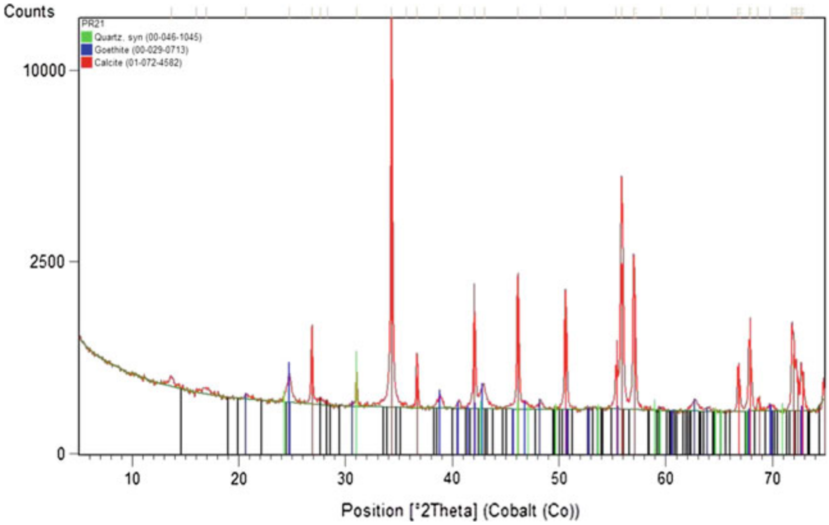
Cave	sample	location
Provalata	Gypsum crust (PR05)	From the floor near st.A18 (Lower Passage)



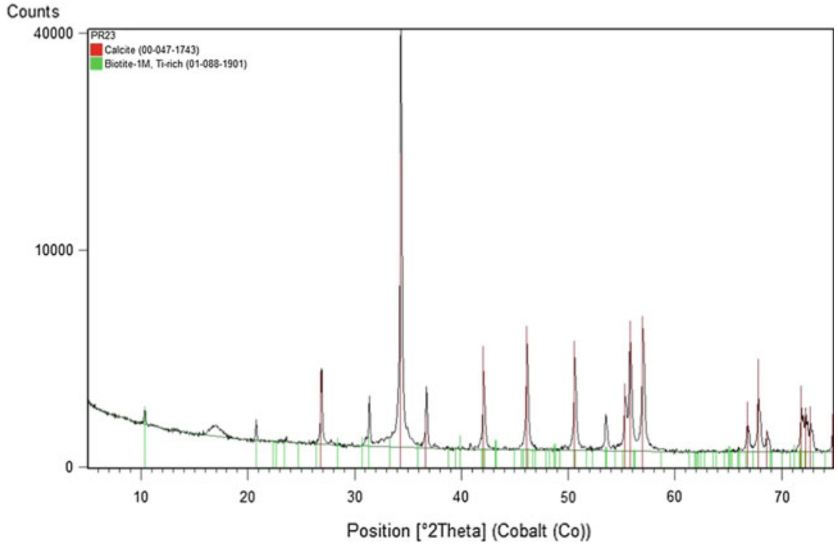
Cave	sample	location
Provalata	Pink clay (PR08)	On the wall at st.A16 (Lower Passage)
		

Cave	sample	location
Provalata	Corroded calcite crust (PR09)	On the ceiling near st.20 (Second Room)
		

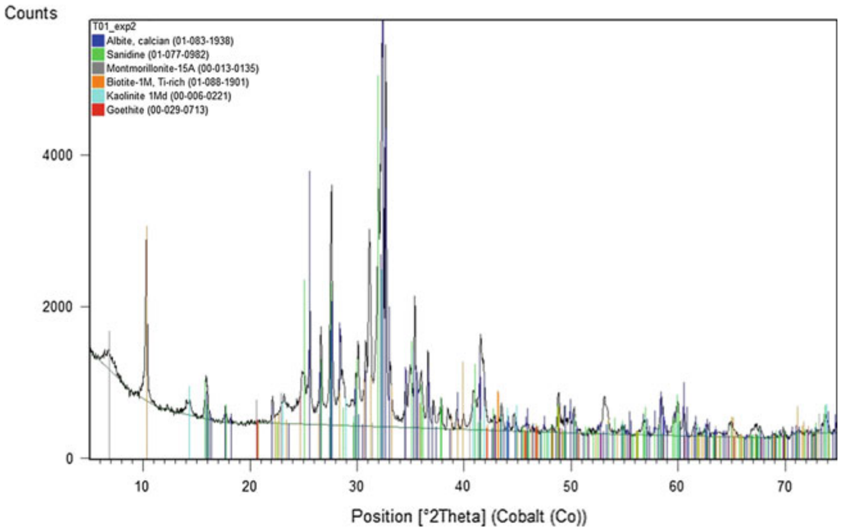
Cave	sample	location
Provalata	Pale yellow sand (PR10)	From the N wall at st.11 (First Room)
		

Cave	sample	location
Provalata	Black, corroded calcite crust (PR21)	On the NW wall near st.4 (First Room)
		

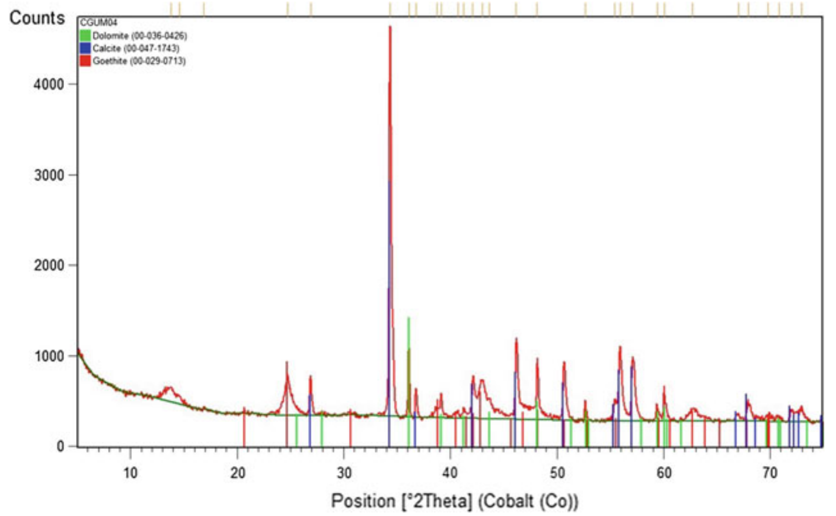
Cave	sample	location
Provalata	Red colored calcite crust (PR23)	On the NW wall at st.A25 (Lower Passage)



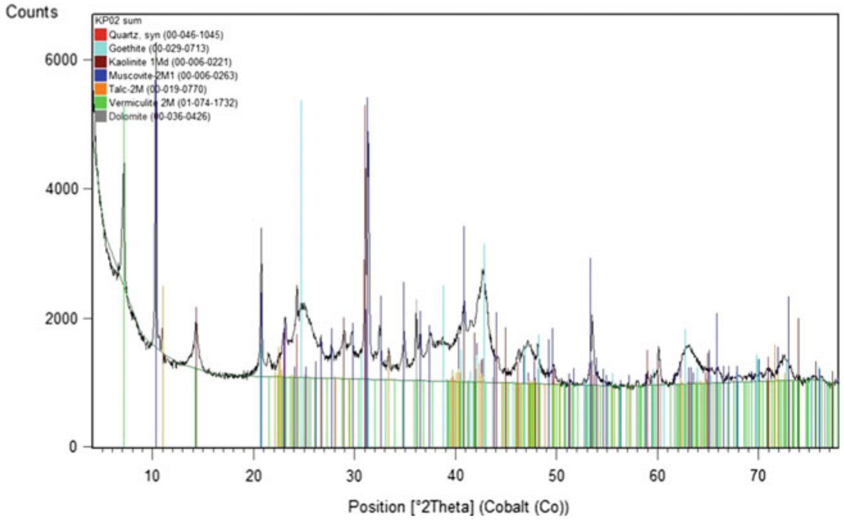
Locality	sample	location
Sadevite	Tuff (T01)	400 m south from Provalata Cave



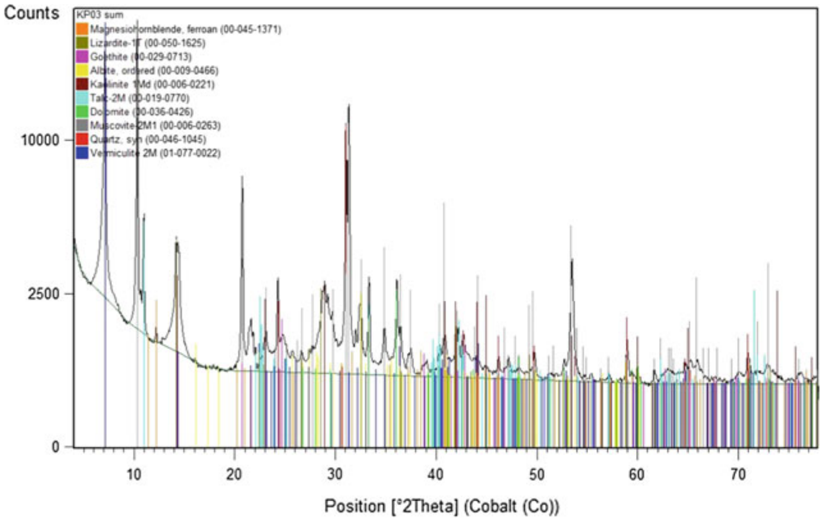
Locality	sample	location
Crveno Gumnište	Black crust (CGUM04)	In altered reddish dolomitic marbles



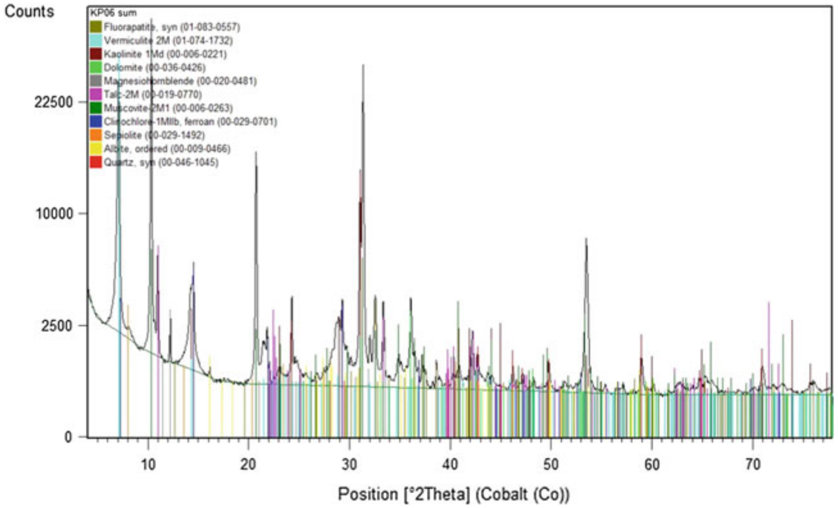
Cave	sample	location
Karši Podot	Red-brown clay (KP02)	On a pendant above first spring (near st.3b)



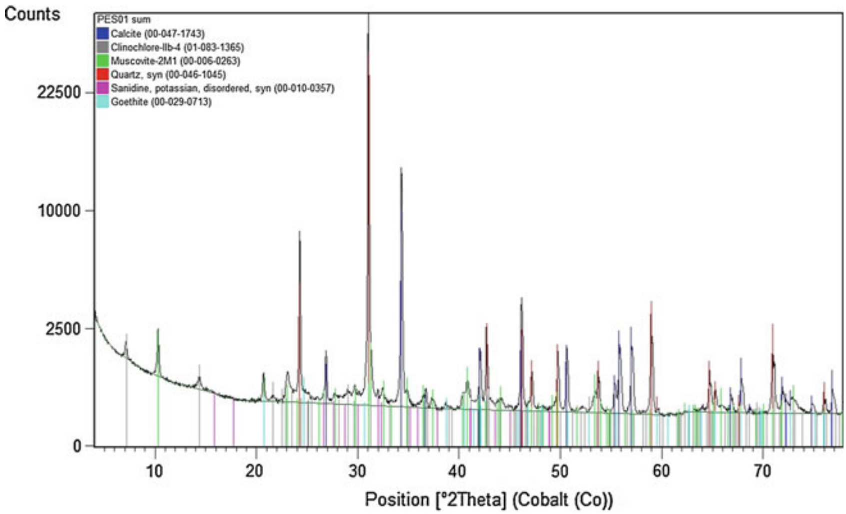
Cave	sample	location
Karši Podot	Brown silt (KP03)	Same as KP02



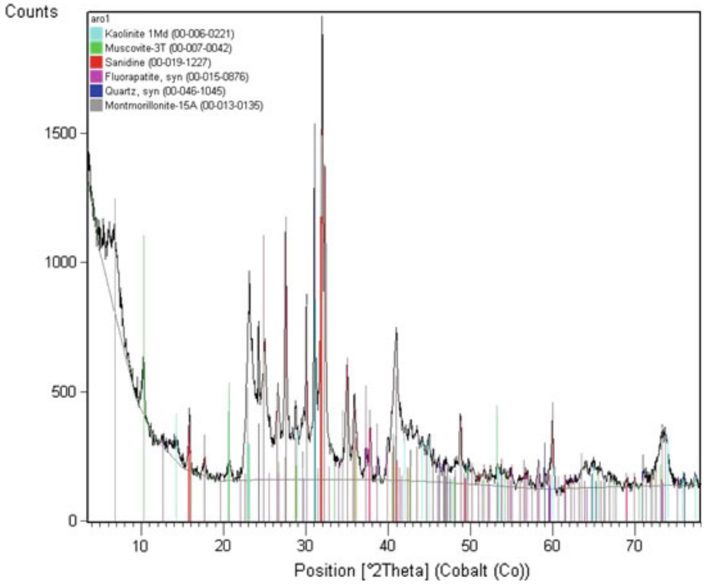
Cave	sample	location
Karši Podot	Brown sand (KP06)	Sediment profile in the southern part of Main Room (near st.1)



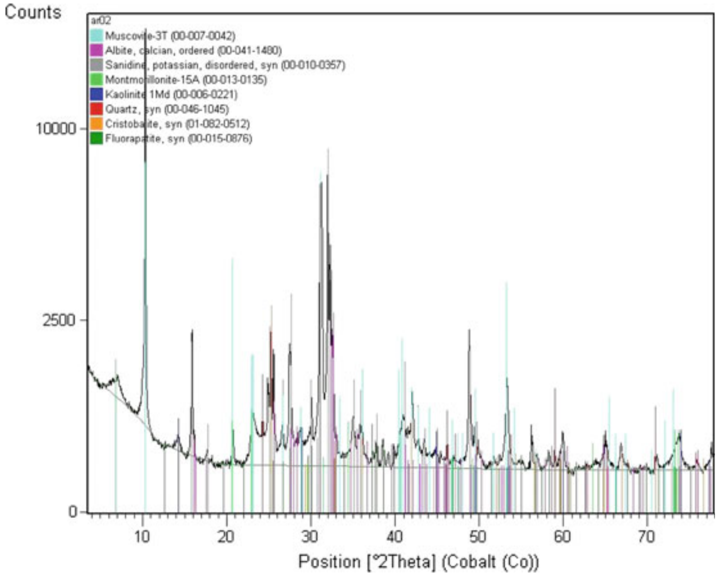
Cave	sample	location
Pešti	Red-brown clay (PES01)	Clay profile in the southern end of the cave (st.29)



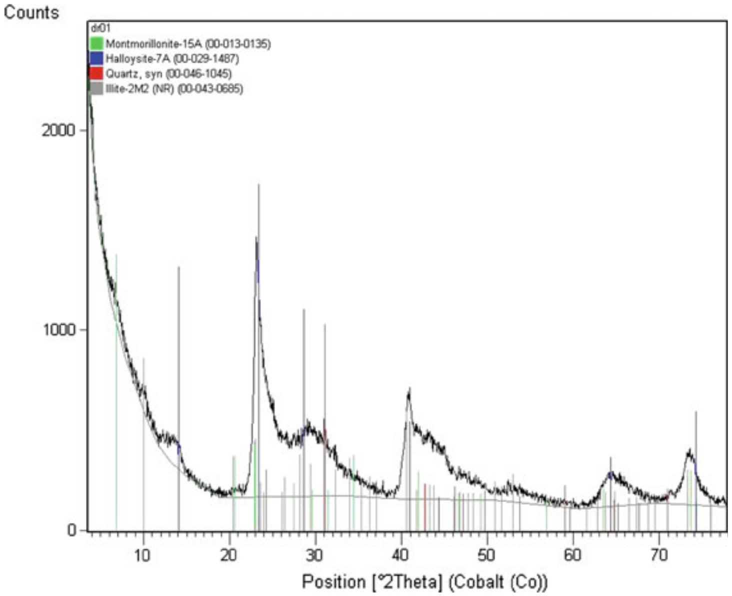
Cave	sample	location
Aramiska Peštera	Pale brown clay (AR01)	Near st.A2 in Room of Bones



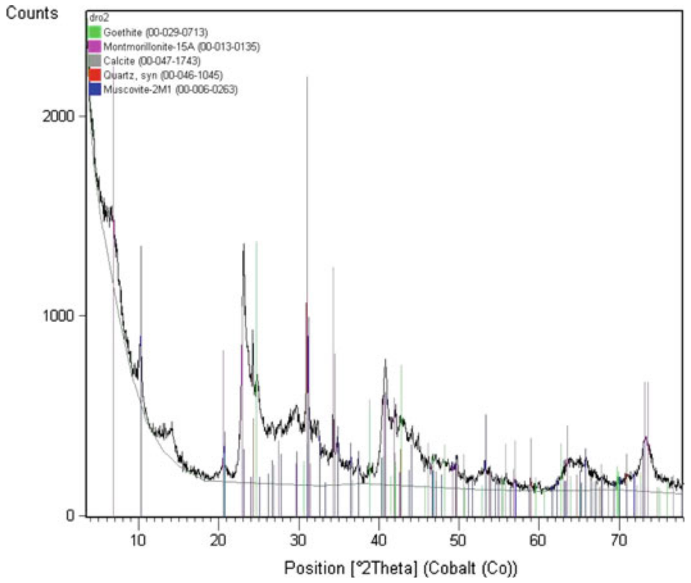
Cave	sample	location
Aramiska Peštera	Sandy layer in sample AR01 (AR02)	Same as AR01



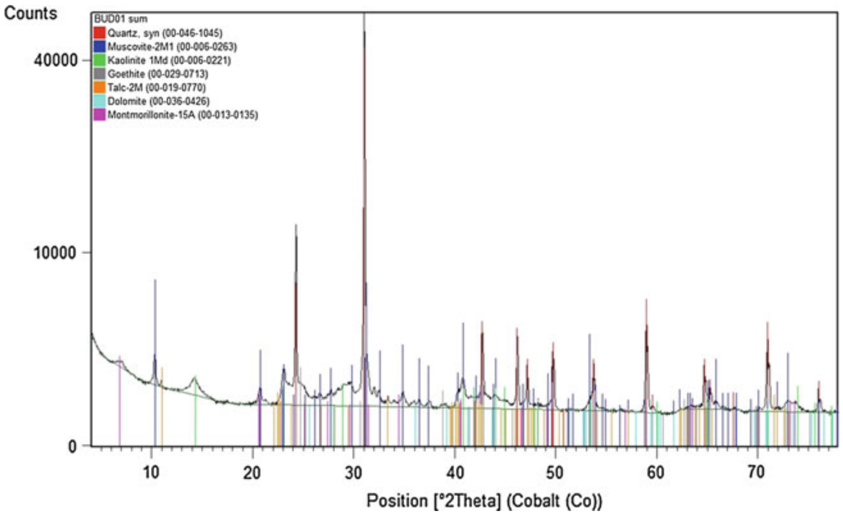
Cave	sample	location
Dragoželska Propast	Dark brown clay (DR01)	From a small vertical channel near st.12 (Big Room)



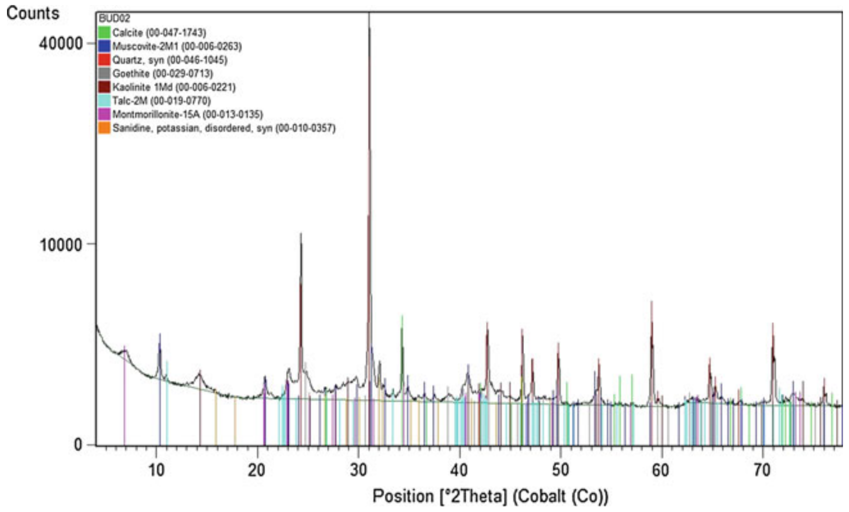
Cave	sample	location
Dragoželska Propast	Yellow layer in sample DR01 (DR02)	Same as DR01



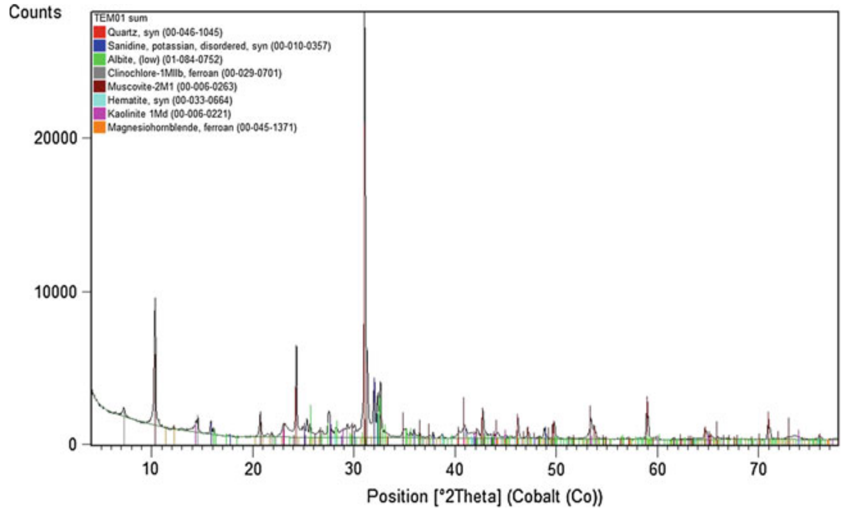
Cave	sample	location
Budimirica	Orange sandy clay (BUD01)	From yellow sediments profile in pit (between 67 and 123 cm of paleomagnetic profile)



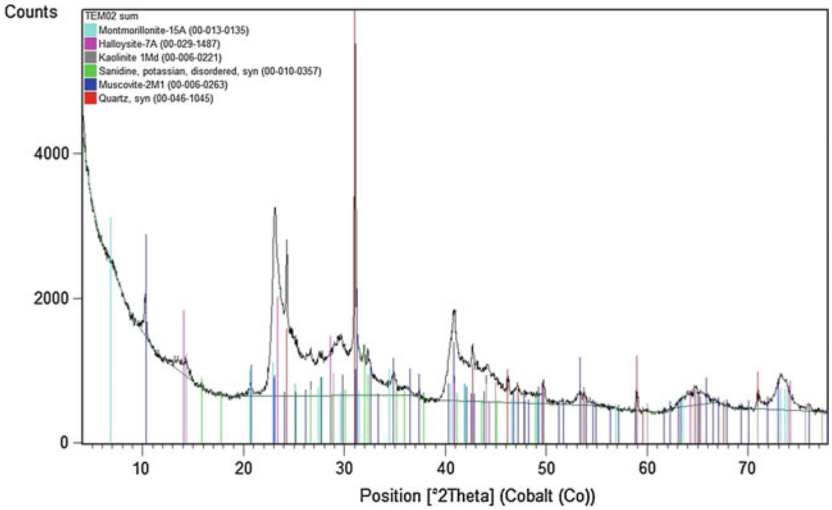
Cave	sample	location
Budimirica	Orange sand (BUD02)	From yellow sediments profile in pit (between 123 and 131 cm of paleomagnetic profile)



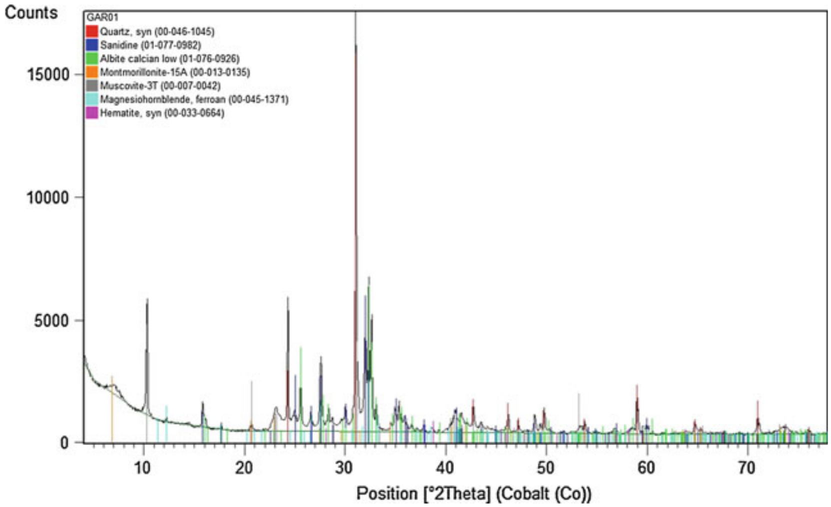
Cave	sample	location
Temna Peštera – Dragožel	Brown silt (TEM01)	From the floor at st.2



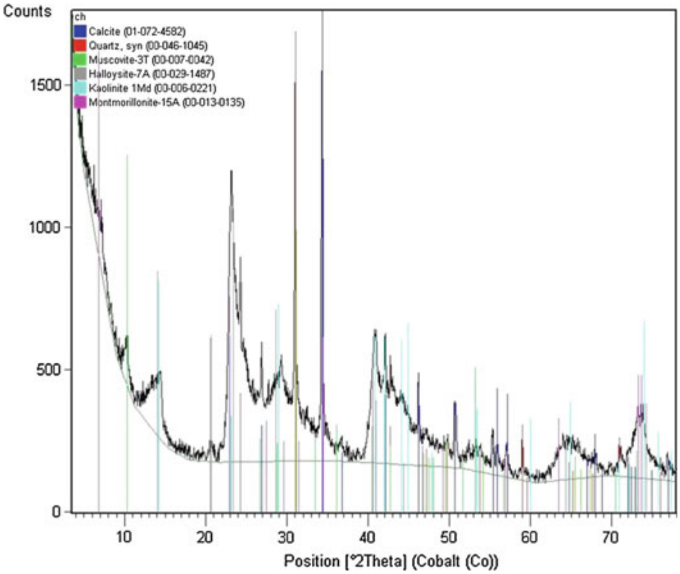
Cave	sample	location
Temna Peštera – Dragožel	Brown clay (TEM02)	From the ceiling (bottom of the flowstone false floor) above st.3



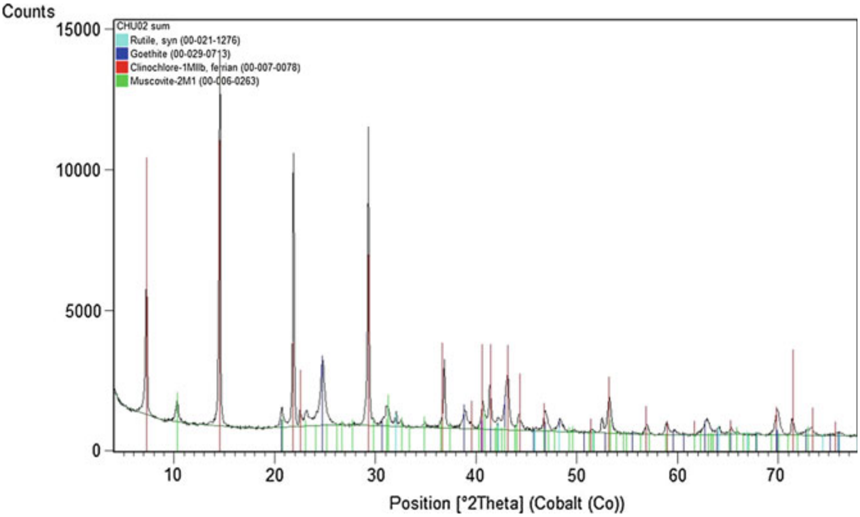
Cave	sample	location
Garnikovska Propast	Grey-brown silt (GAR01)	From a clay filled niche on the S wall between st.201-202 (Upper Waterfall Room)



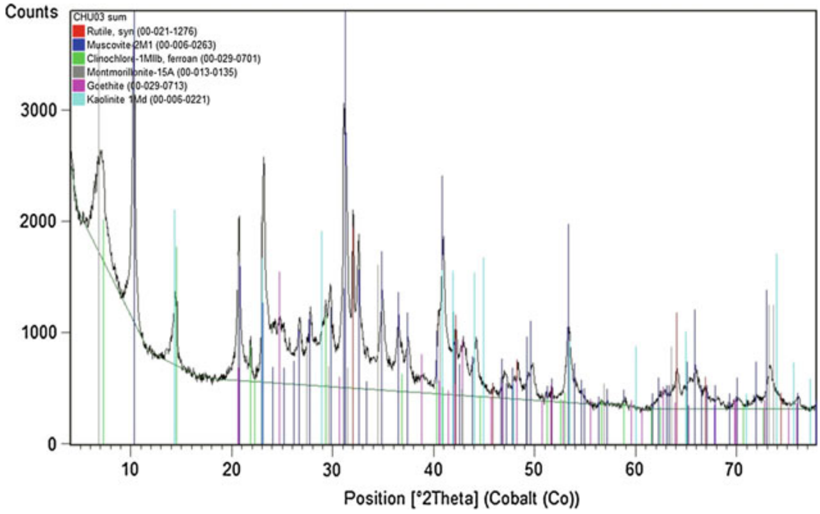
Cave	sample	location
Čulejca	Reddish-brown clay (CH)	From the floor between st.21-22



Cave	sample	location
Čulejca	Paleokarst filling (CH02)	From the wall between st.106B1-106b2



Cave	sample	location
Čulejca	Paleokarst filling (CH03)	From the wall at st.106B



Cave	sample	location
Lekovita Voda	Yellow clay (LEK01)	In a small side passage on the E wall near st.2