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Daniela STRAT [1], Klaudia KISS [2], Judit SZABÓ [3] & János MÓGA [2*]

GEOMORPHOLOGICAL ASSESSMENT OF THE BECIU MUD VOLCANO TERRAIN, EASTERN CARPATHIANS, ROMANIA

Abstract: Strat D., Kiss C., Szabó J. & Móga J., *Geomorphological assessment of the Beciu mud volcano terrain, Eastern Carpathians, Romania*. (IT ISSN 0391-9838, 2020).

Mud volcanoes are widespread geological and geomorphological structures that are usually associated with folded sedimentary deposits bearing hydrocarbons. A significant number of mud volcanoes and gas seepages occur both in the extra-Carpathian area and the intra-Carpathian area in Romania. The most famous region in terms of number, geomorpho-diversity, and area surface of mud volcanoes is the Berca-Arbănași system, which is related to an anticline that belongs to the Buzău Subcarpathians division located in the southern part of the Eastern Carpathian belt, Romania. In this paper we present the results of geomorphological assessment of mud volcanoes from Beciu site that belongs to the Berca-Arbănași system, based on field surveys and drone mapping. The Beciu mud volcano terrain resembling a dome plateau has an area of a half hectare whereon are scattered around 50 active mud vents and gas vents, with a relatively quiescent expulsion of gas, water, and mud. In the area of Beciu site typical features of classical mud volcanoes were identified, as well as peculiar microforms that develop on the mud flows. Badland morphology has formed by the surface water runoff erosion of clay sediments outcropping in the peripheral area of the mud volcano terrain. Although the Beciu mud volcano site is not a protected area, its conservation status is favorable and no anthropogenic threats and pressures have been identified at present.

Key words: Berca mud volcanoes system, Anticline, Hydrocarbons seepage, Buzău Subcarpathians, Mud volcano topographic features.

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Riassunto: Strat D., Kiss C., Szabó J. & Móga J., *Analisi geomorfologica dell'area a vulcani di fango Beciu, Carpazi Orientali, Romania.* (IT ISSN 0391-9838, 2020).

I vulcani di fango sono strutture geologiche e geomorfologiche molto diffuse, di solito associate a depositi sedimentari ripiegati contenenti idrocarburi. In Romania, sia nell'area extra-carpatica che nell'area intra-carpatica, si trova un numero significativo di vulcani di fango ed emissioni di gas. La regione più famosa in termini di numero, geomorfo-diversità ed estensione dell'area a vulcani di fango si trova nel sistema Berca-Arbănași, che è correlato a un'anticlinale che appartiene all'unità 'Buzău Subcarpathians', situata nella parte meridionale della fascia orientale dei Carpazi. In questo lavoro presentiamo i risultati di uno studio geomorfologico condotto sui vulcani di fango del sito Beciu, che appartiene al sistema Berca-Arbănași, condotto con indagini di terreno, rilievi e cartografia da droni. Il terreno del vulcano di fango Beciu assomiglia a un altopiano a cupola, esteso circa mezzo ettaro, che ospita circa 50 vulcanetti di fango attivi e bocche di gas, in gran parte caratterizzati da un'attività relativamente quiescente di emissione di gas, acqua e fango. Nell'area del sito di Beciu sono state individuate le caratteristiche tipiche dei vulcani di fango classici, oltre a peculiari microforme che si sviluppano sulle colate di fango. La morfologia a calanchi che circonda l'area con vulcani di fango è dovuta all'erosione dei sedimenti argillosi affioranti ad opera delle acque superficiali. Sebbene il sito del vulcano di fango Beciu non sia un'area protetta, le condizioni al contorno sono favorevoli e, al momento, non sono state identificate pressioni antropiche in grado di minacciare la sua conservazione.

Termini chiave: Sistema dei vulcani di fango di Berca, Anticlinale, emissioni di idrocarburi, Subcarpazi di Buzău, morfologia dei vulcani di fango.

INTRODUCTION

The research on mud volcanoes has both geological and geomorphological approaches. Mud volcanoes are geological structures formed as a result of the mobilization of deeply buried sediments and the extrusion of mud-breccia, saline water, oil, and gases at the earth terrestrial surface or seafloor (Milkov, 2000; Etiope & *alii*, 2009). They are one of the types of sedimentary volcanoes that occur in the commonly unconsolidated subsoil. Although there are no genetic links between mud volcanism and magmatic volcanoes, these two phenomena share interesting characteristics and similarities, such as the surface morphology and the processes that contribute to their genesis (Revil, 2002; Dimitrov, 2003; van Loon, 2010; Wang & Manga, 2010; Tinivella & Giustiniani, 2012).

From a geomorphological point of view, mud volcanoes are defined as positive topographical features constructed mainly by periodic or continuous extrusion of mud, waters, oil, and gases (Hovland & *alii*, 1997). Mud volcanoes correspond to morphological spots of highly focused gas, water, and fluidized sediments outflows which are associated with highly pressurized source regions at depth (Brown, 1990; Revil, 2002). A conceptual model of structures (a mud reservoir connected to a vertical conduit) associated with the constructional edifice and the eruptive behavior of mud volcanoes is given by Zoporowski & Miller (2009).

Different criteria are used to classify mud volcanoes. Based on the period time and intensity of the eruption, the mud volcanoes are separated in three main types (Kalinko, 1964, quoted by Dimitrov, 2003). According to the activity and behavior of mud volcanoes, they were classified in: eruptive, dormant/sleeping, and extinct types (Mazzini & *alii*, 2009). Size is another criterion of classification: small-size mud volcanoes (< 0.5 km^2), medium-size mud volcanoes (0.5-9 km^2), and large-size mud volcanoes, with an area over 9 km^2 (Etiope & Milkov, 2004). Geomorphological (Yassir, 1989; Hovland & *alii*, 1997) and morphogenetic classifications (Kholodov, 2002) of mud volcanoes were also proposed.

Mud volcanoes occur worldwide, both in terrestrial and submarine geological settings where there is gas in sediments, mainly methane (Revil, 2002), but the overwhelming majority is spread in the submarine environment (Milkov, 2000; Kholodov, 2002; Dimitrov, 2002; Judd, 2005; Baloglanov & *alii*, 2018). Recently, it has been reported that there are over 2 500 investigated and inventoried mud volcanoes spreaded all over the world in a wide variety of tectonic environments, including the bottom of Lake Baikal, but the highest density distribution is along the Alpine Tethys Suture Belt (Khlystov & *alii*, 2017; Baloglanov & *alii*, 2018; Khlystov & *alii*, 2019).

The majority of described terrestrial/onshore mud volcanoes are located in the convergent lithospheric margins with thick sedimentary deposits that belong to the Alpine-Himalayan orogenic system (Dimitrov, 2003). The main locations of mud volcanoes have been summarized and mapped by Milkov (2000, 2005), Tinivella & Giustiniani (2012), and Baloglanov & *alii* (2018). Also, an atlas of world mud volcanoes was published (*Aliyev* & *alii*, 2015), but nevertheless the total number of mud volcanoes on Earth remains still uncertain (Mazzini & Etiope, 2017).

Comprehensive explanations on the genesis of mud volcanoes and processes of mud volcanism are given by many authors (Higgins & Saunders, 1973; Ali-Zade & *alii*, 1984; Najwa, 1989; Dimitrov, 2002; Kopf, 2002; Deville & *alii*, 2003; Pralle & *alii*, 2003; Yassir, 2003; Mazzini, 2009; Mazzini & *alii*, 2009; Bambang & *alii*, 2012; Mazzini & Etiope, 2017) but still, there are no common opinions on describing the origin of these peculiar features, as well as the physics of their dynamics (Revil, 2002). In some circumstances, the intensity of mud volcanoes activity is related or immediately triggered by earthquakes, and the consistence of ejected mud is sometimes associated with the rainy season (Milkov & *alii*, 2003; Frunzescu & Brănoiu, 2004; Baciu & Etiope, 2005; Milkov, 2005; Manga & *alii*, 2009; Bonini & Mazzarini, 2010; Warren & *alii*, 2011; Bonini, 2012; Bonini & *alii*, 2016; Bunila, 2016).

In the last decades, the interest in mud volcanoes has increased due to their huge amount of emission of methane and carbon dioxide, which represent a significant natural geological source of atmospheric greenhouse gases (Hovland & *alii*, 1997). In particular, it has been stated that mud volcanoes are the most important pathways for degassing of deeply buried sediments (Dimitrov, 2002), and are the second most important natural methane source, after wetlands (Heller & *alii*, 2011). Therefore, the role of mud volcanoes in global climate dynamics is far from being negligible, and cannot be ignored (Dimitrov, 2003; Milkov & *alii*, 2003; Etiope & Milkov, 2004; Milkov 2005; Etiope & *alii*, 2009; Etiope, 2005a; Etiope, 2005b; Judd, 2005; Baciu & *alii*, 2007). Also, mud volcanoes can be considered as originators of natural hazards (Mazzini & *alii*, 2009; Madonia & *alii*, 2011), and least but not least, mud volcanoes are studied as analog habitats for possible microbial life on Mars (Hosein & *alii*, 2014).

After the first synthesis of the mud volcano occurrences in Romania (Peahă, 1965), a new GIS based inventory was made recently (Ionescu & *alii*, 2017). According to this data base, the Romanian territory is one of the regions with the largest number of terrestrial mud volcanoes in the world, about 240. Their distribution is closely linked to the intense tectonics caused by the Carpathians orogenesis and post-orogenic basin uplift, as well as to the formation and distribution of hydrocarbon deposits (Peahă, 1965; Baciu & *alii*, 2007).

The largest and most well known mud volcanoes in Romania occur in the Buzău Subcarpathians, a subunit of Eastern Carpathians. In this paper, we present the results of the geomorphological study of the Beciu mud volcanoes based on field observations and analysis of aerial photos acquired by Unmanned Aerial Vehicle. Preliminary results are given with respect to particle size distribution, CaCO3 content, and the total organic carbon content of the sampled ejected mud.

STUDY SITE

The present study was conducted to observe the particular morphology developed in the Beciu mud volcano terrain that occurs along the crest of the anticline named Berca-Arbănași that lies within Buzău Subcarpathians unit, in the Eastern Carpathians section (fig. 1). Tectonically, the area corresponds to a continental unstable transform-transform-compression triple-junction of the East European Plate, Moesian microplate, and Intracarpathian microplate, which has generated a very active seismic zone, named Vrancea area (Zugrăvescu & Polonic, 1997; Besutiu & Zugrăvescu, 2003).

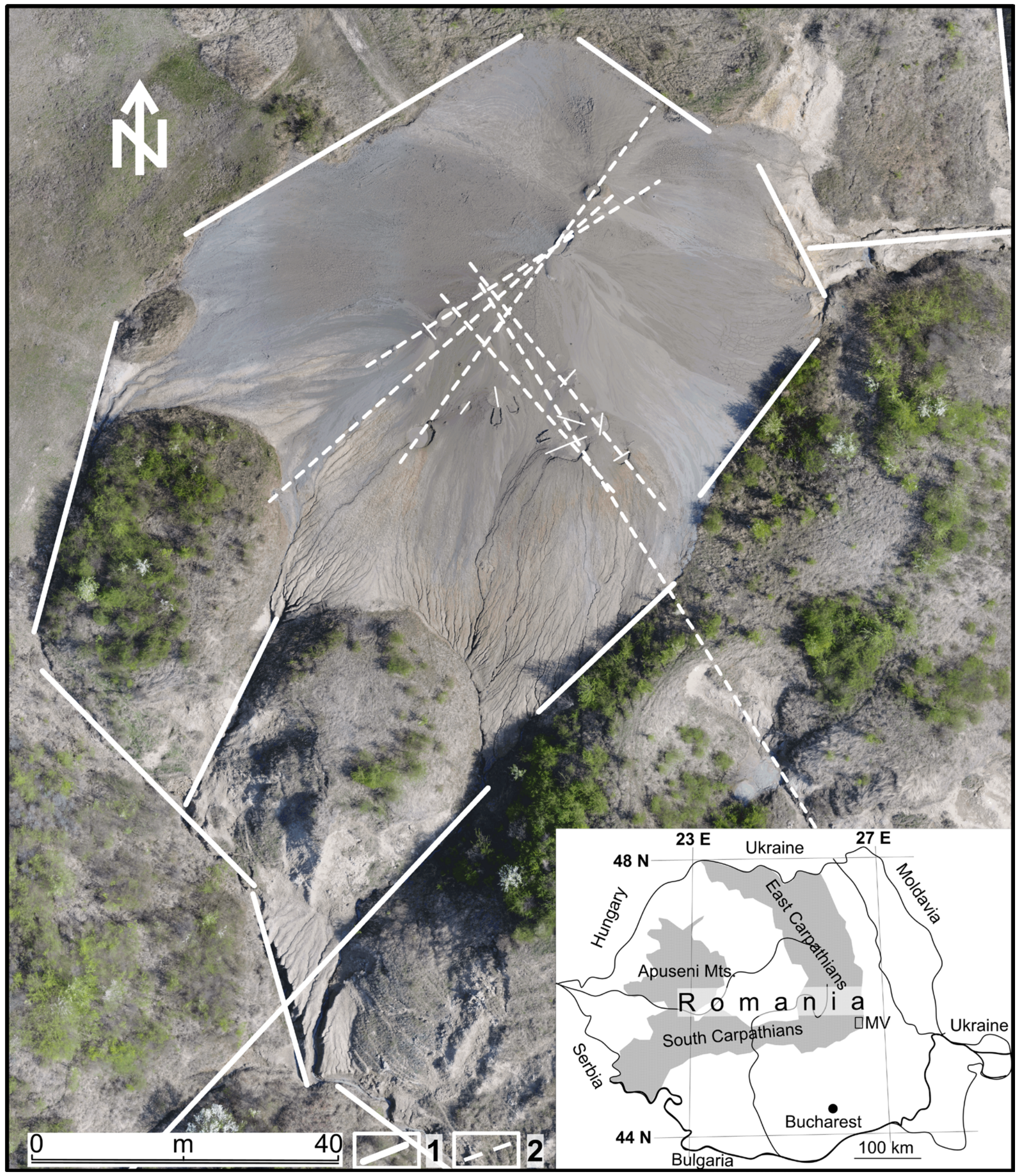


FIG. 1 - Location of the study site (BMV) in the area of Eastern Carpathians, Romania, and the aerial view of the Beciu mud volcano plateau and its surroundings. Photomosaic composed by pictures taken with DJI Phantom 4 Advanced quadcopter in June 2019. 1 – line of faults that control the surface landforms; 2 – line of fault. The occurrence and spatial distribution of the main mud vents illustrate the general direction of fractures that affected the anticline fold with hydrocarbons and salt deposits (see fig. 2).

The Beciu mud volcano is one of the four mud volcano sites that have formed along the crest of Berca-Arbănaşi anticline. This anticline of approximately 30 km length, is generally NNE-SSW oriented and consists of Miocene molasses sediments with salt core that belongs to the outermost geological structure of the Inner Foredeep in the Eastern Carpathians (Stoica & *alii*, 2017). The above mentioned fold is a hydrocarbons bearing-structure that is composed of Miocene and Pliocene sediments (Simionescu, 1927; Ciocârdel, 1949; Sencu, 1985; Brustur & *alii*, 2015; Melinte-Dobrinescu, 2017; Stoica & *alii*, 2017) (fig. 2).

The Berca-Arbănaşi anticline is faulted by a longitudinal fault, which is approximately superimposed on its longitudinal axis, and several transverse faults and local cracks. These fractures reach the hydrocarbon reservoirs, providing pathways for the Sarmatian gas accumulations (fig. 2). According to Sencu (1985), based on boreholes performed during hydrocarbon explorations, the main gas reservoir is located 3 km deep. Locally, the complex fault network breaches the lower Pontian top seal, thereby creating pathways for the upward migration of hydrocarbons and the development of gas vents, oil seeps, and mud volcanoes to the ground surface (Stoica & *alii*, 2017). Thus, the existence of mud volcano fields along the Berca-Arbănaşi anticline corroborates the theory that the genesis of mud volcanoes is typically associated with the crests of over-pressured anticlinal uplifts (Revil, 2002).

The climate in the area is temperate continental influenced by foehn effects that are typical within the Sub Carpathians Curvature region. The mean annual air temperature is around 10 °C and the average annual precipitations are about 700 mm. Drainage network has produced denudation of anticline, especially along the central axis, which subsequently has evolved broadly into erosional depression, a "*boutonnière*-like" *depression* (Badea & Bălteanu, 1971; Sencu, 1985) with more or less rounded hills. Erosion has exposed Pontian deposits and patches of Meotian deposits, as in case of the Beciu site. Generally, the altitude of hills that have resulted from the fragmentation of the crest anticline ranges from 350 to 450 m. Due to erodible rock surface and relatively steep slopes, the entire region is affected by active erosion, which mainly is a combination of gullying and mass movements, especially landslides, mud flows and creeps. The whole territory with mud volcanism from Buzău Subcarpathians, located between Buzău and Slănicu de Buzău river valleys, is generally named Berca mud volcano region. It consists of four distinct mud volcano fields, named Fierbători-Berca, Pâclele Mari, Pâclele Mici, and Beciu. All four mud volcano fields that compose Berca system are positioned on the axis of the faulted anticline, generally at the intersection of the longitudinal faults with the transverse faults (Melinte-Dobrinescu & *alii*, 2017; Stoica & *alii*, 2017).

Indubitably, mud volcanism represents one of the most fascinating geological phenomena of the Earth crust, even though during the past the majority of people deemed mud volcanoes as miracles, strange natural phenomena that usually were associated with fantastic legends and surrealistic explanations. In Romania, depending on the geographical region and referring to the type, color, and consistency of ejected material as well as the crater shape and the emitted sound of bubbling, mud volcanoes have various local names such as *gloduri*, *pâcle*, *fierbători*, *bâhle*, *bolboroși*, *zalțe*, *mocirle*, *băltoage* (Cobălcescu, 1883; Enculescu, 1911; Frunzescu & Brănoiu, 2003).

The folk tale concerning the origin of mud volcanoes in the Berca-Arbănași region is about a wounded dragon that is hidden underground, and it was described in a literary work from the 19th century (Odobescu, 1874). This legend of mud volcanoes is immemorial, wide spread in the Berca-Arbănaşi anticline area and well known by the locals since the hill with mud volcanoes sites is named the Dragon Hill (*Dealul Balaurului*, in Romanian language) (Brustur & *alii*, 2015). This toponym is mentioned on the first detalied topographic map of the region, published in 1790.

The first scientific description of the origin and morphology of mud volcanoes from the Berca region is provided by Coquand (1867). The first geological cross-section that depicts geological strata of the Berca-Arbănaşi anticline, including the location of mud volcano terrain from Berca site, was made by the Romanian paleontologist Grigore Cobălcescu, toward the end of the 19th century. Cobălcescu (1883) noticed the presence of all four mud volcano fields on the Berca-Arbănași alignment and explained his *theory about the mechanism of formation* of mud volcanoes. In particular, Cobălcescu (1883) highlighted the close connection between hydrocarbon deposits, sediment types, and the occurrence of mud volcanoes, excluding any involvement of magmatic volcanism. Cobălcescu (1883) also made thorough geomorphological observations and descriptions on mud volcanoes from Beciu and Berca-Fierbători sites, accompanied by detailed drawings of main features, descriptions of ejected materials and the behavior of eruptions.

Studies on genesis of mud volcanoes from Berca region were resumed at the begining of the 20th century by Costăchescu (1905) who determined the chemical composition of gases that are released along with the muddy material. Later on, an accurate geological map and a cross-section of the Berca-Beciu-Arbanași anticline was provided by Ciocârdel (1949). He also linked the occurrence of mud volcanoes to the accumulation of hydrocarbons in this folded structure and to the complex fault network that crosses it. Subsequently, more elaborated geomorphological studies of the Pâclele Mici and Pâclele Mari, the two mud volcano sites that occur on the anticline, were published (Badea & Bălteanu, 1971; Sencu, 1985), including a block-diagram that depicts the location of mud volcano terrains on the anticline, as well as a morphological classification of the volcano cones (Sencu, 1985).

A comprehensive morphological study of the Pâclele Mici and Pâclele Mari areas was recently published (Brustur & *alii*, 2015), given that these sites are natural reserves since 1924, and currently they are designed key geological and botanical sites of the Buzău Land Geopark (Melinte-Dobrinescu & *alii*, 2017). Indubitably, these two mud volcano sites are famed in Romania and even in Europe, and they have been subject of several scientific studies in the last decades on various topics including the mineralogy and chemistry of the ejected mud (Schniukov & *alii*, 2009; Madeja & Mrowczyk, 2010), chemical composition and estimation of annual gas volume exhalation (Etiope & *alii*, 2002; Etiope & *alii*, 2009; Baciu & *alii*, 2007), chemical analysis of the waters expelled by the mud volcanoes (Brustur & *alii*, 2015), microbial diversity, microbial activity and methano-genesis (Alain & *alii*, 2006), and resistivity measurements of the subsoil in order to diagnose the buried structures (Stochici & *alii*, 2016; Diascopolos & Stoichici, 2016). Due to its geological and geomorphological value, the Beciu mud volcano site was included in the area of a new proposed geopark named "Geoparkul Țara Buzăului" (Andrășanu, 2010; Brustur & *alii*, 2015).

MATERIAL AND METHODS

In order to map and to analyse the morphometry and morphology of the Beciu mud volcano plateau, the fourth site from Berca mud volcano system, field measurements and aerial surveys with an Unnamed Aerial Vehicle were carried out in November 2017, April and August 2018, April 2019. Aerial pictures with 12 Mpx were acquired with DJI Phantom 3 quadcopter during the automatic flights. The flight level was set at 30-50 m above the ground of the study area. The captured images and surveyed ground control points were processed using the photogrammetry professional software Agisoft *PhotoScan, version 1.2*.0. Ground control points were used to georeference the point cloud and 3D point in order to construct the digital surface model by interpolation method. WGS 84 (EPSG: 4326) geographical coordinate system was used to create the digital elevation model and export them as TIFF files. The resolution of the final raster is px/m. Insertion into geographic projection was made on the basis of the GPS points measured in the field. Additionally, a selection of historic aerial photographs taken on different dates and available on Google Earth was used for comprehensive geomorphological and morphometric examinations; the measurements were performed by Global Mapper 17 software. Cross-sections of mud volcano cones were extracted from a combination of the "Structure-from-Motion" method (Westoby & *alii*, 2012; Woodget & *alii*, 2017) and ground elevation data in order to assess the general morphology of them. The mud vents identified were inventoried and labeled with numbers on the resulted photomosaic. The *GeoRose 0.3* program was used to depict the spatial distribution and orientations of the mud vents that follow the major fault lines network of the local geological structure.

The geomorphology description of the active Beciu mud volcano terrain has been carried out according to the coined and generally acceptated nomenclature (Yassir, 1989; Hovland & *alii,* 1997; Brustur & *alii*, 2015). The main threats and impacts within the study site area have been also assessed.

The grain size analysis of the ejected mud was performed. In this respect, in April 2018, three samples of fresh mud from the mud pools and craters were randomly collected, which were named S1, S2, S3, and one more S4 (477798,321; 5025785,580) from a mud lobe close to the largest elongated crater (number 4 on the photomosaic). Granular composition of each sample was determined using both classical pipette method (Olmstead & *alii*, 1930) and laser diffraction particle analyser. The Mie Scattering Theory (Wriedt, 2012) was applied to measure particles size distribution

RESULTS AND DISCUSSION

Following the field works and data gained, the study presents the morphological and morphometrical description of the mud vents developed in the Beciu mud volcano terrain which is located in the northern extremity of the Berca-Arbănași anticline, a hydrocarbon-bearing structure, which is affected by deep tectonic fractures (fig. 2). For the first time, in the Beciu site, field observations and manual measurements have been integrated and corroborated with orthophotos created from drone images, DTM and cross-sections for a geomorphological assessment. Based on the recordings of drone flights dating back several years, it was possible to monitor the spatial and temporal changes of the mud volcanic activity, as well as to learn about the morphological and morphometric changes of the examined 42 objects that occur on an area surface of around 0.5 ha. Most of the objects are located within a radius of about 50 m. Tab. 1 summarizes the morphological features and morphometrical data of all identified vents on the Beciu mud volcano area during 2017-2018.

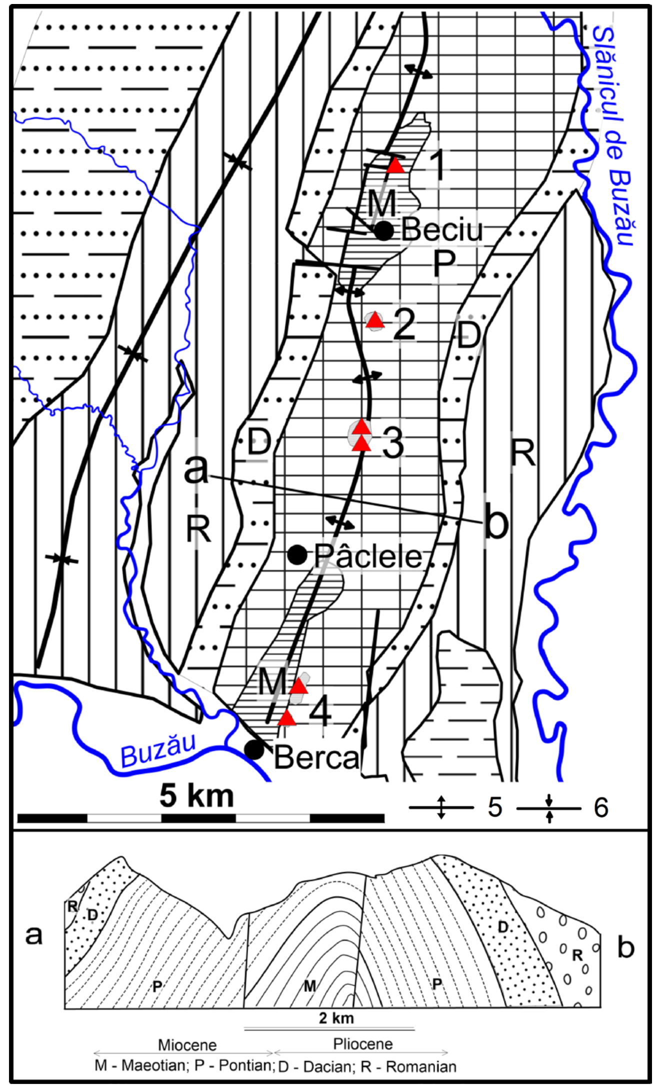


FIG. 2 – The geological map of the Berca-Arbănași anticline, Eastern Carpathian belt, Romania, and the locations of mud volcanos sites of the Berca system (red triangles): 1 – Beciu (45° 23′ 06″ N; 26° 42′ 58″ E), the present study site; Pâclele Mari (45° 20′ 22″ N; 26° 42′ 28″ E); Pâclele Mici (45° 21′ 31″ N; 26° 42′ 42″ E); Fierbători - Berca (45° 17′ 25″ N; 26° 41′ 27″ E). Redrawn after the geological map of Romania, 1: 200 000, Covasna Sheet (Dumitrescu & *alii*, 1968). Geological cross-section (a-b) of the faulted Berca-Arbănași: M – Maeotian (Upper Miocene) – sands and calcareous sandstones, oil-bearing formations; P – Pontian (Upper Miocene: marls, siltstones; D – Dacian (Pliocene): marls, siltstones, sands, coal and coaly schist intercalations; R – Romanian (Pliocene): clays and silty/sandy clays; 5 – anticline; 6 – syncline (Redrawn after Ciocârdel, 1949; Sencu, 1985; Etiope & *alii*, 2004; Melinte-Dobrinescu & *alii*, 2017).

Mud volcanic eruptions behavior

During our field works, we have noticed both quiet and explosive mud-vent eruptions, but most of them seemed to be quiet and not spectacular in terms of volume of ejected material, height of the mud jet, and the accompanying sounds. The viscosity of the muddy material, along with the gases flow and pressure that drives the material to the surface, controls the intensity of the eruptions. Based on field observations, the activity of mud volcanoes was always higher in the rainy periods. This observation suggests that the production of the ejected mud material and its viscosity is closely related to the infiltration of the meteoric water, which then is ejected by the gas seepages, mainly methane and carbon dioxide, whose average annual emission was recently estimated, in the case of methane, to at least 1350 t/yr (Frunzeti & *alii*, 2012).

Table 1 - Morphological features developed on the Beciu mud volcano site (see fig. 4) and their descriptive indices. 1 – punctiform mud ejections into pool; 2 – multiple mud ejections into pool; gryphon; 4 – dormant gryphon; 5 – mud maar; 6 – monogenetic mud dome; 7 – mud hole; L – long diameter; l – short diameter; P – perimeter of the crater rim; A – surface area.

Name / Morpho-type vent	1	2	3	4	5	6	7	Figure number	L (m)	l (m)	P (m)	A (m^2)
B1 (S1)	x								3.5	2.8	12.3	8.4
B2A		x						9f	5	3.5	14	13.5
B2B (S2)	x								3.5	2.9	11.5	9.7
B3	x							9e	2.1	1.9	6.9	3.5
B4 (S3)			x					9a	3.5	1.3	10	4.6
B5			x					9c	1.7	1.1	4.9	1.7
B6		x							3.2	1.2	9.8	7.3
B7		x							1.4	0.9	4	1.1
B8		x							2.3	1.0	6.1	2.1
B9	x								2.8	2.2	8.1	4.8
B10	x								0.3	0.25	0.8	0.1
B11	x								0.9	0.8	3.4	0.9
B12		x							2.9	2.1	8.8	5.7
B13		x						9b	< 0.3	< 0.3	0.94	0.28
B14							x	10f	< 0.3	< 0.3	0.94	0.28
B15		x							2.0	1.5	7.1	3.8
B16		x							0.9	0.7	3.1	0.8
B17	x								0.9	0.7	3.6	1.0
B18*					x				< 0.3	< 0.3	0.94	0.28
B19	x								0.5	0.4	1.9	0.3
B20		x							2.3	1.4	6.3	2.9
B21				x				9d	2.0	2	2.6	0.5
B22	x								0.8	0.7	2.8	0.6
B23	x								0.8	0.7	2.7	0.7
B24					x				< 0.3	< 0.3	0.94	0.28
B25*							x		< 0.3	< 0.3	0.94	0.28
B26							x		< 0.3	<0.3	0.94	0.28
B27*				x					0.45	0.45	1.9	0.28
B28**							x		< 0.3	< 0.3	0.94	0.28
B29							x		< 0.3	< 0.3	0.94	0.28
B30							x		< 0.3	< 0.3	0.94	0.28
B31*						x			< 0.3	< 0.3	0.94	0.28
B32*						x			< 0.3	< 0.3	0.94	0.28
B33*					x			11a	< 0.3	< 0.3	0.94	0.28
B34*						x		10e	< 0.3	< 0.3	0.94	0.28
B35			x						< 0.3	< 0.3	0.94	0.28
B36		x							2.0	2.0	6.7	2.4
B37		x							4.7	4.7	13.0	1.2
B38		x							5.0	5.0	11.5	7.5
B39*					x				< 0.3	< 0.3	0.94	0.28
B40**	x								< 0.3	< 0.3	0.94	0.28
B41	x								0.6	0.6	1.9	0.28
B42*					x				< 0.3	< 0.3	0.9	0.28

* Extinct in April 2018, covered by mud flow; ** extinct in August 2018, covered by mud flow.

Fig. 3 - Grain size distribution of the mud sampled from active mud cones and a mud lobe. The samples, numbered from S1 to S4, were collected as follows: S1 – mud pool (1); S2 – mud pool (2b); S3 – elongated crater (4); S4 – mud lobe close to the largest elongated crater, the number 4 on the photomosaic (45° 23′ 06.8425″ N; 26° 42′ 59.0423″ E). The number from brackets indicates the place of the sample on the photomosaic (fig. 4).

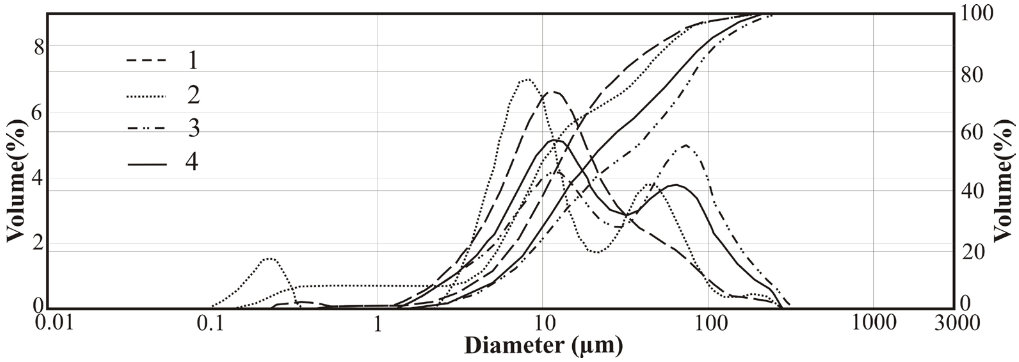
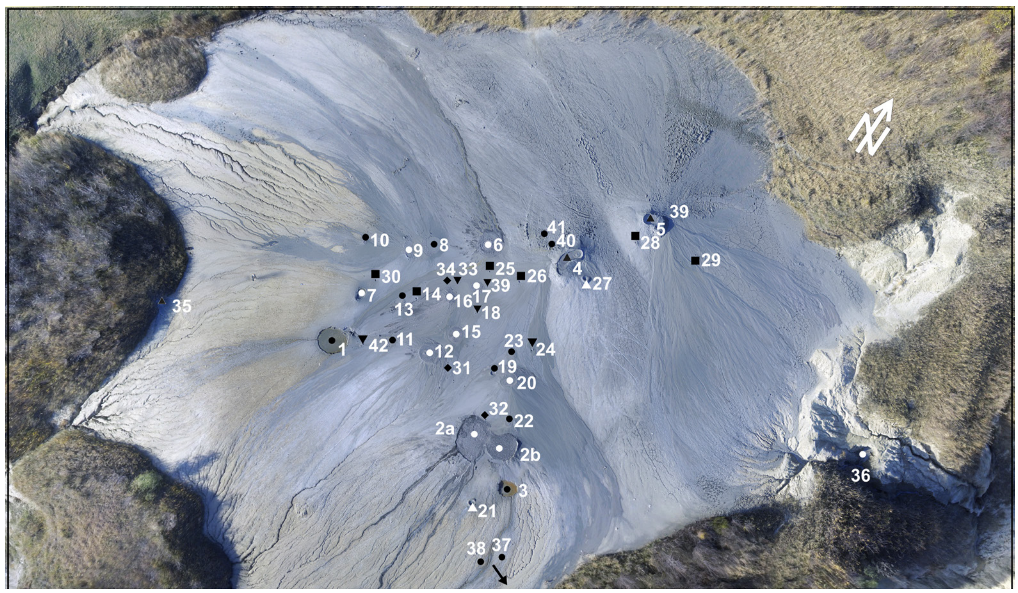


Fig. 4 - Detail of the Beciu mud volcano terrain – a photomosaic from 2017. All active mud ejections were inventoried and labeled with numbers from 1 to 42. 1 – pool with punctiform mud ejections; 2 – pool with multiple mud ejections; 3 – gryphon with punctiform mud ejections; 4 – inactive cones; 5 – mud maar; 6 – monogenetic mini mud cones; 7 – funnel mud holes.



The mud formed in the strata underlying the mud cones is cast by gases to the surface through a feeder system. The discharged material is fairly constant but the volume of the material is not quantitatively appreciable and the mud overspills are erratic. Bubbles appear on the surface of the mud filling the craters at intervals ranging from a few seconds to tens of seconds. Temporal and spatial changes in bubble densities developed in craters are highly heterogeneous, suggesting strong variability in factors affecting the gas bubbling. After a cycle of formation and breaking of bubbles has taking place several times, few mud jets may rise simultaneously at a certain distance above the crater. It also happens that in case of volcanoes that eject viscous oily mud; a single large bubble emerges, which then breaks and spreads splashes of mud. Bubbling frequency and size of bubbles is determined by the viscosity of ejected material (the mixture of mud, water, oil, and detritus) as well as by the quantity and pressure of gas seepages. During field trips it was noticed that in several craters the bubbling process was slight or even hardly discernible.

On the surface of some of the aqueous mud pools the bubbling process is more intense. It generates numerous minuscule bubbles and consequently their bursting produce effervescence sounds. If the fluid mud is mixed with oil and the bubbling process is intense, then muddy foam is produced on the surface of bubbling material. When the ejected mud drains out from craters and flows along with mud foam through channels that furrow the mud volcano plateau, the mud foam gets hard and „scoriaceous" by desiccation. However, the „mud scoria" is an ephemeral structure, as its consistence is disintegrated easily by the rain water. At the microscale, keeping proportions, short mud tubes are noticeable along mud channels analogous to lava tubes developed by the flowing lava.

Granular composition and grain size distribution of ejected mud samples

Meotian sediments outcrop in the area of the Beciu mud volcano site. The ejected mud is unctuous due to the mixing of clay material with water and crude oil. The results of grain size distribution analysis of the mud ejections have revealed that the clay fraction proportion was low, less than 10%, following both laser diffraction and pipette applied methods. The frequency curves (q %) show bimodal distributions, except for sample S1 that has only one-peak curve (fig. 3). The higher peak for each sample develops in the range of 8-12 µm, which corresponds to the fine silt fraction. The smaller peak of the S2 and S4 samples belong to coarse silt fraction (at 30-40 µm), whereas in the case of sample S3, that was

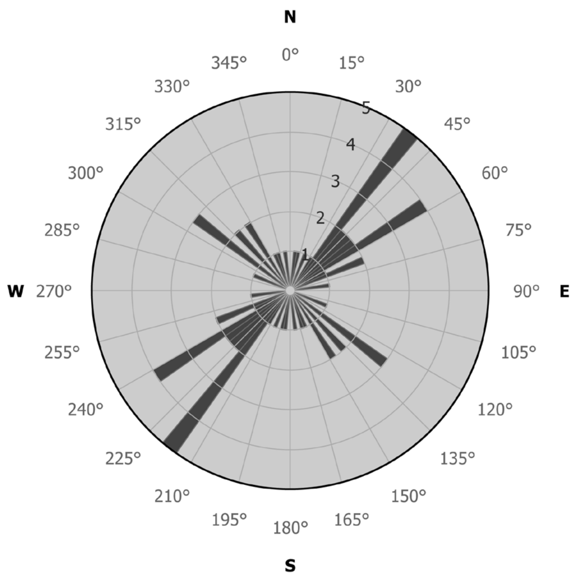


FIG. 5 - The Rose diagram shows the geometry of tectonic preformation in the Beciu site which resulted in the occurrence and spatial locations of mud vents and as well as in the direction of straight-line gullies and valleys (figs 1 and 4). The oval shape of the mud pools and craters elongate in the direction of major fault lines.

collected from the elongated crater, number 4 on the photomosaic, the second dominant particles size belongs to the very fine sand fraction (50-100 µm), according to particle size classes of Unified Soil Classification System (USDA, 2012).

Based on the grain size distribution curves, the dominant fraction of sampled mud is fine silt (2-20 µm), which represents 60-70% for S1, S2 samples, and slightly above 40% for the other two samples, S3 and S4. The difference between the first two patterns of distribution curves and the other two samples is due to the fact that the first two samples have a higher sand content (20-30%) and a lower content of clay compared to the latter two samples (S3, S4). Therefore, based on the grain size distribution graph (fig. 3) and according to USDA classification, all four samples are classified as "silt(y)" material. The high content of silt means a high porosity volume.

The geomorphological diversity of the Beciu mud volcanic area

As it was mentioned above, the first description of the Beciu mud volcano site was made more than 130 years ago (Cobălcescu, 1883). There are not mentioned information about the size of area at the time of investigation. Acording to Cobălcescu (1883), the mud volcanoes from Beciu site were older and more geomorphologically complex than those from Berca-Fierbători. However, on the Lesser and Greater Wallachia Map from 1790 at the scale of one to 57 600 (https://mapire.eu/en/map/romania-1790/), all four sites with mud volcanoes are drawn and named „Pukla", being the transliteration of the Romanian word „Pâclă", the old Romanian word for „mud volcano".

The study site is located in an important oil field that has been exploited for decades and despite detailed geological and topographical surveys should have been performed in the area, large scale maps or drawings are not available freely to public domain, which makes difficult to analyse the morphological and morphometrical evolution of the area over decades. Currently, the Beciu site is the smallest of the four known mud volcano field of the Berca-Arbănaşi anticline. It has an area of less than one hectare, but in the absence of historical topographic documents, it is difficult to make assessments referring to size variations and accurate identifications of geographical coordinates of the initial place of emergence. However, the presence of the bad-land terrains on the eastern and southern side of the Beciu site, as well as the occurrence of several isolated mud vents outside of the present well delineated barren plateau, require thorough studies on evolution of this area (figs 1, 4).

The surface with active mud volcanoes consists of a broadly rectangle area, dome-shaped, with sides of at least 110 m x 80 m length, clearly delineated by a ravine on the eastern side (fig. 4). On the mud volcano surface terrain, especially along the north-south median line of dome and in the southern part of it, there are scattered active mud vents (cones and mud pools), inactive cones (possibly in a dormant stage), and small gas vents. They are numbered on the photo-mosaic from 1 to 42 (fig. 4).

The formation and occurrence of the mud volcanoes is controlled by faults which provide ways for the natural gas through confined and phreatic aquifers and clayey rocks. In the Beciu area, the spatial distribution of vents (figs 4 and 5) follows the main fractures alignment developed within Berca-Arbănași anticline, as it is illustrated on the geological map (fig. 2). The major alignment of the vents depicts NNE direction, which is consistent with the longitudinal fault from anticline (fig. 5). The second alignment that is oriented on ESE direction, as it can be seen in fig. 5, can be associated with a transverse fault. Therefore, the Beciu mud volcano plateau overlaps on the intersection of fractures, which may explain the high density of mud vents on a relatively small area. The straight-line gullies and valleys developed in the area and the oval shape of mud pools and craters and their elongation seems to be conforming to the general direction of major fault lines.

The highest point of the Beciu mud volcano plateau is 299.5 m, in correspondence with the most well defined morphological mud cone, which on the aerial image is numbered B4 (figs 4, 6 and 7). The typical features and geomorphologic components developed on the mud plateau are depicted by the topographical profiles (figs 6, 7): a steep-sided big cone, with craters, sharp rims, and secondary craters on the slopes.

In addition to mud vents, there are many gas seeps with distinct smell of hydrogen sulphide. The dome shaped mud volcano surface has a dominant declivity that ranges from 5 % to 12 %, with the highest values on the eastern and southern sides, as well as on the slopes of main active crater cone.

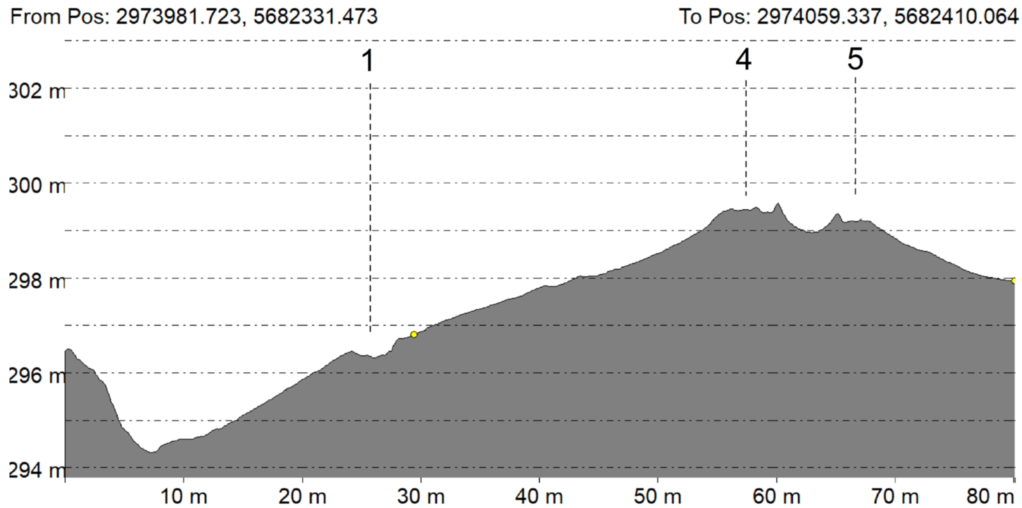


FIG. 6 - The cross section of the Beciu mud volcano terrain on the South-Nord direction depicts its dome-shape and the biggest mud cones in the area, labelled 1, 4 and 5 (fig. 4)

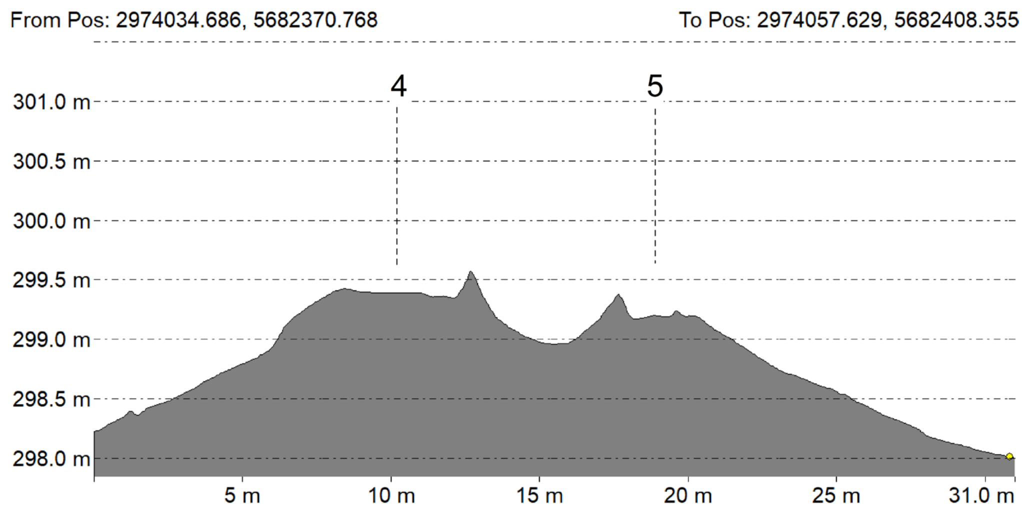


FIG. 7 - Cross sections of the biggest mud cones from the Beciu terrain.

The topographical features as a result of mud volcanic activity

The typical landforms that develop due to mud volcano eruptions and deposition of mud layers are mud volcanic cones, gryphons, punctiform cones, mud pools, and mud flows. In the area of the Beciu mud volcanic field there are around 42 individual cones. The majority of them are located on the dome-shaped barren plateau (fig. 4, tab. 1) and several in the surrounding area. In terms of morphology and activity, the biggest mud cones are the cones number 4 and 5 (fig. 4). They reach the highest elevation of the area and have the classical geometric steep-sided shape of the mud volcanic cones (figs 6, 7). The height of each mud cones above the plateau is around 1.5 m (fig. 7) and the surface area confined by the crater rim is around 5 m^2. The morphology and morphometry of each mud vent that was identified in the area is given in the table 1 and the appearance of some of them is illustrated with pictures.

Gryphons are small secondary vents that occur around the main mud volcano body. They emit gas, mud, and water and produce discernible cone-shaped features. These secondary cones are layered structures that consist of mud flows and develop due to either intermittent or continuous mud overflows (fig. 9a). The sloping angle of these kind of cones exceeds usually 45° and their average height ranges from a few tens of centimetres to one meter. Analogous to the main craters, the mud emitted from gryphons regularly overflows and spreads radially around the cone. Gases bubble vigorously within the mud-filled craters (fig. 9b). Much smaller in size are splashing gryphons (fig. 9c). In their case, the mud with high viscosity is periodically splashed from a narrow funnel. Gryphon channels may dry out and clog after a while. If the feeding channel continues to be sealed, then the cone becomes a dormant one. Two dormant cones, evolved from gryphons, labelled 21 and 27, were identified (figs 4 and 9d). Both of them are small, no more than half meter high, but only number 27 has a well preserved crater.

The mud pools are filled with aqueous mud and muddy water where gasses bubbling at their surfaces. They have mostly low edges or no edges at all. In the study area their diameter ranges from several centimetres to 1.5 m. The water is salty and oily and welling up continuously to the surface, together with gas and small amounts of fine-grained sediments. The oil content from water (fig. 9e) differs from one mud pool to another, which may indicate the presence of an underground drainage system. Based on the type and

FIG. 8 - The largest and most active mud cone in the area of the Beciu site, the number 4 (fig. 4), resembling the classic feature of magmatic volcano. Also, it marks the highest elevation of the study area that is 299.5 m (figs 4, 6 and 7).

place of the bubbling process, central and diffuse feeding mud pools can be distinguished.

Central feeding mud pools are circular or elliptical-shaped small pools that contain oily water, muddy water or viscous mud. Liquid and gaseous ejections take place in a specific point and they look like cauldrons with boiling liquid springing up, which is the reason why local people named them ”fierbători”, especially that there are only gas emanations within mood pools.

In case of diffuse feeding mud pools or mud pools with multiple mud ejections, the ejection of muddy materials to the surface takes place in several points. Bubbling activity is accompanied by resting periods, followed sometimes by strong discharges of muddy materials. From time to time, most of the mud pools have outpourings of mud through one or several breaches. Water, muddy water, and viscous mud spread on the slope surface as a sheet flow, shallow concentrated flow, and open channel flow (figs 9f and 10a).

Mud escaping from the crater runs down the sides of the cone. The successive mud flows build up the mud volcano and increase the size of the cones. The seasonal activity and amount of extruded material by feeding conduits change frequently and also affect the type and direction of the outflow. The mudflows spread in sheets but also can be organised in mud streams or rills. Mud flow directions change over time, thus older and dried-up mud paths are crossed by more recent and active mud flows. Due to the small distances between the active cones and their relatively high density in the area, mud flows from different vents join and overlap. When a big amount of viscous mud gets mixed with crude oil, mud flows have a braided pattern, similar to that of the pahoehoe lava (fig. 10a). In particular, the mud fluid is drained and washed away during the rainy season to the main valley, which borders the mud volcano site, through a deep gully system (fig. 10d).

Both splitting and merging of mud flows (troughs) are frequent. When different mudflow types coalesce, spectacular small and transient features may develop, such as bridges and tunnels, where the dense mud layer forms a crust on top of the mud flow (fig. 10b). These tunnels developed in mud flows resemble the lava tubes developed into lava flows from magmatic eruptions (fig. 10c).

Overall, comparing the forms from the Beciu site with those existing in the other three sites belonging to the Berca mud volcano system and that have developed in the same geological context, the diversity of features is similar. Instead, there are differences in terms of size and density per unit area. The mud cones from Beciu mud volcano plateau and their associated features are smaller but the density on the area is higher, with a clumped spatial distribution (fig. 4).

Several micro features associated with mud volcanism were identified on the surface mud volcano terrain. These are monogenetic mini mud cones, funnel mud holes, mud maars, and alveoli. *Monogenetic mini mud cones* are positive microforms without crater (number 31, 32, and 34) that look like mushroom caps. Their diameter do not exceed 0.2 m and the average height is less than a half meter. Usually, monogenetic mini mud cones develop due to a single viscous mud ejection (fig. 10e), and on the mudflow sheet surfaces they look like swirly buttons. Probably, the high compressive power of the gases presses the dense and viscous mud through the funnel, which then solidifies and obstructs the opening of the vents. It is possible that their genetics to be similar to that of the volcanic origin lava domes (Mazzini & Etiope, 2017).

Funnel mud holes are empty small craters with open conduit and no any visible sign of seepage activity. They occur on the mud surface as a result of activity of former secondary side vents dominated by gas and water ejections. The diameter of funnel mud holes is around 0.1-0.2 m (la-

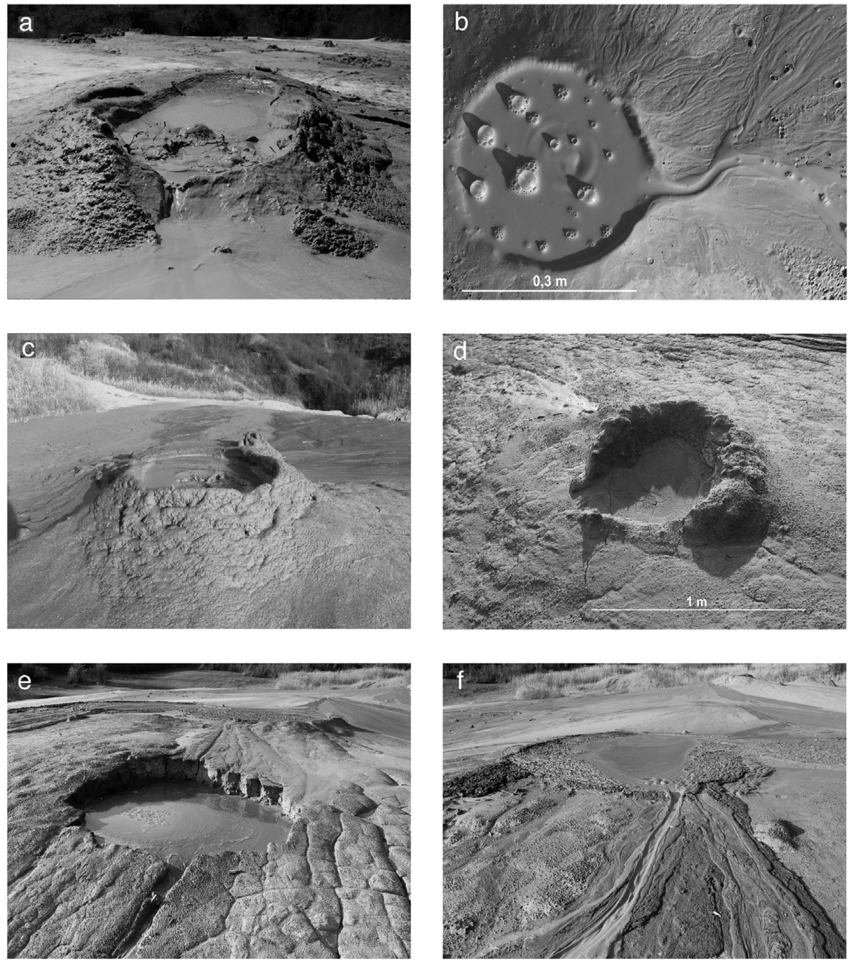


FIG. 9 - Various behavior and features of mud volcanoes: a – mud ejection (4); b – gas bubbling on the surface of mud in a filled crater (13); c – The mud regularly overflows and spreads radially around the cone, labelled (5); d – Dormant cone (21). Taking into account that the crater rim is well preserved, its eruptive activity has recently ceased; e – oil spill in a bubbling aqueous mud pool (3); f – The mud material with different viscosity accumulates in craters/mud pools and further overflows though one or several breaches (2a). The mud flows spread on the slope surface and overlap each other (16). Due to high oil content of the muddy material and the gas emissions that causes bubbling, it forms muddy foam which flocks to the edges of craters or spills over the rim of craters. The numbers from brackets show the position of the illustrated subject on the photomosaic (fig. 4).

belled on the photomosaic with the numbers 14, 24, 25, 26, and 30). Most of these mud holes look like they are extinct. Others are in dormant stage, which means the activity of conduits is reactivated occasionally (fig. 10f). *Mud maars* are, by contrast, crater like positive monogenetic micro-landforms, without chimney/vents (number 34) and surrounded by rims of 0.1-0.2 m in diameter (fig. 11a).

Alveoli develop on the mud flows. They are small pits on the surface of the mud flows, which develop due to the gas that is stuck in (and then released from) the fresh mud flows. Such invisible gas emissions are called "mini seepage" (Etiope & *alii*, 2011; Mazzini & Etiope, 2017). Mini seepage is a rounded, degassing micro formation that surrounds the vent, although it may occur on the whole ground surface of mud volcanic area (fig. 11b). These micro mud landforms are ephemeral features. They vanish with the overlapping of successive mud flows and weathering processes.

Subsequent morphology developed on the mud volcanoes terrain

The surface of mud volcano field consists of ductile and unctuous clay that has been accumulated in time by successive overflows of mud ejected by active cones. It has been partly indurated upon drying as the distance to the crater rims increases and mud cracks are developed on the surface of the youngest mud flows as a result of drying. The older extrusive mudflows and the exposed topographical bedrock surface display instead typically serrated gullied surfaces due to weathering and surface runoff erosion, which are more prominent on the south-eastern side of the mud volcano field. Consequently, weathering has produced badland topography, although the area surface of runoff activity is reduced and declivity is lower compared to the other three mud volcano sites located on the Berca-Arbănaşi anticline alignment. Due to the general dome-shape of mud volcano terrain, an overall radial drainage pattern has been developed within this area.

After enough dewatering has taken place, mud cracks and desiccation polygons will start developing on the mud flows ejected from mud volcanoes. They are shrinkage cracks that are induced by tensions generated within the mud material by its volumetric contraction caused by desiccation. Initially, the fracture network develops a rectilinear pattern; cracks meet at "T" junctions of 90° and 180°, forming detached crack-bound polygons. Cracks and "T" junctions show clearly well defined edges and the surface of the mud polygons is smooth. Then, following the desiccation processes of the mud material, they are covered by a white sodium chloride salt crust. The well-defined cracks

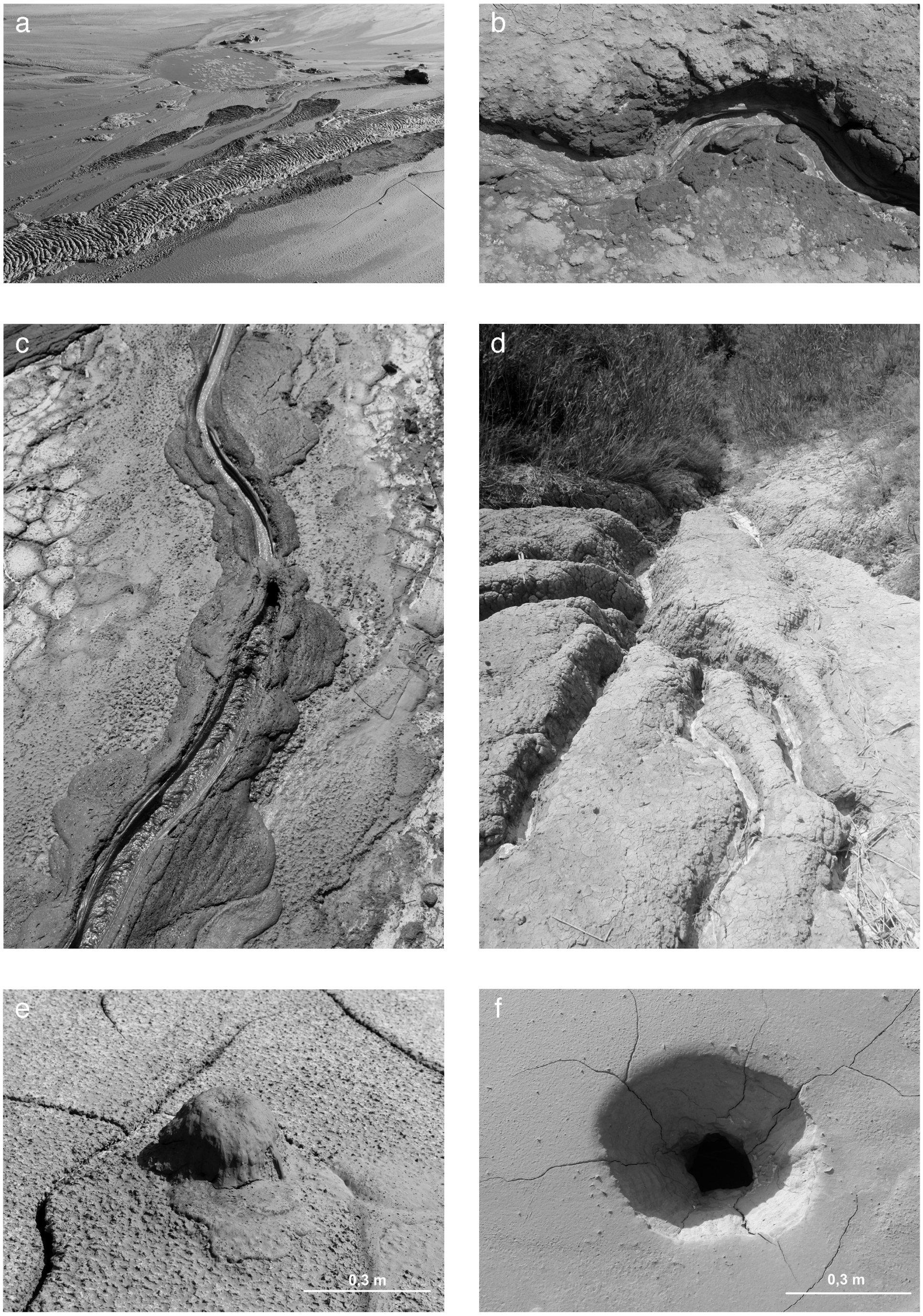


Fig. 10 - The types and patterns of mud flows and microforms: a – viscous mud flow mixed with high oil content display braided pattern, similar to the pahoehoe lava; b – mud bridges and tunnels develop in thick and dense mud that flow through channels due to progressively drying of it; c micro-tunnels developed in mud flows resemble lava tubes that occur in lava flows; d – Part of the ejected mud flows is collected by the gullies network and further from the main valley. Same gully system drain washed mud by runoff erosion. e – monogenetic mini-mud cones without crater developed due to a single viscous mud ejection; f – mud holes, resulting from the activity of former secondary side vents dominated by gas emissions and water ejections.

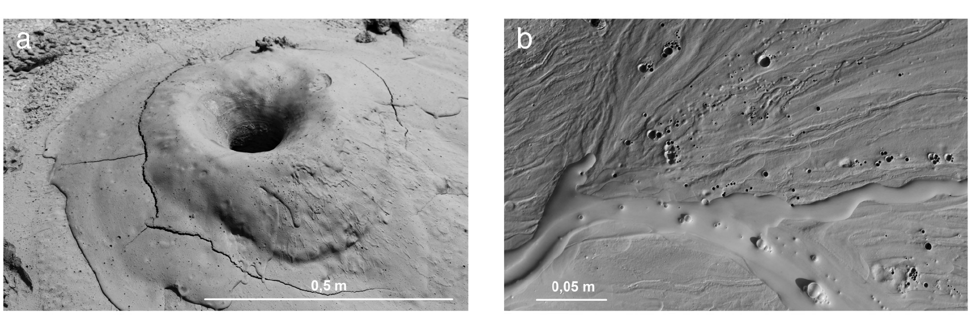


Fig. 11. - Microforms and subsequent morphology developed on the mud volcanoes terrain in Beciu site: a – mud maars; b – mini gas seepages and degasified alveoli in the fresh ejected mud.

FIG. 12. Mud cracks network developed on the mud sheets. A white crust of salts is deposited on the ground surface during the summer after a prolonged period of low rainfall.

reach sizes of up to lengths of 40 cm, widths of 1-3 cm, and up to a depth of 5-7 cm. The thickness of the polygons depends of the thickness of the mud flow sheets. The fractures usually penetrate the entire thickness of the mud, up to the contact with the underlying surface, which can be a previous sheet mud flow, with mud cracks and salt crust precipitation. Each polygon delineated by the primary crack network is itself broken into families of smaller polygons. No surveys have been made regarding if there is a correlation between the existing mud crack network of the ground surface and cracking process developed in a new mud layer, but most probably the underlying surfaces act as flaws that have a discernable effect on initiating and developing mud crack networks (Weinberger, 1999; Weinberger, 2001). The curling of the polygons is extremely slight but the curvature of their surface was observed in the case of polygons that developed on very thin layers of mud and in the mud that fills rills, close to the walls of the channels as a result of boundary effects.

After the formation of the primary mud crack network in the newest desiccated mud layer, over a series of wetting and drying cycles and water runoff, the geometry of fractures changes. In particular, the junction patterns change from „T" to „Y" type, the roughness of cracks increases with time and cracks outline polygonal areas that define a honey combed surface (fig. 12).

Due to recurrent fresh mud covers, the argillaceous composition of bedrock, and its dome shape with distinct gradient and lack of vegetation, the Beciu mud volcano terrain is subject of the surface runoff and rill erosion evolving as a badland area. A conspicuous micro relief pattern is developed on the southeastern and eastern side of the plateau where slopes are dissected by a dense drainage of rills network (fig. 1, 4). The area thereby reveals, in a miniature spatial scale and a shortened temporal scale, processes and landforms that resemble fluvial landscapes.

Mud crack networks feed rills and main channels with rainwater but they also initiate the rilling process. On the other hand, rills may be filled and covered by mud flows. However, there is an interplay between mud flow sheets, mud crack network evolution and runoff-rill erosion. It was observed that the latest mud cover can be entirely removed by sheet erosion during heavy rains. The remaining evidence consists of regolith materials and small remains of polygons which look like as 3-5 cm balls and mushrooms. Surfaces with popcorn appearances are also present, as typical micro-topographic features in badlands that is created by repeated volume changes of argillaceous ground surface due to hydration and dehydration processes.

Threats and types of impact in the area of Beciu mud volcano terrain

The Beciu mud volcano terrain is part of the aspiring Buzău Land Geopark area but it is not a protected area so far and not as well-known as the Pâclele Mari and Pâclele Mici sites. By comparison with the two sites, the Beciu site is visited by few tourists, occasionally and often accidentally, but this situation is expected to change in the near future. The main reason of its isolation is related to its location in an old oil field with scattered active wells. Furthermore, the Beciu mud volcano site is relatively difficult to reach, as being peripheral with the main roads, and last but not least, the site is not promoted in any way by local authorities. More surprising is that the nearest human settlement is a small village, partially depopulated, only one km away. In addition, the surrounding area of mud volcanoe site is an afforested territory and abandoned orchards, without any high pressure of anthropogenic activities.

Animal foot prints and feces, both wild (wild boars and deer) and domesticated (sheep, horses), are visible on the surface of the mud terrain, but after a rainy period, they vanish. Human foot prints in fresh mud are concentrated around the main cones, close to the rim, but the human trampling does not impact dramatically the morphology of mud volcanoes features; it is rather an aesthetic deterioration. All kind of foot prints are removed by water runoff and surface erosional processes.

Others damages to the mud cones are made by visitors who introduce wood debris into craters to check their depths or break the rim of craters in order to change partially the flow direction and the amount of drained mud. Unfortunately, the wood poles are abandoned inside of craters.

In the late summer of 2018, significant damages were noticed on the surface of the mud volcanoes caused by motorcycles and ATVs rides. Although there is no any tradition in the area and no documented evidence of curative properties of ejected volcanic mud, during the summer of 2018, in the vicinity of the mud pools, artificial mud bathing pools were made by those visitors who wished to take a mud bath, most probably to have unique experiences. With all these actions, visitors are interfering in the natural processes of the mud volcanoes but without causing any dramatically or irreversible changes, especially since mud volcanism is naturally dynamic and could remove any damages caused by visitors. As a result of the assessment of human impacts on the area of Beciu mud volcano during the last three years of survey, we consider that there are not major threats in the near future and the area will evolve under natural control factors.

CONCLUSIONS

This study represents a geomorphologic survey over Beciu mud volcano terrain that has developed on the hydrocarbons bearing anticline Berca-Arbănași, the most famous region for mud volcanic phenomenon in the southern part of the Eastern Carpathian belt, Romania.

The Beciu mud volcano activity is linked to the faulting of the anticline that has provided pathways to natural gas and oil of Sarmatian age to ooze out of the ground and underlined the formation of the Berca mud volcano system. The analyze of the spatial distribution of mud vents in the Beciu area shows that they follow two alignments which are subparallel to the longitudinal and transverse faults and cracks that fractured the anticline.

On an area of less than one hectare it has been identified 42 mud vents which tend to be clumped in the middle of the site and depict the typical topographical features of mud volcanoes. The mud-volcanic processes are active, without spectacular mud eruption in terms of intensity and ejected mud amount. The emergence of four new cones in 2019 outward of the mapped area may be a sign of the extension of the Beciu mud volcano terrain toward peripheral area.

The Beciu site is the best preserved mud volcanic terrain in the Berca mud volcano system, both because of its geographical isolation as well as because its location in an operating hydrocarbon field limits the practice of other types of land use and even access to the area for security reasons. The assessment of human impacts in the area of mud volcano plateau during the last three years survey shows no imminent major threats. Considering that this site was nominated as one of the points of interest of the future Buzău Land Geopark, it is expected to be more visible for visitors and thus the touristic pressure to increase.

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