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CHARACTERISTICS OF THE MICROPSEUDOKARST LANDFORMS IN PÂCLELE MARI MUD VOLCANIC AREA (ROMANIA)

ZNAČILNOSTI MIKRO PSEVDOKRAŠKIH OBLIK NA OBMOČJU BLATNEGA VULKANA PÂCLELE MARI (ROMUNIJA)

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Abstract UDC 551.435.1:551.311.8(498)

János Móga, Katalin Fehér & Daniela Strat: Characteristics of the micropseudokarst landforms in Pâclele Mari mud volcanic area (Romania)

In this paper, we present the results of the geomorphological study of the micro pseudokarst landfoms developed on Pâclele Mari mud volcanic site that belongs to the famous mud volcanic area Berca-Arbănași, Buzău Subcarpathians, Romania. Different types of pseudokarstic cavity formation can be observed in the area, especially in the sloping periphery of the mud volcanic area, where badlands developed (badland pseudokarst), and rheogene pseudokarst in the mud flows. The liquid mud material gets denser and wimple on the surface of the mud that flows in the trough, it compiles and then covers the liquid mud channel. These micro-size covered tunnels are similarly formed as lava tubes at the lava flows of real volcanic areas. In order to complement the field measurements, we carried out surveys with a DJI Phantom 3 and 4, and Mavic Pro quadcopter to determine the landforms for the photogrammetry. Granular composition tests were carried out on sediment samples collected in the mud volcanic area by a laser diffraction particle analyser.

Keywords: pseudokarst, badland, mud tubes, Păclele Mari mud volcanos, Buzău Land Geopark, Romania.

Izvleček UDK 551.435.1:551.311.8(498)

János Móga, Katalin Fehér & Daniela Strat: Značilnosti mikro psevdokraških oblik na območju blatnega vulkana Pâclele Mari (Romunija)

V članku predstavljamo rezultate geomorfološke študije mikro psevdokraških oblik, ki so nastale na območju blatnih vulkanov Pâclele Mari, ki je del znanega območja blatnih vulkanov Berca-Arbănași v okrožju Buzău v podkarpatski regiji, Romunija. Na proučevanem območju je mogoče opaziti različne vrste psevdokraških votlin, zlasti na nagnjenem obrobju območja blatnih vulkanov, kjer so nastala erozijska žarišča (psevdokras erozijskih žarišč), in na blatnih tokovih, kjer se je razvil reogeni psevdokras. Na površini blatnega plazu, ki teče v koritu, se blato zgošča in naguba, pri premikanju se blato kopiči, nato pa zapolni jarek tekočega blata. Ti zapolnjeni jarki mikro velikosti so podobno oblikovani kot lavine cevi v tokovih lave na območjih pravih vulkanov. Za dopolnitev terenskih meritev smo opravili raziskave s kvadrokopterji DJI Phantom 3 in 4 ter Mavic Pro, da bi določili reliefne oblike za fotogrametrijo. Na vzorcih sedimentov, odvzetih na območju blatnih vulkanov, so bili opravljeni testi zrnate sestave z analizatorjem laserske difrakcije delcev.

Ključne besede: psevdokras, erozijsko žarišče, blatne cevi, blatni vulkani na območju Păclele Mari, geopark Buzău, Romunija.

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1. INTRODUCTION

Pseudokarsts are specified as surface areas with subsurface water networks; areas where natural cavities have been formed by processes other than dissolution are observed in loess, lava flows, glaciers, permafrost areas and other places; and areas where dolines, caves or other specific features that are often observed in karsts occur in the poorly soluble and insoluble rocks. The organizing committee of the 12th International Congress of Speleology in 1997 defined pseudokarsts as follows: "Pseudokarsts refer to forms resembling to karst morphology, water drainage takes place mainly through subsurface channels, however, karst dissolution (corrosion) and erosion processes are not part of their morphogenetic character" (Kempe & Halliday, 1997). Knebel, 1908; Gvozdetskij, 1947; Otvos, 1976; Bryan & Yair, 1982; Parker et al., 1990; Kempe & Halliday, 1997; Grimes, 1997; Gallart et al. 2002 and many others authors have captured the essence of pseudokarsts: a karst-like morphology formed by processes other than dissolution. Pseudokarst caves are natural subterranean cavities of a size accessible to humans, formed by non-dissolution processes. In Central Europe, pseudokarst formations with doline-like depressions, sinkholes, drainage channels – also known as suffosion forms, piping, loess karst, semi-carbonate karst – are observed mainly in loess sediments (Jakucs, 1977; Zámbó, 1993; Veress, 2004; Móga & Németh, 2005; Kiss et al. 2007).

The following classification is used to identify pseudokarsts in general:

1. rheogenic pseudokarsts - pseudokarst formed on lava flows;
2. glacier pseudokarsts - pseudokarst formed in glacial ice and ice caps;
3. badland pseudokarst;
4. pseudokarsts and cavities formed by tectonic processes;
5. talus pseudokarsts with cavities formed between large piles of rock;
6. permafrost pseudokarsts;
7. littoral pseudokarsts, formed especially in the intertidal zone;
8. consequent pseudokarsts formed by the collapse of artificial underground cavities.

Pseudokarst forms also occur in mud volcanic areas where develop very dinamic badlands, which has not yet been recorded in the literature. These formations have been identified and studied in the mud volcanic areas of Buzău Geopark, close to river Buzău; most of them are small or micro-sized (Móga et al., 2020).

Since this study is not concerned with pseudokarst formations in general, but focuses on pseudokarst processes and landforms occurring in mud volcanic areas, our aim is to provide a brief review of the literature and research history of badland areas and rheogenic pseudokarsts observed in the area of the famous mud volcanoes terrains located in Curvature Subcarpathians, Romania.

The pseudokarsts of badland areas bear a striking resemblance to real karst forms – even if the carbonate content of the sediments is minimal – due to subsurface drainage that creates channels, caves, sinkholes, funnel-like drainage holes, dry valleys, natural bridges and doline-like depressions. The characteristic landforms are formed by periodically changing water flow in bare, moderately steep areas, mainly on slopes of granular rocks rich in silt and clay (Jakucs, 1977; Parker et al. 1990; Zhu et al., 2002; Veress, 2004; Móga & Németh, 2005; Halliday, 2006; Kiss et al., 2007). As water flows down the slope, it seeks a path partly on the surface and partly in small cracks, removing and displacing fine particles from the coarse ones, ultimately leading to loss of material and cavitation (Parker et al., 1990). In clay-rich sediments, which tend to swell when they absorb water and shrink when they dry out, swelling and shrinkage alternate continuously, resulting in the formation of larger and smaller cracks in the rock, which provide favourable conditions for the formation of subsurface drainage channels (piping).

In regions with alternating dry and humid climate and seasonal temperature changes, badland landscapes are affected by erosion processes during the wet season, although microclimate may also have a strong influence on the development of landforms (Bryan & Yair, 1982). In mountainous regions, during winter, freeze-thaw cycles cause significant amounts of material to move across steep and unstable slopes due to frost heaving and creep processes. Wetting, drying and freeze-thawing processes are also involved in the formation of the regolith layer covering the bedrock (Gallart et al., 2002), which also plays an important role in controlling erosion processes in badland regions.

The phenomena of pseudokarst formation in lava flows are used as an analogy in our study to understand the formation of mud tubes in mud flows, which is a micro-scale version of *rheogenic pseudokarst*. Among non-karstifying rocks, caves and cave systems form in basaltic lavas with the highest frequency and size (Thomas & Goudie, 2006; Gadányi, 2007, 2008a, 2008b). Basalt lava caves form in a very short period of time – compared to caves in karstic areas – and karst dissolution has no significant effect on their formation. Although the genetics of small mud tubes formed in mud volcanic areas differ from the genetics of lava tubes and actual karst caves, we can observe similarities in their shape and form. There is a considerable body of literature on the study of rheogenic pseudokarst (pseudokarst formed on lava flow) and much of it is concerned with the larger and more spectacular lava crust caves. Without being exhaustive, it is important to mention the names of those involved in the morphogenetic classification of lava tube caves (Halliday, 1993, 2004, 2007; Licitra, 1993; Peterson et al., 1994) – the latter identified the following cave types among Icelandic basalt lava caves: lava tube caves, vent caves, gas blister caves, so-called 'pseudocrater caves', sea caves, river erosion caves and crevice caves. Palmer (2007) subdivided basalt lava caves into further groups by briefly describing their morphogenetic characteristics.

Since only lava crust caves are relevant to the subject of our study, due to their resemblance to rheogenic pseudokarst forms, no further review will be made on the other existing forms. Liquid basalt lava flows are Pahoehoe-type lava flows, which can travel long distances in a short period of time and cover a large area around the eruption centre. Pahoehoe-type basalt lava flows (braided lava, ropy lava) – which have a temperature of 1000-1200 °C at the time of outpouring – gradually thicken their crust as they cool, due to 'swelling', where liquid lava intrudes and piles up under the gradually cooling and thickening surface crust, simultaneously with its formation, causing the crust to elevate several metres in height. The lava flow piles up and arises from the inside of the crust, reaching a final thickness as it solidifies. The English literature refers to them as 'inflated pahoehoe' (Peterson et al., 1994; Gadányi, 2008b). As the lava solidifies while in motion, it acquires a specific folded and braided shape during the flow. These studies have contributed immensely to our understanding of the genetics of syngenetic basalt lava caves and, more broadly, of rheogenic pseudokarsts.

This paper presents the results of the examination carried out on the pseudokarst landforms of the Pâclele Mari mud volcanic area located in the area of the UNESCO Buzău Geopark, along Buzau River, on the peripheral region of the Eastern Carpathians. Our aim was to investigate the connection between microscale pseudokarst forms and mud volcano activity, as no references were found on these microforms in the literature on pseudokarsts or in the studies on mud volcanoes.

2. GEOLOGICAL AND MORPHOLOGICAL CHARACTERISATION OF THE STUDY AREA

The study site is the Pâclele Mari mud volcanic area (45° 21' 29.1620" N, 26° 42' 44.7563" E), one of the geosite and geomorphosite of the Buzău geopark with intrinsec scientific value but also with educational and cultural values. The study site is located in one of the most tectonically active zones of the Carpathians, near the Vrancea zone (Figure 1). In terms of rocks it is composed by typical sedimentary and tectonic formations of the Flysch and Molasse, salt diapirs. The same factors have been involved in the formation of mud volcanoes as in other areas of the Eurasian mountain range (Apennines and Sicily in Italy, the Sea of Azov in Ukraine and Russia, Absheron Peninsula in Azerbaijan, etc.). We can observe hydrocarbon (oil and gas) traps in the area, together with active tectonic movements that form landslides and asociated mass movements, folded structures and salt diapirs from series of sediment layers of clayey and often highly saline composition. Tectonic effects have created overpressure zones in structures containing methane gas (Dimitrov, 2002, 2003; Kopf, 2002; Etiope et al., 2009; Bonini & Mazzarini, 2010), which have contributed to the formation of mud volcanoes.

Pâclele Mari is one of four mud volcanoe sites (Figure 1), which are situated in the outer part of the Eastern Carpathians (named Subcarpathians range) in a geological structure called the Inner Foredeep. Gas and oil seeping and eternal flames occur in this area. However, this region is recognised for its long history of oil and gas extraction activities and for its salt diapirs. Mud volcanoes occur along a N-S oriented anticlinal axis between Berca (located in the Buzau river valley) and Beciu settlements (located about 30 km north of Berca) (Andrăşanu, 2010; Brustur et al., 2015; Mazzini & Etiope, 2017; Stoica et al., 2017).

Mud flows rise towards the surface, together with saline and oily waters, due to the pressure of methane gas (Figure 2) in the Berca-Arbănaşi anticlinal axis and along the intersecting fault zone.

The mud volcanoes are relative small with majority from 0.5 to 100 m in diameter of craters, which a maximum height of only a few metres, yet their micromorphology is diverse. Quite close to Pâclele Mari, there are three other mud volcanic areas, which are not part of this study. These are Pâclele Mici (located about 3 km south

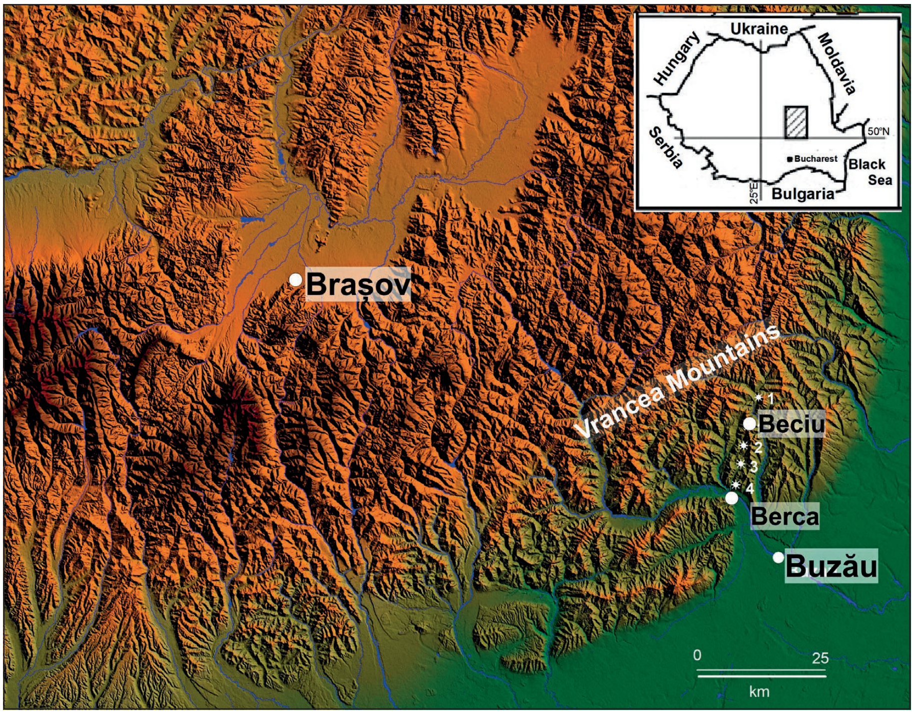

Figure 1: Four mud volcanic areas (marked with stars) formed in the southern part of the Eastern Carpathians (Subcarpathians). 1- Beciu, 2 - Pâclele Mari, 3 - Pâclele Mici, 4 - Fierbători-Berca. The vernacular name of mud volcanoes in Romanian language is "pâcle".

of Pâclele Mari), Fierbători-Berca (located about 7 km south of Pâclele Mari), and Beciu (located 4 km north of Pâclele Mari).

Gryphons and mud pools occur sporadically in the four investigated areas, which either stand alone or in small groups, surrounded by a large number of active and inactive mud flows. The Pâclele Mari area is about 500x400 m large, and named after the large mud volcano located in the centre of the mud hill (45° 21' 29.1620" N, 26° 42' 44.7563" E). This mud volcano is the largest one, over 100 m in diameter. The main cone is surrounded by smaller cones and parasitic craters, which can spill out and create a mudflow while spreading in a fan-like pattern in all directions (Figure 3).

Mud volcano activity depends mainly on the amount of gas emitted (internal pressure) and on weather factors, especially on the amount of precipitation. We have observed on several occasions that after a prolonged period of rainfall, a more intense bubbling took place in craters and mud pools, older dormant vents became active again, mud emissions became more frequent and formed longer – sometimes newer – mud flows over the older ones. Mud volcanic cones, which often have a crater at the top, are the largest and most spectacular landforms of the studied mud volcanic areas (Figure 4).

Mud emission spots usually appear in clusters in the central part of the mud volcanic area or are arranged in a formation defined by tectonic lines (e.g. along ma-

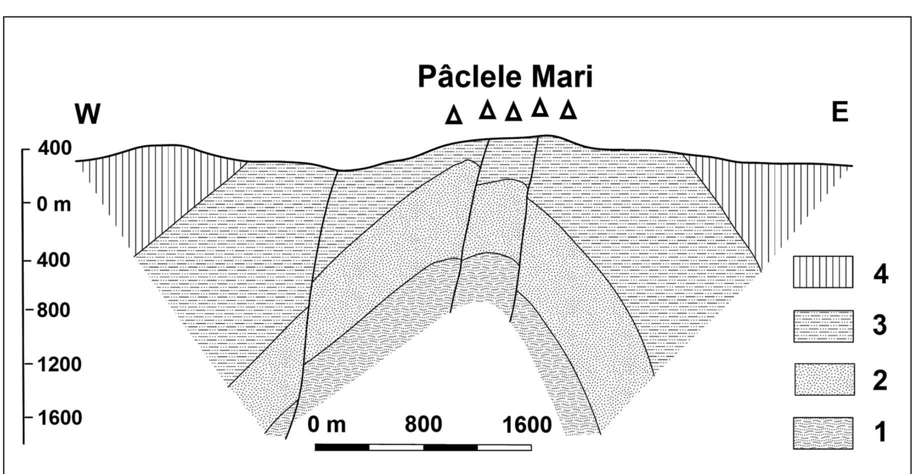

Figure 2: The Berca-Arbănaşi anticline, the axis of the faulted anticline, generally at the intersection with transversal faults (Modified after Ciocârdel 1949). 1 - marl with sand intercalation and salt breccia intrusions (Middle Miocene), 2 - sands and calcareous sandstone, oil-bearing formation (Upper Miocene), 3 - marls, siltstones (Upper Miocene), 4 - marls, siltstones, sands, coal and coaly schist intercalations (Pliocene). The y-axis shows the altitude and depth compared to 0 m sea level. Triangles are presenting mud volcanoes.

Figure 3: Overview of the Pâclele Mari, the trough-forming mud flows, which cut into the sloping surface, developed at the edge of mud volcanic area.

jor fault lines). Gryphons are conical landforms of overlapping mud flows from frequent or continuous mud spills. The slope of the cone is usually 45°, while the steepness of the slope depends on the grain size and the density of the discharged material. These mud cones either stand alone or occur in groups; their average height ranges from a few tens of centimetres to 3–4 metres and diameters at their basis from 0,5 m to more than 100 m. They are referred to as bubbling gryphons, due to the fact that a continuous gas bubbling takes place in the mud-filled craters. In most cases, a mud chamber can be found beneath the bubbling gryphon, which provides a continuous supply of mud, water and gas to the mud-filled crater – through a narrow passage – where bubbling is continuous. When the crater's pool fills up, the mud overflows and spreads out in a radiating pattern around the cone.

Mud pools are small circular or elliptical pools that

Figure 4: The largest and most spectacular landforms of the studied mud volcanic area are mud volcanic cones (gryphons).

dip into the mud surface without forming a rim. They are filled with oily water, liquid or viscous mud. We may distinguish between two types of mud pools, depending on whether gas allows liquid and gaseous materials to erupt at one single location above the vent or at several locations (Brustur et al., 2015). They can vary depending on the quantity and quality of the discharged material. Depressions, where only gas erupts, are drainless areas with gas exhalation; in most cases, however, mud overflows in one or more places, feeding silty water and liquid or viscous mud flows of tens of metres that spread out in a fan-like pattern over the sloping areas around the pools.

We can observe active and inactive mud flows in the Pâclele Mari mud volcanic area, as the seasonal activity and the material of mud volcanoes, as well as the amount of the discharged often varies, which may affect the type and direction of the mud flow as well. Although, mud flows spread radially (in a centrifugal pattern) around the cones, their activity and direction are constantly changing. On the other hand, the overflow vent of a crater or pool usually allows mud to flow in only one or two specific directions; the location of these vents may change over time, therefore older and dried-up mud flows are often intersected by the fresh and active flows. On flat surfaces that lie further away from the cones, two mud flows from different discharge vents may cross paths, and the denser mud flow may divert the other from its original path.

The fluids emanating from the pools are very diverse in terms of their material and viscosity. The most dilute fluids are those with minimal suspended matter and those mixing with the more fluid oily water; these fluids and dilute mud flows cut into the steeper slopes. They form a few cm wide and deep trough, where the deposited and dried mud forms a collar-like rim at the edge. On the steeper slopes of the mud hills, they often cross paths with mud flows from other discharge vents or with older, dried-up mud flows covered with a polygonal network of cracks. On rare occasions, dense and viscous mud flows can be observed as well, with a braided pattern similar to pahoehoe lava.

The trough-forming mud flows, which cut into the sloping surface, are similar to the karrens (rinns) of the burren areas, although quite different factors are involved in their formation. We can observe (more or less) straight and meandering troughs. They may have a rim of a few centimetres at the edge, which is a typical phenomenon of denser mud flows, but there are troughs that have no rim at all. The shape of mud flows varies intermittently, depending mainly on the slope of the surface. Mud flows generally run from a specific channel-bed on the steeper slopes; they may incise, meander as the slope decreases, then form wide mud lobes while spreading out. As they run towards the trough structure that formed along the margins of mud volcanic domes, they once again cut into the surface and form badlands.

3. MATERIALS AND METHODS

The pseudokarst formations were remarked during our first field work in 2014 in the aforementioned mud volcanic area. Since then, we have visited the area on an annual basis to monitor the evolution and transformation of pseudokarst formations. Monitoring surveys were carried out to examine the pseudokarst formations observed in trenches formed by the liquid mud and silty water flow and in their surroundings, on the sloping peripheral regions of the Pâclele Mari mud volcanic area. In order to identify the landform types occurring in the study area we used field measurements to examine the specific morphometric features of the microforms (Figure 6, 7, 8, 10. The identified features were divided into two separate groups: forms that are associated with *suffosion (piping)* and forms resembling in appearance to *lava crust caves*, but are much smaller in size – micro-scale forms, mud bridges, and mud tubes.

The field work measurements and observations were complemented with the analysis of orthomosaics produced from drone imagery using UAV photogrammetry, although the image resolution limits their applicability in the assessment of microforms. In order to complement the field measurements, and follow the landform changes we made several ortophotos of the investigation area in years 2017 to 2023. During the UAV fly every time 300-600 drone picture were made at a minimum 30 m and maximum 80 m elevation above the ground, depending of our goal. Sometimes we prepared a general image to see the whole area, on other cases we focused on detailed ortophoto about the microlandforms (Figure 3, 6, 7, 8, 10, 13). The stereophotogrammetric processing of the 12 Mpx resolution images was performed by Agisoft 1.2 professional software between 2017-2023.

For the labwork we taken sediment samples on 2 sites; one from the ceiling of Transit cave (see Figure 10, 11, 12) and one fresh sediment from the bottom of the same cave. We performed grain size analysis using

Horiba Partica LA 950V2 laser diffraction grain size analyser at the Central Research and Instrument Center of the Faculty of Science of ELTE. Our aim was to determine whether the formation of karst-like structures is more affected by dissolution processes or grain size distribution – which contributes to the formation of badland structures (sinkholes, cave-sized drainage channels, spring caves) without any dissolution process. The carbonate content, expressed as CaCO3%, was determined in a calcimeter containing 10% HCl, using the Scheibler method.

4. RESULTS

Our grain size composition analyses have revealed the presence of both fine and coarse grained sediments in samples taken from the cave and from the layers above the cave (Figure 12). Granular composition tests were carried out on two sediment samples, collected in the mud volcanic area, by a laser diffraction particle analyser. Both of the samples are classified as silty loam according to the USDA classification. The most characteristics particle sizes in each sample are the fine and medium silts (60–70%). The $CaCO_3$ content was low, varied between 7 and 11%. No significant difference between the samples was observed.

Our examinations were aimed at determining whether the cave sedimentary host rocks shown in Figures 11 and 12 and the sediments deposited in the recent stream bed are identical, or whether there is a difference in grain size, and whether this grain distribution is suitable for piping. There was little difference between the two samples, and the same could be said for the other five samples – taken from the nearby mud volcanic areas – when compared to the test results. We also examined the carbonate content of the two samples collected here, which showed a very low value, not sufficient to generate karstic dissolution. From these, we concluded that "piping" phenomenon was the initial process in the formation of the cave, and then, erosion took over the cavity-forming role as the passages widened.

A total of 146 small landforms were included in our database (year 2013) and later examined in the field, on which we found no previous references in the literature, and which are represented in the orthophoto taken from our drone images (Figure 6, Table 1). The identified features were divided into two separate groups: 1. badlands pseudokarst landforms (142 items) and 2. rheogene pseudokarst landforms (4 items). Their number is constantly changing, new forms are created within weeks or months, or they are buried or destroyed.

We classified the 146 small landforms based on the field and drone imagery (orthophoto) surveys and observations. The central and eastern part of the study area has the lowest number of pseudokarst forms, due to the presence of active mud volcanic cones and due to the fact that the surface is regularly covered with fresh mud by fan-like mudflows. Occasionally, however, syn-

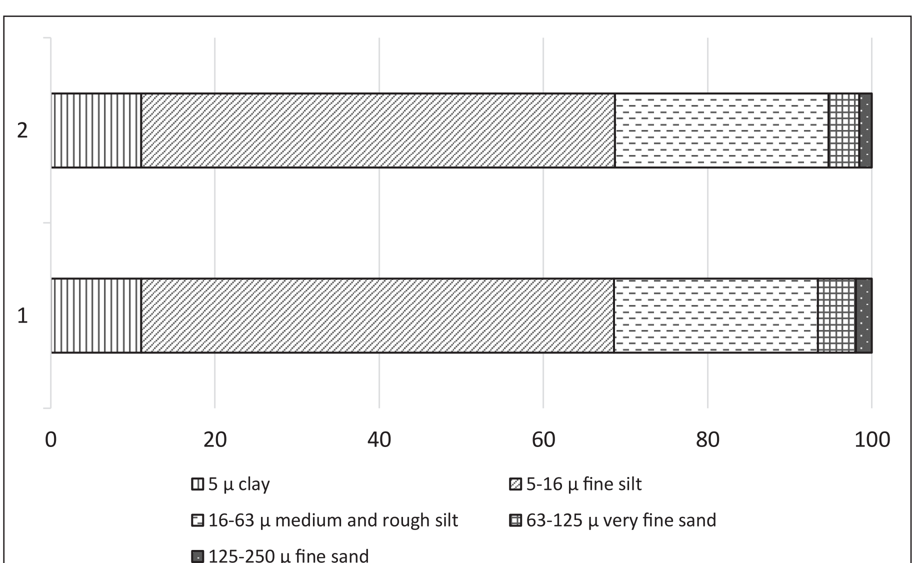

Figure 5: Grain size distribution of the rock samples after the classification of wenworth. Bar chart 1 - sample from the ceiling of transit cave shown the Figure 6, 10, 11. Bar chart 2 - sample from the bottom of the same cave.

genetic mud tunnels are created from the thickening mud, which are ephemeral forms. Piping tunnel forms are common features in the north-west part, while sinkholes are mainly present in the badland area, in an eastern direction. Meander tunnel forms also occur in this latter region. The other pseudokarst forms are scattered and occur in much smaller numbers.

Our morphogenetic views, formulated on the basis of our own observations and analogies, can be found in the discussion chapter.

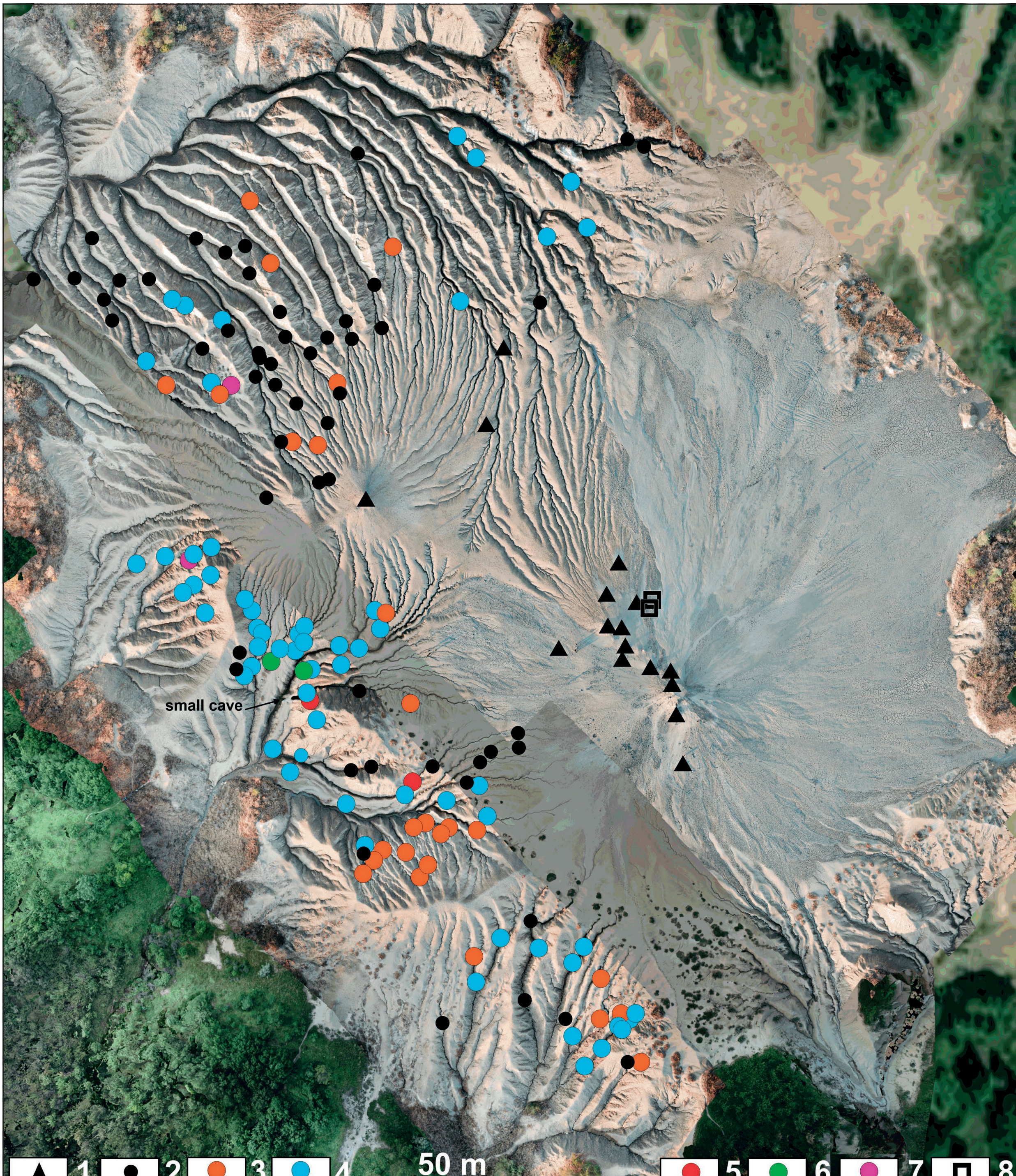

Figure 6: The surface ortophoto of Beciu mud volcanic area made by 2019 drone pictures partly combined with Google map. Legend: 1 - mud volcano, 2 - piping tunel, 3 - meander tunel, 4 - sinkhole, 5 - mud arch, 6 - dry valley, 7 - „uvala", 8 - syngenetic mud tube.

Table 1: Pseudokarstic landform types on the investigated area (2013).

Landform types	Number	Location	Remarks
Badland pseudokarst	**150**		
sinkhole	**59**		
sinkhole + dry valley	**2**	45° 21' 29. 5732" N, 26° 42' 39.4782" E	
piping tunel	**52**		
meander tunel	**26**	45° 21' 32.2338" N, 26° 42' 38.4480" E	
uvala	**2**	45° 21' 32.2338" N, 26° 42' 38.4480" E	
transit cave	**1**	45° 21' 29.0969" N, 26° 42' 39. 3554" E	
Rheogene pseudokarst	**4**		
syngenetic tube, window, mud arch	**2**	45° 21' 29.1620" N, 26° 42' 44.7563" E	In 2023 both objects were covered by new mudflow
postgenetic mud bridges (mud arch)	**2**		

5. DISCUSSION

5.1. RHEOGENE PSEUDOKARST LANDFORMS AND FORMATIONS

On the sloping margins of mud volcanic areas, mud bridges and mud tubes connect to dense mud flows, which results relative similar features that are characteristic for pahoehoe type of lava. The dilute mud flows found in the troughs where the silt matter piles up – while becoming denser due to evaporation on the surface of the mud or silty water draining in the trough – and covers the mud channel. Mud bridges and mud tubes may be *syngenetic* – when the tube or bridge is formed in the still viscous and liquid mud flow, thus the parent sediment or rock is contemporaneous with the formation of the cavity – or *postgenetic*, when cavity formation takes place later, in the already consolidated mud deposits due to erosion processes.

Syngenetic mud tubes develop – after our field studies – when the densified matter becomes wimpled on the surface of the mud draining in the trough, it compiles and covers the formerly developed mud channel. The mud flow creates a collar-like rim at the edge of the channel, which widens laterally and runs into the densified mud crust at the top of the liquid mud flow. The formation of the formerly mentioned mud crust is usually enhanced by evaporation during hot, dry periods (Figure 7, 8). Small twigs and other plant debris may form a barrier in the path of the mud flow, blocking a section of the mud trail, which contributes to the formation of an vault. These micro-scale covered tubes form in a similar way to lava crust caves that occur at pahoehoe-type lava flows in volcanic areas. In respect to the mud flow that runs north of the central large crater in the Pâclele Mari mud volcanic area, it has been discovered that the already densified but not yet solidified mud crust is lifted by the stronger waves of rhythmically approaching mud flows, resulting the upwarp of the external mud layer (roof) – this process is similar to the formation of *"inflated pahoehoe"* lava tubes (Peterson, et al., 1994, Gadányi 2008b).

We were able to observe the formation of syngenetic mud tube; we saw semi-open, closing and already covered tubes side by side in the same mud flow, between open trough sections, and we could observe the process of micro-scale mud tube formation through small holes (windows) that formed in the tube wall in some places (45° 21' 29.1620" N, 26° 42' 44.7563" E) (Figure 8).

An example of the *transition of syngenetic* and *postgenetic* formation of mud bridges and mud tubes is when a trough formed in solidified mud is crossed by another mud flow, which forms a crust over the trough, leaving it open underneath (syngenetic), or a section of the trough becomes partially closed, then exposed again by a subsequent liquid mud or water flow (postgenetic).

Since mud volcanoes emit more mud during wet periods, the emanating mud may completely fill the formerly developed trough, or even overflow and flood adjacent areas, partially or completely covering nearby troughs. In sloping areas that lie further away from the mud volcanic cones, the erosion of rainwater is strongly involved in the formation, as well as in the destruction and filling of the troughs as a result of the deposition of sediments. During periods of heavy rainfall, the water carries fine clayey sediment from the soaked surface; the sediment

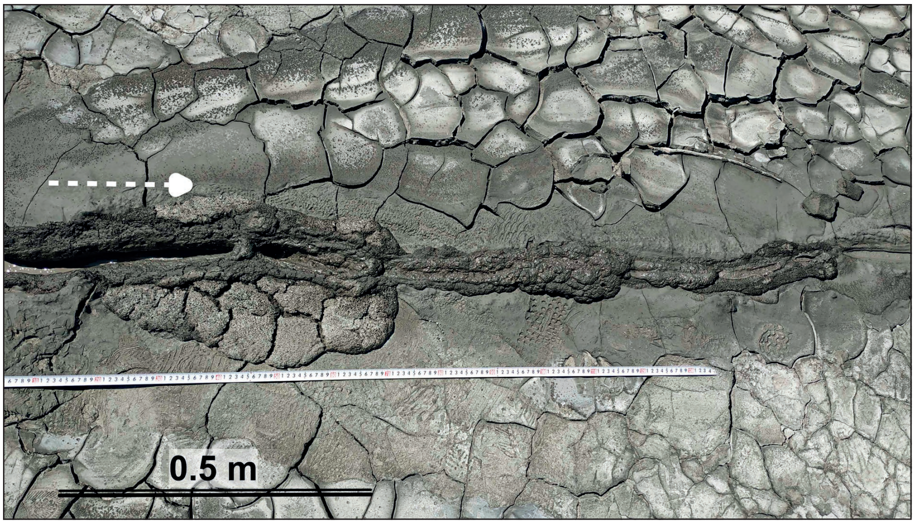

Figure 7: Syngenetic mud bridges and mud tubes may evolve during the evaporation of silty water, where the dense mud layer forms a crust on top of the liquid mud flow. The arrow show the flow direction.

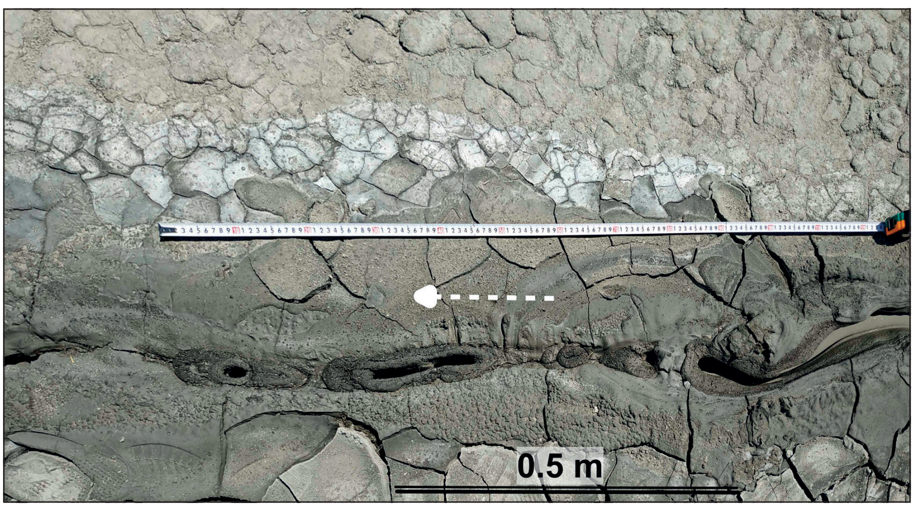

Figure 8: The process of micro-scale mud tube formation was observed through small holes (windows) opening on the roof of the mudtube. The arrow show the flow direction.

is spread over the flat surface and partially or completely fills the troughs. Open, semi-covered and covered trough sections may alternate along a mud flow as well. These mud bridges and mud tubes occur in large numbers in the Pâclele Mari mud volcanic study area (Figure 7), but are found only in micro sizes (size of a few cm or dm). The mud tubes have a diameter of 5-10 cm and rarely exceed half a metre in length. The covered mud tubes are sometimes exposed by holes (windows) (Figure 8) opening onto the surface (45° 21' 27.9533" N, 26° 42' 42.1558" E), and in rare cases, covered tubes form with a length of several tens of metres, with well-observable in-flow inlets or outlets (45° 21' 27.9533" N, 26° 42' 42.1558" E). Their shape and forms are less varied than that of the lava crust caves, and due to their small size, we cannot even refer to them as caves, however, drainage takes place inside them through subsurface channels, which is a typical feature of pseudokarsts (Kempe & Halliday, 1997; Palmer, 2007). The majority of mud bridges and mud tubes are persistent, they can be recognised clearly in the four drone images taken between 2017 and 2023 despite the fact that they have been covered in some places or reshaped by younger mud flows.

5.2. BADLANDS PSEUDOKARST LANDFORMS AND FORMATIONS

The studied mud volcanic area rises from its surroundings as a dome to a height of about 20-30 m, causing longer mud flows (with high water yield) and precipitation water to reach the foot of the adjacent valleys through a rapidly deepening trench system (Figure 3, 6). *Badland pseudokarst landforms and formations* (such as subsidence, suffosion forms and piping) – another type of pseudokarst landforms – develop on these marginal and entrenched surfaces that consist of loose sedimentary and are covered with continuous and sparse vegetation. In the badland areas of the investigated mud volcanic areas, a large number (150) of micro-scale pseudokarst forms

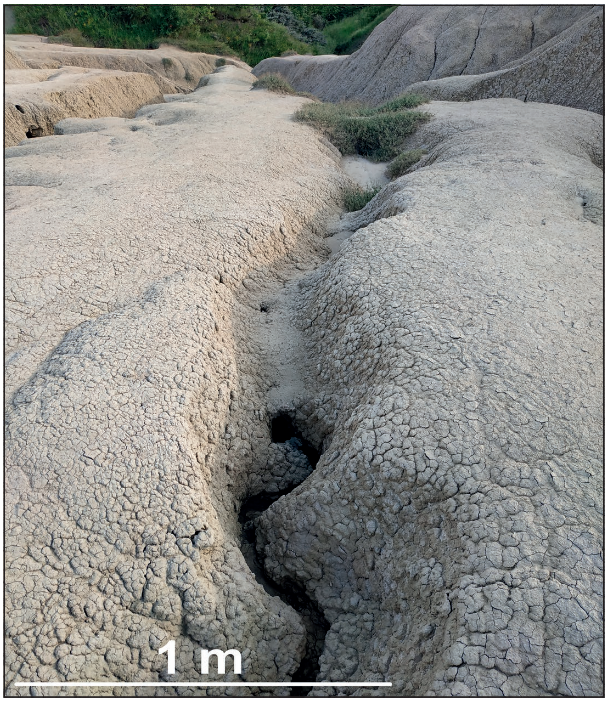

Figure 9: Sinking stream formed by a temporary brook on the Pâclele Mari mud volcanic area (No 9 on the Figure 10).

were observed in the smooth sediments that lie further away from the centre of the sites. In the area, we mainly observed small sinkhole openings with subsurface drainage channels connecting to them, and periodical outlets that connect to periodical water flows. These torrential streams flow partly on the surface and partly below it, creating short blind valleys of a few metres (Figure 7, 8), and dry valleys that formed by bathycapture (45° 21' 29. 5732" N, 26° 42' 39.4782" E) (Figure 9). The drainage vents evolved in them are not real sinkholes, but are part of the suffosion/piping phenomenon.

We also observed a few small natural bridges in the studied area. These forms are shorter and lower than 1 m. The small bridge represented in the Table 1 has been destroyed since 2019, although its edge is still visible.

The largest pseudokarst formation in the area is a periodically functioning cave we discovered and mapped on the research area. It is an approx. 3 m long tunnel (active transit cave) with a height up to about 1.7 m (45° 21' 29.0969" N, 26° 42' 39. 3554" E); which is traversed by a temporary brook running from a trench (Figures 10, 11, 12). Two small vents formed in the ceiling of the cave, through which water flows periodically, as indicated by traces of erosion. The water that accumulates

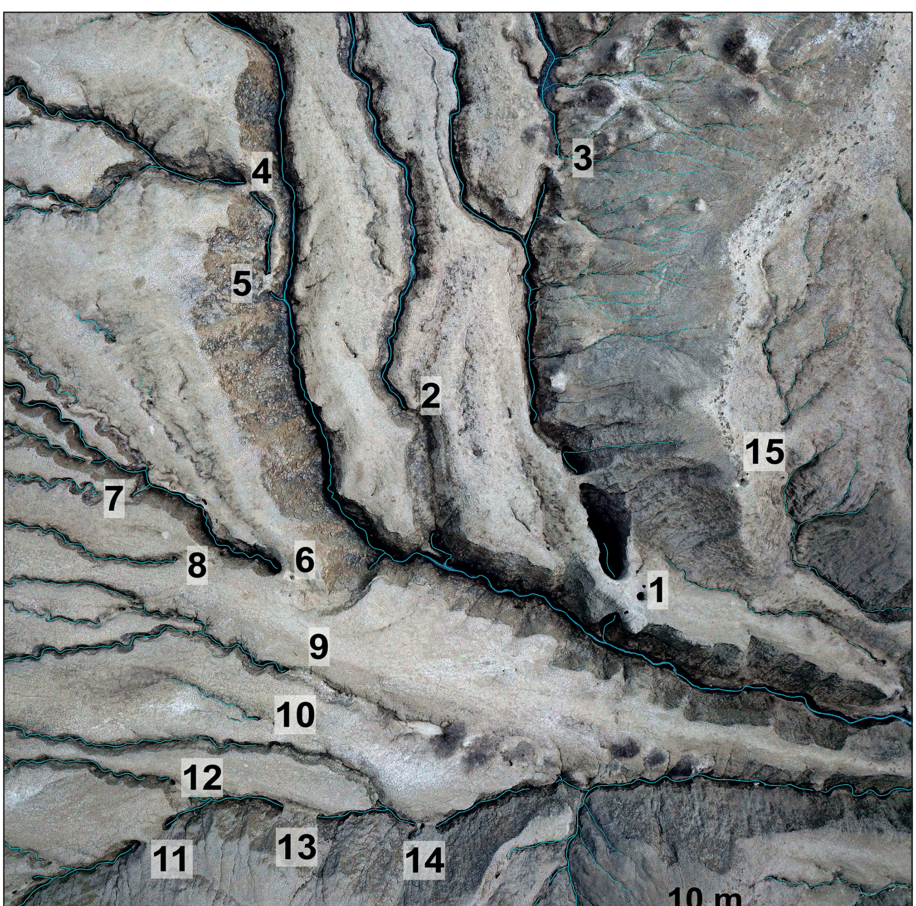

Figure 10: Micropseudokarst landforms on the SW part of Pâclele Mari. 1 - transit cave, 2-8 and 10-15 - sinkholes, 9 - dry valley.

Figure 11: Transit cave along the flow of a temporary brook (Pâclele Mari mud volcanic area).

in the trench during rainfall and flows through the cave has formed two levels in the cave. The upper, older passage level is only preserved in few places in the form of mud bridges due to collapse. The water reaches the lower level through the vents formed in the bed of upper passage. The lower level is aligned with the base of the main trench (the base level of erosion). The two levels merge in the main passage of cave. Three other channels are connected to the erosion cave corridor. These channels attest to the presence of an extensive tunnel system below the surface. The ceiling of the small cave is expected to be soon ripped by erosion of the water flowing through the vents.

Dolines, which are common formations in other badland areas, cannot be found in this region. The erosive action of the adjacent sinkhole vents, which have a small drainage area (of a few m^2), has resulted in the development of a polygonal set of shallow depressions due to the lack of fine-grained sediments transported by pipes below the surface. These depressions are connected in an uvala-like pattern to form a 57 m^2 large depression with subsurface drainage (45° 21' 32.2338" N, 26° 42' 38.4480" E). The draining water flows through an outlet that is located in the side of the nearby trench (Figure 13).

As discussed in the introductory part of this study, piping occurs when fine-grained dispersed clay and debris particles are gradually transported from poorly consolidated sediments by groundwater movement (Eberhard & Sharples, 2013; Bartolomé et al., 2015), leading to the formation of underground channels (Parker et al., 1990). The landforms show a striking similarity to real karst forms, even if the carbonate content of the sediments is minimal (around 10%, based on our examinations). Typical landforms are formed by periodical water flows in bare, moderately steep areas, mainly on slopes rich in silt and clay, composed of granular rocks (Jakucs, 1977; Parker et al. 1990; Zhu et al., 2002; Veress, 2004; Halliday, 2006; Móga & Németh, 2005). The water flowing down the slope moves partly on the surface and partly through small cracks, drifting and transporting fine particles away from the coarse ones, eventually leading

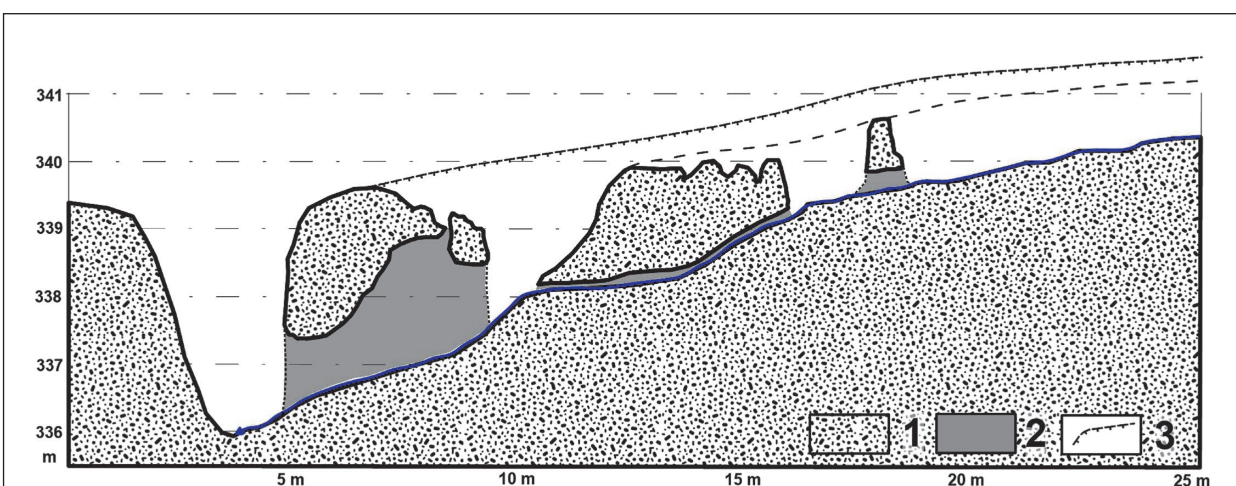

Figure 12: Hand drawn cross section of the transit cave along the flow of a temporary brook (Pâclele Mari mud volcanic area) Legend: 1 - mud layers, 2 - caves and tubes, 3 - former surface level.

to loss of material and forming of cavities. As the cavity expands, more and more water flows through it; erosion plays an increasing role in the shaping of the cavity. In clayey sediments, which tend to swell as they absorb water and shrink as they dry out, the constant change in volume results in the formation of cracks, both large (few cm) and small (few mm), which provide favourable conditions for piping.

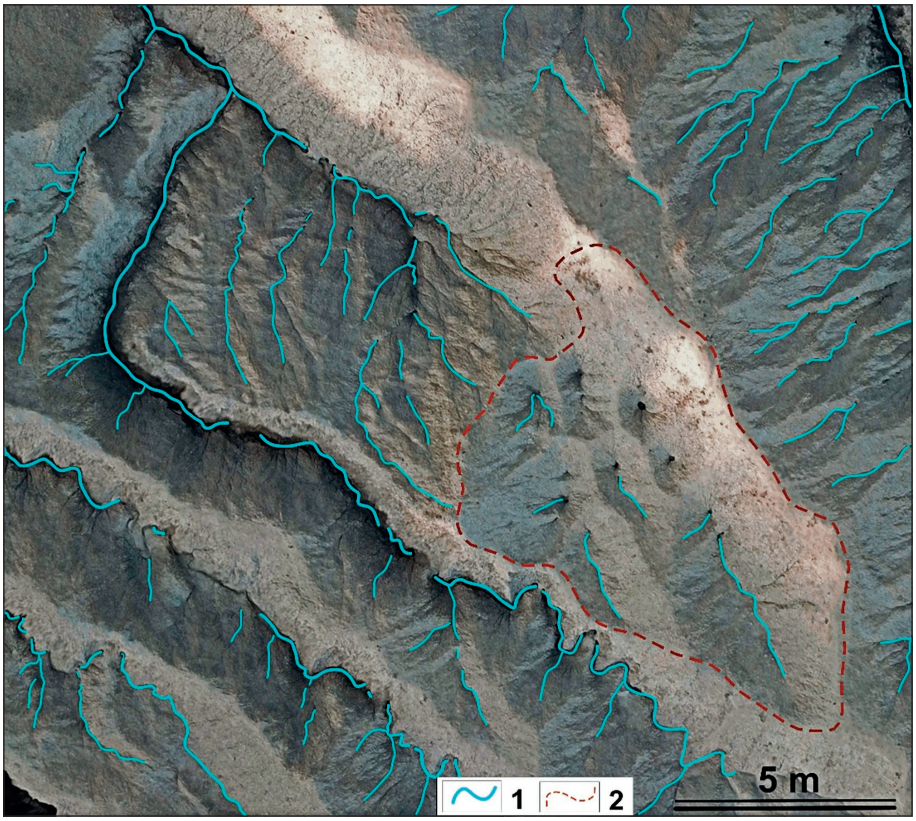

Figure 13: The erosive action of sinking water has resulted in development of a polygonal set of shallow depressions, which are connected in an uvala-like pattern. Legend: 1- Temporary waterflow on the surface, 2 - Rim of the small „micro uvala".

Figure 14: On the bottom of meandering trenches the temporary brook flowing through tunnel below the obstacle. 1 - current water flow, 2 - former flow direction.

Another typical landform on the area is the meander tube. These microforms can be associated with meandering trench systems with a lenghts of several ten meters and depth of 0.5-3 m that formed on the minor slopes of mud volcanic domes. Torrential streams deepen the bottom of the trenches rapidly, in which meanders develop – which are similar to the meander karrens of bare karsts (Veress, 1998, 2000). In the bottom of the trenches, asymmetric bank slopes developed, similarly to those in surface watercourses, due to the drift line's deflection from the centre line. The concave side of the bank – where water in the channel reaches main level – is more undercut by temporary water flow than the convex side. Meanders become deeper and gradually extend downwards in the bottom of the trench. Meander bends, deepened by low-water flows, can be observed in the wider base in the mid-water bed. The deepening and incision of low-water beds is interrupted by small ridges that meanders just do not develope there. The drifting water often breaks through the dam. The small tunel is formed due to the transport of fine particles (suffosion, piping), through small tubes in the concave bends (rather than in the surface level bed) (45° 21' 32.2338" N, 26° 42' 38.4480" E). This phenomenon is similar to the formation of rock bridges in meandering karren troughs (rinn), however, in this case, the forms found in the dry silt matter are "softer" and structure formation is not affected by dissolution processes (Veress, 1998, 2000) (Figure 14). We can find under-developed, developed, mature and over-developed bends in the meandering trenches. Some of the trenches lead to a blind valley, as the accumulating water leaves the trench through a tunnel (Figure 14). These small tunnels, which are typical pseudokarst features of the badlands of mud volcanic areas, are found in the meanders at the bottom of most trenches.

6. CONCLUSIONS

The periodical activity and substance of mud volcanoes, as well as the amount and density of the discharged mud often vary. These transformations determine the type and direction of the discharged mud flow.

Meandering mud flows (mud flows formed in troughs) often split and merge. Particularly spectacular microforms are formed when various types of mud flows (different in material or viscosity) intersect.

During our field work and the analysis of UAV imagery, we have distinguished two groups of the microforms: forms that are associated with *suffosion (piping)* and micro-scale forms resembling in appearance to *lava crust caves*, mud bridges and mud tubes.

Syngenetic mud bridges and mud tubes develop where dense mud forms crusts on top of the liquid mud flow, the densified matter becomes wimpled, it compiles and covers the mud channel. These micro-scale covered tubes, although being plain and small in size, form in a similar way to lava crust caves that occur at pahoehoe-type lava flows in volcanic areas.

A tunnel-like form may also occur when a trough is crossed by a more viscous mud flow, which forms a crust over the trough, leaving it open underneath, or a section of the trough becomes partially closed, then exposed again by a subsequent liquid mud flow (postgenetic mud tube).

On the sloping periphery of mud volcanic areas, where the silty water flow cuts deeper trenches into the old mud surface, several formations associated with subsidence (suffosion, piping) have been observed as well, such as sinkholes, cave-sized drainage channels and spring caves, ranging from micro-size (decimetre-scale) to an extent of few metres. A large number of meander tubes form at the bottom of meandering trenches.

Our study, which investigates the connection between micro-scale pseudokarst forms and mud volcano activity, fills a gap in the literature, as no references were found on these microforms in the literature on pseudokarsts or in studies on mud volcanoes.

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REFERENCES

Andrășanu, A., 2010. Buzau land geopark. Steps in building a new geopark in Romania, Scientific Annals – School of Geology. Special volume (100), Aristotle University of Thessaloniki, Proceedings of the XIX CBGA Congress, Thessaloniki, Greece, 23-26 September 2010, pp. 503–512.

Bartolomé, M. Sancho, M.C., Moreno, A., Oliva-Urcia B., Belmonte, Á., Bastida, J., Cheng, H., Edwards, R.L., 2015: Upper Pleistocene interstratal piping-cave speleogenesis: The Seso Cave System (Central Pyrenees, Northern Spain). Geomorphology, 228, pp. 335–344. https://doi.org/10.1016/j.geomorph.2014.09.007

Bonini, M., Mazzarini, F., 2010. Mud volcanoes as potential indicators of regional stress and pressurized layer depth.Tectonophysics, 494(1–2), pp. 32–47. https://doi.org/10.1016/j.tecto.2010.08.006

Brustur, T., Stănescu, I., Macaleț, R., Melinte-Dobrinescu, M.C., 2015. The mud volcanoes from Berca: a significant geological patrimony site of the Buzău Land Geopark (Romania), Geo-Eco-Marina, 21, pp. 73–96.

Bryan, R., Yair, A., 1982. Perspectives on studies of badland geomorphology. In: Bryan, R.,Yair, A. (eds.), Badland Geomorphology and Piping. Geo Books. Regency House, Norwich, pp. 1–14.

Ciocârdel, R., 1949. Regiunea petroliferă Berca–Beciu–Arbănași. Comunicări de Geologie, Studii tehnico-economice A1. București, 32 pp.

Dimitrov, L.I., 2002. Mud volcanoes – the most important pathway for degassing deeply buried sediments. Earth-Science Reviews, 59, pp. 49–76.

Dimitrov, L.I., 2003. Mud volcanoes – a significant source of atmospheric methane. Geo-Marine Letters, 23(3), pp. 155–161. https://doi.org/10.1007/s00367-003-0140-3

Eberhard, R., Sharples, C., 2013: Appropriate terminology for karst-like phenomena: The problem with 'pseudokarst'. International Journal of Speleology 42(2), pp. 109–113. https://doi.org/10.5038/1827-806X.42.2.2

Etiope, G., Baciu, C., Caracausi, A., Cosma, C., 2009. Gas flux to the atmosphere from mud volcanoes in Eastern Romania. Terra Nova, 16(4), pp. 179–184. https://doi.org/10.1111/j.1365-3121.2004.00542.x

Gadányi, P., 2007: Bazaltláva barlangok morfogenetikai típusai Izlandon – Karszt és Barlang 2006. I-II. pp. 19–32.

Gadányi, P., 2008a. Caves under uplifted surface crusts of basaltlava flows. Proceedings of the 10th International Symposium on Pseudokarst, Gorizia, Italy, pp. 119–126.

Gadányi, P., 2008b: Kéregalatti bazaltláva barlangok – Karszt és Barlang 2008. I-II. pp. 21–33.

Gallart, F., Sole, A., Puigdefabregas, J., Lazaro, R., 2002: Badland Systems in the Mediterranean – In: Bull, L.J., Kirkby, M. (eds.), Dryland Rivers: Hydrology and Geomorphology of Semi-Arid Channels. John Wiley & Sons Ltd. pp. 299–326.

Grimes, K.G., 1997. Redefining the boundary between karst and pseudokarst: a discussion. Cave and karst Science. Transactions of the British Cave Research Association. 24 (2), pp. 87–90.

Gvozdetskij, N.A., 1947. Karsztovaja Konferencija V. G. Molotove – Voproszi Geografii.

Halliday, W.R., (ed.) 1993. Proceedings of the 3th International Symposium on Vulcanospeleology – A Special Session of the 39th Annual Convention of the National Speleological Society Bend, Oregon, 1982, 132 pp.

Halliday, W.R., 2004. Vulcanospeleology: History. In: Gunn, J. (ed.), Encyclopedia of Caves and Karst Science, pp. 765–766.

Halliday, W., 2006. Piping caves and badlands pseudokarst. In: Gunn, J. (ed.), Encyclopedia of caves and karst science. pp. 1260–1968.

Halliday, W.R., 2007. Pseudokarts in the 21st century. Journal of Cave and Karst Studies, 69 (1), pp. 103–113.

Jakucs, L., 1977. Morphogenetics of Karst Regions. John Wiley & Sons, New York, 284 pp.

Kempe, S., Halliday, W., 1997. Report of the discussion on pseudokarst. Proceedings of the 12th International Congress of Speleology, Vol. 6, Basel, Switzerland: Speleo Projects, pp. 107.

Kiss, K., Zámbó, L., Fehér, K., Móga, J., 2007. A lösztakaró karsztosodásban játszott szerepének vizsgálata a Tési-fennsíkon. Karsztfejlődés XII. Szombathely. pp. 193–205.

Knebel, W., 1908. Höhlenkunde mit Berücksichtigung der Karstphänomene. Braunschweig, Friederich Vieweg und Sohn. 224 pp.

Kopf, A.J., 2002. Significance of mud volcanism. Reviews of Geophysics, 40(2), pp. 2–52. https://doi.org/10.1029/2000RG000093

Licitra, G.M., 1993. Essay on Genetic Classification of Volcanic Caves – In: Halliday, W.R. (Eds.), Proceedings of the 3th International Symposium on Vulcanospeleology. A Special Session of the 39th Annual Convention of the National Speleological Society Bend, Oregon, pp. 118–120.

Mazzini, A., Etiope, G., 2017. Mud volcanism: An updated review. Earth-Science Reviews, 168, pp. 81–112. http://dx.doi.org/10.1016/j.earscirev.2017.03.001

Móga, J., Németh, R., 2005. The Morphological Research of the basalt and loess covered plateaus in the Bakony mountains (Transdanubian Middle mountains – Hungary). Acta Carsologica, 34 (2), pp. 397–414.

Móga, J., 2020. A Keleti-Kárpátok iszapvulkánjai, GeoMetodika 4. 1. pp. 19–33. https://doi.org/10.26888/GEOMET.2020.4.1.2

Otvos, E.G., 1976. Pseudokarst" and "pseudokarst terrains": Problems of terminology – Geological Society of America 87(7), pp. 1021–1027. http://dx.doi.org/10.1130/0016-7606(1960)71[467:ABFMTS]2.0.CO;2

Palmer, A.N. 2007. Cave geology. Cave Books, Dayton, OH, 454 pp.

Parker G.G., Higgins, C.G., Wood, W.W., 1990. Piping and pseudokarst in drylands – In: Higgins, C.G., Coates, D.R. (eds.), Groundwater Geomorphology; The role of Subsurface Water in Earth-Surface. Processes and Landforms, 252, pp. 77–110. https://doi.org/10.1130/SPE252-p77

Peterson, D.W., Holomb, R.T., Tilling, R.I., Christiansen, R.L., 1994. Development of lava tubes in the light of observations at Mauna Ulu, Kilauea Volcano, Hawaii. Bulletin of Volcanology, 56, pp. 343–360.

Stoica, M., Andrăşanu, A., Palcu, D., Popa, R.G., 2017. The Miocene from Buzău area. A geological and geoconservation perspective. The 11th Romanian Symposium on Palaeontology Bucharest, September 25-30, 2017. Editura Universitații din Bucureşi, pp. 43.

Thomas, D.S.G., Goudie, A., 2006. The dictionary of physical geography – Blackwell Publishing, 76 pp.

Veress, M., 1998. Karrmeanderek. Karsztfejlődés, 2, pp. 35–58.

Veress, M., 2000: Karrformák összeolvadása. Karsztfejlődés, Szombathely, 5, pp. 143–157.

Veress, M., 2004: A karszt – Szombathely. 382 pp.

Zámbó, L., 1993. A karsztosodó kőzetek alaktana (Karsztgeomorfológia). In: Borsy, Z. (ed.) Általános Természet Földrajz, Nemzeti Tankönyvkiadó, Budapest, pp. 544–592.

Zhu, T.X., Luk, S.H., Cai, Q.G., 2002. Tunnel erosion and sediment production in the hilly loess region, north China. Journal of Hydrology, 257, pp. 78–90.