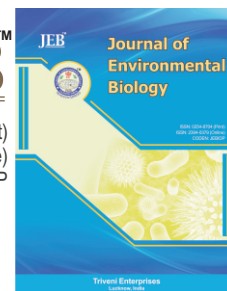




JEB™

 ISSN: 0254-8704 (Print)
 ISSN: 2394-0379 (Online)
 CODEN: JEBIDP
DOI : [http://doi.org/10.22438/jeb/38/5\(SI\)/GM-30](http://doi.org/10.22438/jeb/38/5(SI)/GM-30)

Complex speleogenetic processes and mineral deposition in the Caucasus region of Georgia

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Key words

Limestone massif,
 Nakerala range,
 Sediments,
 Speleothems,
 Speleogenesis

Publication Info

Paper received : 30.09.2016
 Revised received : 20.06.2017
 Accepted : 27.06.2017

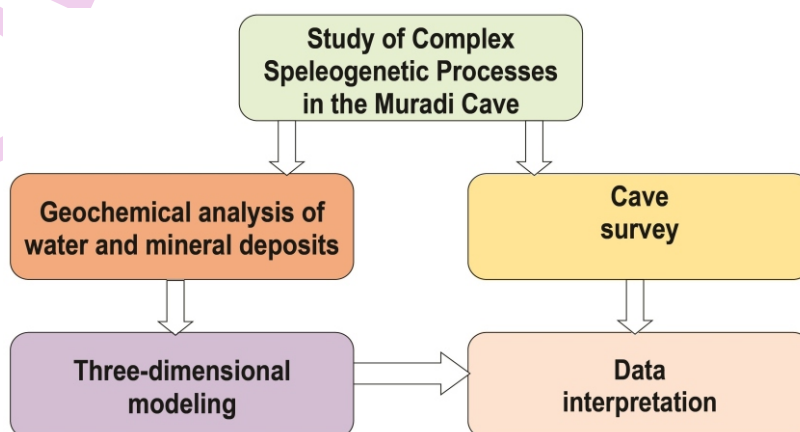
Abstract

Aim: The present study aimed to characterize the speleogenesis, associated karst morphological processes and rare mineral deposition in Muradi Cave, which is located in the Caucasus region of Georgia. In this research, it was important to make basic survey and mapping of the Muradi Cave. Also, one of the goals was to collect information from a speleological point of view in order to understand the speleogenetic processes.

Methodology: Multiple methods were utilized to investigate Muradi Cave, including both physical and geochemical analyses, to characterize the cave's origin, morphology and mineralogical deposits. The morphological parameters and tectonic directions of Muradi Cave were identified by compass-clinometer and laser distance meter, from which we compiled the schematic plan and 3D model of the cave. Air temperature was measured in two different places within the cave using an Onset HOBO Pro V2 Data Logger. Speleothem mineralogy was analyzed using XRD.

Results: In the present study, recently investigated Muradi Cave in the Racha limestone massif, which contains different speleological, mineralogical and hydrological features providing insight to its formation and possible influences on cave development in the region. The uniqueness of Muradi Cave is given by the fact that it contains almost all types and subtypes of speleothems and sediments recorded nowadays in the caves of Caucasus. The mineral aggregates found in Muradi Cave are rare for the caves of the Caucasus. By taking into consideration, the geological-geomorphological peculiarities and the results of the archeological materials of the region, it became possible the identification of the age of the oldest deposits.

Interpretation: Collectively, this investigation of an investigated area in Georgia, as well as the discovery of unique formations, provide new insight on the development of large limestone massifs in the region and has implications for deep cave development and the understanding of the region's speleological and geomorphological evolution.



Introduction

The country of Georgia is home to multiple, widespread limestone massifs with well-developed karst areas and their associated landscape features found throughout the country. The limestone massifs occupy 4.475 km² or 6.4%, of the entire territory of Georgia (Asanidze *et al.*, 2013a; Asanidze *et al.*, 2013b), which includes over 1,500 known caves. Of these, Krubera Cave is currently the deepest in the world (over 2,100 m in depth). Although it is the deepest known thus far several other massifs in the region also have the potential to host extensive, deep cave systems (Tintilozov, 1976; Klimchouk, 2006, 2012; Klimchouk *et al.*, 2009).

Here, we present a study of an exemplary cave system in the region, Muradi Cave, and relevant speleogenetic processes of its formation, including minereological deposits, in an effort to improve the understanding of cave formation in the Caucasus region. This was achieved using a morphometric cave analysis with a situational plan and 3D model of the cave and data on the geochemical and hydrological influence on its development. This is useful for comparative studies that may attempt to advance knowledge regarding cave formation in the region using a horizontal cave example.

The Racha limestone massif is located in the eastern part of the karst zone of western Georgia and is a classical example of high-mountainous karst region (Kiknadze, 1972), where diverse surface and subsurface karst landforms are found. Geographically, the massif is located in the Oni and Ambrolauri regions, the total area of which exceeds 590 km². The highest elevation of the massif ranged from 2,239-2,402 m above sea level, while the estimated thickness of the massif is 1,100-1,300 m. This limestone massif contains many karst features, such as dolines, caves, ponors, and others, though few studies have focused on the area's karst features, including horizontal caves. In Georgia, similar karst landscapes are found in the Bzipi and Gagra ranges (Aphkazeti, Georgia), where the world's deepest cave exists (Lezhava, 2015; Kipiani, 1974). The Caucasus region may well serve as an example of this and Muradi Cave provides important clues to the possible origin and evolution of karst processes in the area.

Materials and Methods

Study area : Muradi Cave is located in the southwestern part of Racha limestone massif in the Nakerala range. The Nakerala range comprises a small piece of Racha limestone massif. Racha limestone massif is a classic geomorphic region throughout the

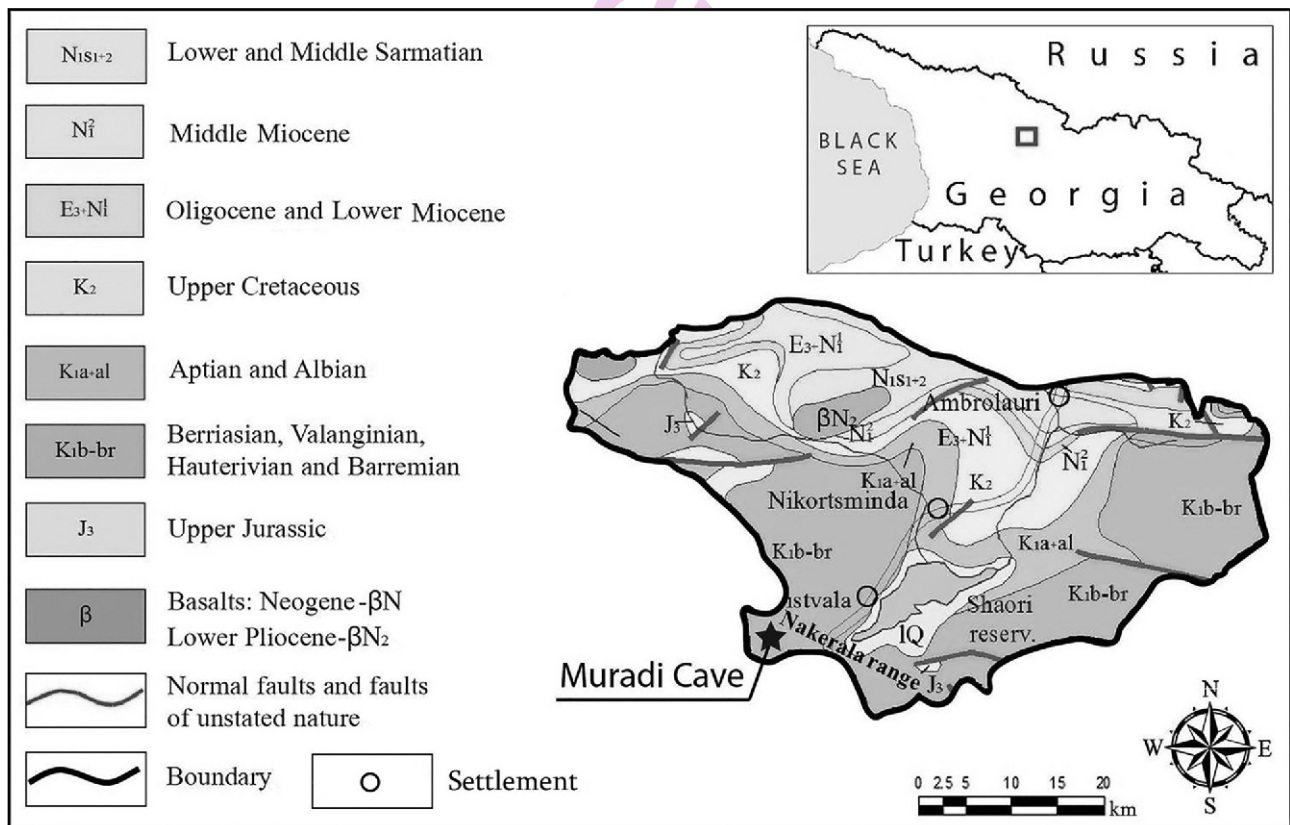


Fig. 1 : Geological map of the Racha limestone massif (after Gudjabadze, 2003); Location of Muradi Cave in the Nakerala range

Caucasus in terms of development of karst processes and landforms. The Bajocian porphyritic suite is the basis of massif and Cretaceous carbonate rocks also influence the structure of the stratigraphy (Rakviashvili, 1985). Rocks from almost every part of the early and late Cretaceous exist in the region (Fig. 1). The Nakerala range consists mainly of Cretaceous and Paleogene limestones, which have an important influence on the origin and development of the surface and underground karst features and on the water table and its fluctuations due to their geologic characteristics.

In the Racha limestone massif area, the mean annual temperature is 11.2°C; the mean air temperature of the coldest month (January) is -0.3°C, while the mean air temperature of the warmest month (August) is 22.1°C (Kavrishvili *et al.*, 1978). Humid air masses blown from the Black Sea (~120 km away from the study area) significantly influence the climate of the Racha limestone massif and its karstification due to the amount of precipitation it receives. A major obstacle is the Nakerala range with its steep slopes, blocking humid air masses arriving from the west. In these areas, updrafts of air masses develop due to the orographic influence and produce a mean annual precipitation total of 2,760 mm, according to the Nakerala weather station

(Kavrishvili *et al.*, 1978).

The arch-like entrance of Muradi Cave (4 x 1 m) is located on the northern slope of the Nakerala range at an elevation of 1,498 m asl. The total length of Muradi Cave is 660 m with an average passage width of 5 m, average passage height of 8 m, and the floor's mean area is 3,500 m², contributing to a total cave volume of 29,000 m³. A narrow corridor descending westward at 60° from the entrance is filled with large amount of breakdown. After 20 m, the passage turns into a sub-horizontal corridor that connects to around passage with a high ceiling (10 m) by a vertical drop of 2.5 m. In the right corner of the passage (azimuth 95°), a wide (5 m) and long (34 m) tunnel-shaped passage is formed in the Urgonian limestones.

Multiple methods were utilized to investigate Muradi Cave, including both physical and geochemical analyses, to characterize the cave's origin, morphology and mineralogical deposits. These data were combined to provide an interpretation of various stages of its development and place the speleogenetic evolution of the cave within that of the Racha limestone massif and common speleogenesis theories. Air temperature was measured at two different places within the cave using an Onset

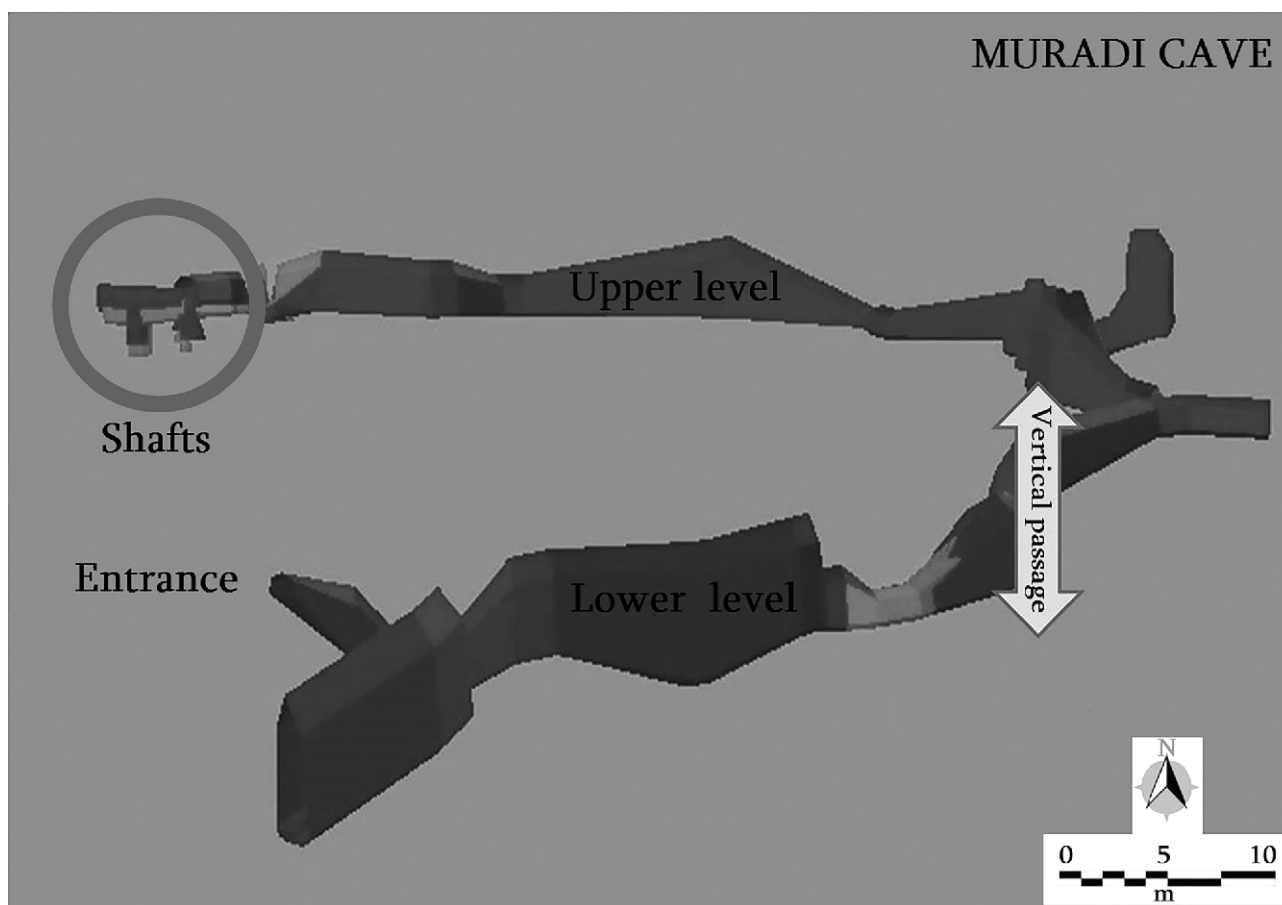


Fig. 2 : Compass-generated 3D model of Muradi Cave (by L.Asanidze)

HOBO Pro V2 Data Logger. Water temperature was measured in one section containing a pool of dripwater also forming nearby speleothems using an Enviro Safe portable thermometer. Water geochemistry analyses were carried out at the Ivane Javakhishvili Tbilisi State University water analysis laboratory. Speleothem mineralogy was analyzed using XRD. The cave was surveyed using a compass, clinometer and laser distance meter. These data were input into Compass cave survey software and ArcGIS to produce a 3D map of the cave within the context of the landscape (Fig. 2).

Results and Discussion

Here, we present the results of an initial study on Muradi Cave as an example of speleogenesis in a large limestone massif in an area Traditionally more associated with vertical cave development and hypogene speleogenesis in Georgia. Collectively, this research was undertaken to provide the foundation for future research to determine the geologic and geomorphological influences on cave development and karst hydrology of the Racha limestone massif and form a comparative basis for interpreting other cave development within the region and other similar areas of the world.

Cave survey : A cave survey is the first step necessary to place a cave within the context of its originating bedrock and to determine its geomorphic evolution with respect to the area's hydrology and rock-water interactions. The survey of Muradi Cave revealed that it has one main passage with three shorter branches. The 171 m long horizontal section of the main, lower cave level connects with

the upper level through a 10 m vertical passage (Fig. 2). It is likely a waterfall entering from the surface and breaching a fracture until reaching a lower level created the vertical connecting passage. The cave's main passage and the adjacent branches indicate traces of past streamflow; specifically, clay-loam and sandy-loam sediments and breakdown were present on the floor, whereas alluvium deposits were left on the walls likely from intermittent higher flow conditions. The lower section of Muradi Cave was characterized by strong airflow, large breakdown deposits, and mostly lacks speleothems, except some that are desiccated or weathered. There was a high likelihood of other passages existing that were not able to be surveyed due to their size or lack of easy connections to the main passages based on the airflow in the cave.

The upper level of the cave was sub-horizontal and canyon passage with several side passages formed along a vertical fracture over tens of meters. Located in the contact zone of the tectonically influenced fractures and bedding planes, there was a large dripwater pool at the end of the upper level passage; however, like the rest of Muradi Cave, it lacked permanent streams. There were clear signs of previous active stream influences in forming the cave along the walls in this section, which included vugs, rounded arches, and scallops from water moving at high velocity. On the floor, there was a series of shafts with depths of 11, 42, 35 and 37 m, respectively. These shafts are interconnected with each other through a series of fractures and also terminated at the lower level, thus indicating simultaneous evolution driven by water levels.

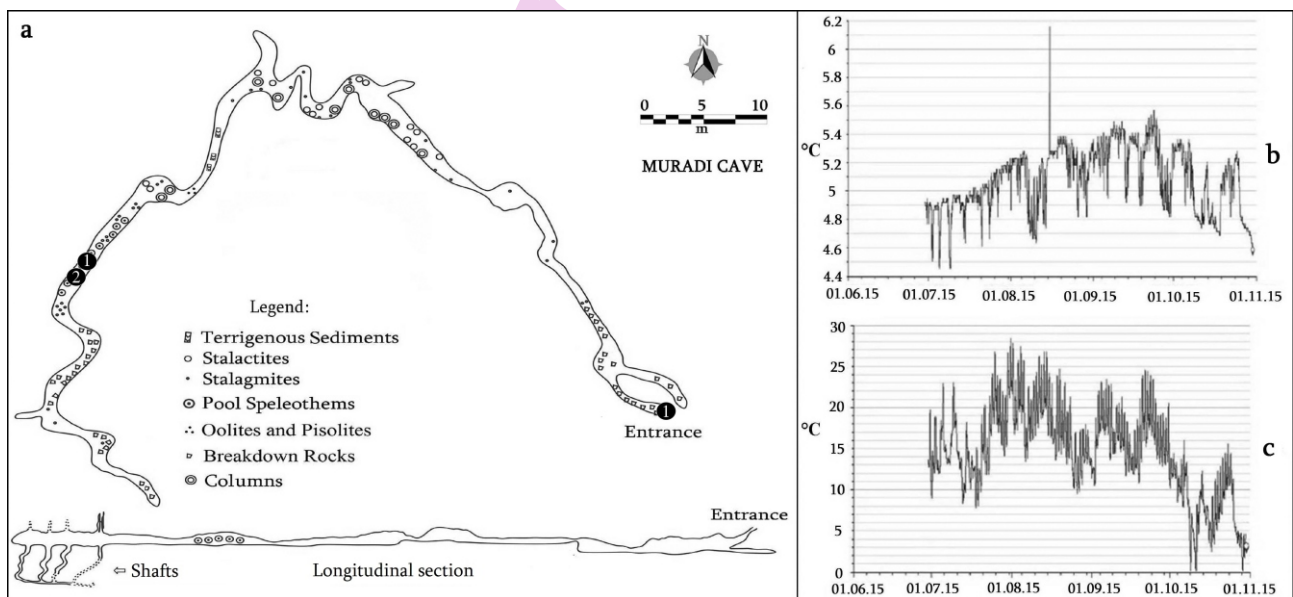


Fig. 3 : (a) Schematic plan and cross-section of Muradi Cave. Number 1 indicates the places where the air temperature was measured; Number 2 indicates the place where the water temperature was measured, (b) Air temperature data from 01.06.2015 to 01.11.2015, measured in the middle of Muradi Cave, (c) Air temperature data from 01.06.2015 to 01.11.2015, measured at the entrance of Muradi Cave

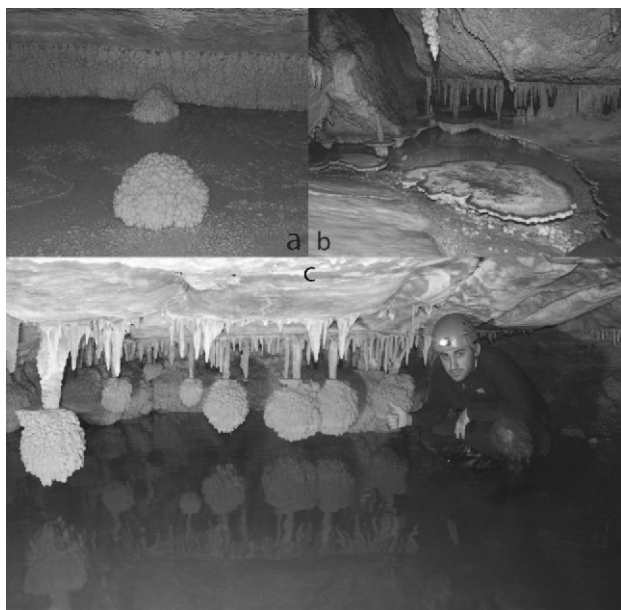


Fig. 4 : Photographs of some speleothems from Muradi Cave. (a) Pool calcite speleothem deposited subaqueously in cave pools at multiple places of the cave, (b) Shelfstone type of speleothems formed around the edges of the small pool surface. It looks like the pool level still changes and slowly disappears (photos by Lasha Asanidze), (c) Spherical examples of pool speleothems, which could be formed from water level fluctuations over time. X-ray diffraction (XRD) analysis confirmed these are 100% calcite deposited (photo by George Lominadze)

Cold air movement was evident in the vertical section between the lower and upper passages, indicating the existence of additional cave beyond that point, but inaccessible. In 2015, the air temperature was measured in two sections of the cave, one at the entrance (slightly above 7°C) and the second in the middle of the cave, near where the speleotherms were formed in a pool of water (Fig. 3). Near this pool, the water temperature was also measured to be 7°C. Stable air temperature and associated water temperature indicated consistent air movement and connection between the cave passages at this stage of its evolution.

Cave morphology : Muradi Cave is no longer actively forming from flowing water, as the two levels of the cave likely formed as the water table shifted either from climatic or tectonic influences. Later, tectonic stress and the resultant collapse of the entrance, along with the change in the water table, drastically changed the hydrological conditions of the cave and the active flow of permanent and ephemeral streams into the cave ceased. The cave is likely a fluvial cave developed in the vadose zone consisting of sub-horizontal and vertical passages, with hypogene influences apparent at some point in its evolution, likely from higher water tables during tectonically active periods. It seems that an intense collapse of the ceiling of the cave, formation of shafts in the floor, and the action of the infiltrating surface water depositing chemical (chemogenic) and silt deposits

were the primary drivers of the changing morphology of the cave after its initial inception. Movement of water upward likely influenced the development of the shafts and erratic morphology after the passage was originally formed.

Muradi Cave was developed from the stratified limestones of Barremian age (Urgonian facies) with a northwestern (290°-300°/10°-15°) dip of the bedding planes along tectonic features. At the sections where Muradi Cave was developed along bedding planes, the underground passages are characterized by clearly linear and smooth profiles. Most of the upper level of the cave is of this type. In the zone of tectonic fractures influencing the cave's development, where the passages intersect with bedding planes, the cave morphology was more complex and domes were present in the ceiling.

In Muradi Cave, the large passage of 10 m between the lower and upper levels of the cave are important, as they are likely originated as a result of waterfalls from the vertical or very inclined sections of uplifted bedrock creating the fractures upon which they formed. Their dissolution intensified as they penetrated the bedrock and additional uplift occurred, possibly forcing the water table to rise as well, creating features much like the vertical domes found in Mammoth Cave and elsewhere in the world (Palmer, 2007).

Mineralogical deposits : The upper level of the cave was rich in calcite speleothems. The modern climatic conditions were dry, with small areas that have intense air movement. They were found in areas away from where collapses occurred. The upper level would have formed first, then drain, in order for speleothem formation to occur in this manner. Almost all types of speleothems found in the upper level exist in other caves of Georgia, including stalactites, stalagmites, helictites, columns, shields, calcite flowers, oolites, pisolites, cave pearls, flowstone and in some areas moonmilk from condensation. Within the dry passages containing no modern drips, most of the calcite formations were desiccated or weathered.

One of the interesting formations found in Muradi Cave was moonmilk, which is not very common in the caves of the Caucasus (Lezhava, 2015). This formation is mostly found in the wet passages and occupies pools of water. Moonmilk is actively formed under the aggressive influence of condensation waters (Tintilozov, 1961). The aggressive waters, by dissolving the limestone walls, lead to the formation of the moonmilk (Hill and Forti, 1997; Merino *et al.*, 2014) and, infiltration waters often also participate in this process. Geze (1965) reported that microorganisms play an active role in their formation (biochemical weathering) as well, but more work is needed in Muradi Cave to determine that possibility; however, Shumenko and Olimpiev (1977) did not find microorganisms in the moonmilk. It appears, that microorganisms are possible, but not essential factor in the formation of moonmilk (Hill and Forti, 1997).

Mineralized calcite aggregates, including oolites, pisolites, shelfstone, some types of pool speleothems, and other similar formations are mostly found in underground pools. Spherical formations (pool speleothems) formed by calcite mineral aggregates give the cave a particular uniqueness and there is no known analog in caves in the Caucasus (Fig. 4). These deposits provide some additional insight to the speleogenesis of the cave due to the nature of their form. They are mostly subaqueous, lithified calcite balls of different sizes (the smallest is 16 cm and the largest is 180 cm in circumference) grown around stalactites at one level in a shallow pool in Muradi Cave in the upper level. They seem to have been formed at the same level in the water, perhaps as formations similar to phreatic overgrowth from supersaturated waters existing at higher water levels during times of tectonic change, flooding, or baselevel shifts, and thus indicating a period of higher water table and stability in between tectonic shifts (Merino *et al.*, 2014; Jacek, 2015). The formations have similar morphological characteristics to some of those found in hypogene caves, such as Lechuguilla, given their uncommon shape and likely relationship with water level fluctuation.

The facts described above and the field observations prevent us from identifying a single, specific condition of origination and process for the development of the calcite balls at this time. In addition, it seems that the conditions of their origin and development was created as a result of their combination and cementing, including a potential microbiological influence (Borsato *et al.*, 2000; Moral *et al.*, 2012; Sallstedt *et al.*, 2014). XRD analysis confirmed these as 100% calcite (Leél-Óssy *et al.*, 2011; Bieniok *et al.*, 2011).

The answers to some questions of the morphology and evolution of Muradi Cave must be sought in determining and understanding the geologic context of the cave's development and how it fits within the context of the massif's evolution. The formation and development of Muradi Cave is closely associated with the formation of the Nakerala range in general (Tsagareli, 1964) and it is likely that the inception of caves in the Nakerala range (including Muradi Cave) and their subsurface hydrology seems to have occurred in the pre-glaciation age (before the Pleistocene) under different climatic and tectonic conditions.

We suggest that the limestone relief of the Nakerala range follows the limestone relief of the southern slope of the Caucasus, together with the inception of the subsurface drainage network (dolines, shafts, etc.) before the Pleistocene glaciation, and was subject to deep erosive jointing and collapse followed by a shift in baselevel. The fact that the origination and development of Muradi Cave ended before the Pleistocene age is evidenced by Acheulean-age deposits and the cultural sediment layer found in the Tsona Cave (abs. altitude of 2,100 m) in the eastern part of the Racha limestone massif (Lubin, 1960; Kalandadze, 1962), corresponding to the Early Pleistocene. This is further supported by the remains of a cave bear (*Ursus spelaeus*) found in

Tskhrajvari I cave (abs. altitude of 1,435 m) located on the Nakerala range, only three km away from Muradi Cave. The bears lived there no later than the Riss-Wurm Interglacial (Tsereteli, 1956). This is evidenced by the fact that the remains of the aforementioned cave bear in many caves of Crimea and Caucasus are found together and the remains date to be Acheulean age (Lezhava, 2015). The same is evidenced by the results of the lithostratigraphical study of the terrigenous deposits at the southern slope of the Nakerala range (Lezhava, 2015). Based on the results of that study, an assumption that the caves of the Nakerala range had developed before the Pleistocene age is given based on the other speleogenesis characteristics. Therefore, our findings are consistent to earlier evidences.

The evolution of Muradi Cave at the early stage of its development is closely associated with the action of phreatic waters. It must be emphasized that there are traces of the mechanical and chemical influences of these waters preserved in the cave today. This evidence is clearly seen in the cave due to two primary features: the arches of the cave within the areas of the said formations which is totally deprived of the network of fractures and therefore possible ingress of infiltration waters, and such preservation was additionally promoted by the absence of significant temperature variation or winds underground and very slight physical weathering. The ingress of phreatic water seems to have occurred from the terminal sections of the cave (the sites with the shafts), which is clearly evidenced by the depressed (etched) holes and scallops developed on the walls during phreatic flood currents.

Tectonic movement and intensely developed karst processes significantly changed the surface and underground processes of the study area in which Muradi Cave had developed. These are closely linked with the geomorphic evolution of the Nakerala range and myriad other caves in the area also appear to have originated within the same timeframe. An analysis of the cave's morphology from 3D survey, mineralogical deposits, and sediments indicate that it formed initially under phreatic conditions, then developed additional levels of vadose canyons and shafts during tectonic uplift, which caused rapid incision and a lowering of the water table in stages over time. During these periods, when stable, epigenic overprinting continued to evolve the cave's passages and connect them, while simultaneously forming speleothems in vadose passages and calcite raft deposits in the pools where the water table remained for long enough periods of time. Unlike many of the hypogene caves in the region, Muradi Cave is formed from a more traditional mechanism of speleogenesis, but the influence of tectonic activity and complex hydrologic regimes led to the development of speleothems and passage morphology less common in the region and likely from hypogenic overprinting, which is in reverse temporally compared to most cave systems exhibiting both epigenic and hypogenic characteristics. This

study presents one of the first and most modern attempts to classify these types of caves in the region and provide speleogenetic context for their existence and further study and comparison.

Acknowledgments

We would sincerely like to thank the Ivane Javakhishvili Tbilisi State University and the Vakhushti Bagrationi Institute of Geography for the financial support. We would also like to thank the Shota Rustaveli National Science Foundation for the research funding within the Doctoral Programs Grant № DO/80/9-280/14 and the Fundamental Research Grant № FR/218/9-280/13.

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