THE GEOLOGICAL HERITAGE OF THE TRANSYLVANIAN BASIN: ASSESSMENT OF GEOLOGICAL RESERVES WITH MUD VOLCANOES

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Abstract. Among the 26 nature reserves established in the Transylvanian Basin, 13 have the status of geological reserves, and four of them are represented by mud volcanoes. Active volcanoes currently occur only in the area of Băile Homorod. The other three reserves, Filiaş, Monor and Hăşag, represent mud volcanoes in their late stage of development. Assessment of these four reserves indicate that they show scientific importance, but only those from Homorod present interesting feature of active mud volcanoes as well as a high scientific value. Educational and touristic values of the three reserves with inactive mud volcanoes are rather limited, especially that they are remotely situated and they are more difficult to find, as there are no signs for location or explanatory panels. Also, the risk of degradation of the three inactive mud volcano fields are greater, due to cessation of their activity, possibly caused by exhaustion of gases generating them, or drying of the groundwater level crossed by the gases in their way to the surface.

Key words: mud cone, mud flow, gas seeps, quantitative assessment

1. INTRODUCTION

Since 2019, GeoEcoMar runs a project on geological reserves, entitled „Capitalization and promotion of the geological heritage from Romania through elaboration of a unitary geoconservation strategy at national level". The main focus of this project is a geological audit of selected sites from the main geotectonic units of Romanian territory, the assessment of their protection status, of anthropogenic and natural threats and elaboration of action plans for geodiversity.

The nature reserves from the Transylvanian Basin represented the objective of the third phase of our studies within the project. A total of 26 nature reserves of IUCN (*International Union for Conservation of Nature*) categories III and IV were established in the area of the Transylvanian Basin by law 5/2000 (and its further modifications). These reserves occur in the counties of Alba, Braşov, Bistriţa-Năsăud, Cluj, Harghita, Sălaj and Sibiu and include 6 paleontological reserves (fossil sites), 13 geological reserves, 6 of mixt type (geologic and landscape) and 1 of landscape type.

The existence of at least 73 mud volcanoes and gas seeps, distributed along the major fault systems in the Transylvanian Basin was documented by Spulber (2010) and Spulber *et al.* (2010). Several of these occurrences were recently investigated for gas flux, gas composition and morphology: Boz (Alba county), Deleni (Cluj county), Atid, Băile Dungo, Băile Seiche, Cobăteşti, Corund, Dârjiu, Forteni, Goagiu, Mihăileni, Porumbenii Mici, Sânpaul, Filiaş, Praid (Harghita county), Cându, Maia, Sărmăşel, Sângeorgiu de Pădure, Sânger, Vălişoara (Gloduri) (Mureş county), Monor (Bistriţa-Năsăud county), Hăşag (Sibiu county) and Homorod (Braşov county) (Vancea, 2007; Gál, 2010; Spulber, 2010; Spulber *et al.*, 2010; Pop, 2014). A main characteristic of mud volcanoes in Transylvania is their abundance, although they are small and scattered. These features can be the result of factors like discontinuity and heterogeneity of tectonic elements, small thickness of the mud-producing clay layers, low pressure of microbial gas in shallower pools (Spulber *et al.*, 2010). Salt diapirism, increased brittleness of gas seals and remobilization of shale horizons could have been related to basin uplift, which started in Late Miocene (Krézsek and Bally, 2006; Krézsek *et al.*, 2010).

The morphological features are mud cones, associated with small craters and gryphons, or mounds and small flat plateaus, covered by vegetation during inactive periods. Today, most Transylvanian mud volcanoes are apparently inactive or have experienced long phases of inactivity, but some observations suggest that reactivation may be related to meteorological and hydrogeological inputs (gas bubbling is enhanced after rainy periods) (Baciu *et al.*, 2007).

Only four of the mud volcano occurrences in the Transylvanian Basin were designated as nature reserves of geological type. Except for the Băile Homorod mud volcanoes (IV IUCN category), active in 2010, the other three are included in IIIrd IUCN category (natural monuments), and all of them are currently inactive and almost extinct. This paper describes the four geological reserves with mud volcanoes and presents the results of their qualitative and quantitative assessment (Fig. 1).

2. GEOLOGICAL BACKGROUND

Situated in the central part of Romania, the Transylvanian basin is surrounded by the Alpine belts of the East Carpathians, South Carpathians and the Apuseni Mountains (Fig. 1). The basement of the Transylvanian basin is quite complex, including a Cretaceous nappe pile with metamorphic rocks and their sedimentary cover (similar to rocks in the nearby Alpine belts), as well as ophiolitic formations of the Vardar-Mureş zone (Săndulescu, 1984). These intense metamorphosed and deformed rocks are overlain above a major unconformity by a Late Cretaceous-Middle Miocene succession, showing strong lateral and vertical stratigraphic variations (Ciupagea *et al.*, 1970). The main litostratigraphic units of the basin established by Hofmann (1879) and Koch (1894, 1900) are still in use, although many new formations were established in the XX-th century. A synthesis of the Cenozoic litostratigraphic units is presented by Filipescu (2001), while their sedimentary environments and tectonic settings were established by Krézsek and Bally (2006).

The sedimentary infill of the Transylvanian basin (2.4-4 km thick) includes mostly concordant series of molasse deposits accumulated during Middle Miocene-Pliocene (Koch, 1900). At the base of molasse sediments there is the Dej tuff, a rhyolite tuff marker deposited above a regional unconformity (Ciupagea *et al.*, 1970). The Dej tuff (Early Badenian) is overlain by an up to 300 m thick salt layer (Ciupagea *et al.*, 1970), locally forming diapirs (Mrazec, 1907; Visarion *et al.*, 1976). Conglomerate layers occur at the base of the salt. On top of the salt, a dominantly siliciclastic molasse succession develops, with the coarse facies at the basin rim, and finer lithology toward the basin centre (Marinescu *et al.*, 1994; Mărunțeanu, 1997). Several andesitic tuff layers are intercalated in the clastic deposits (Ciupagea *et al.*, 1970). The Badenian deposits are overlain by a mostly undisturbed Sarmatian concordant series, locally up to 1500 m thick (Marinescu *et al.*, 1981), marking an interval of high subsidence and sedimentation rates of 350m/Ma (Sanders

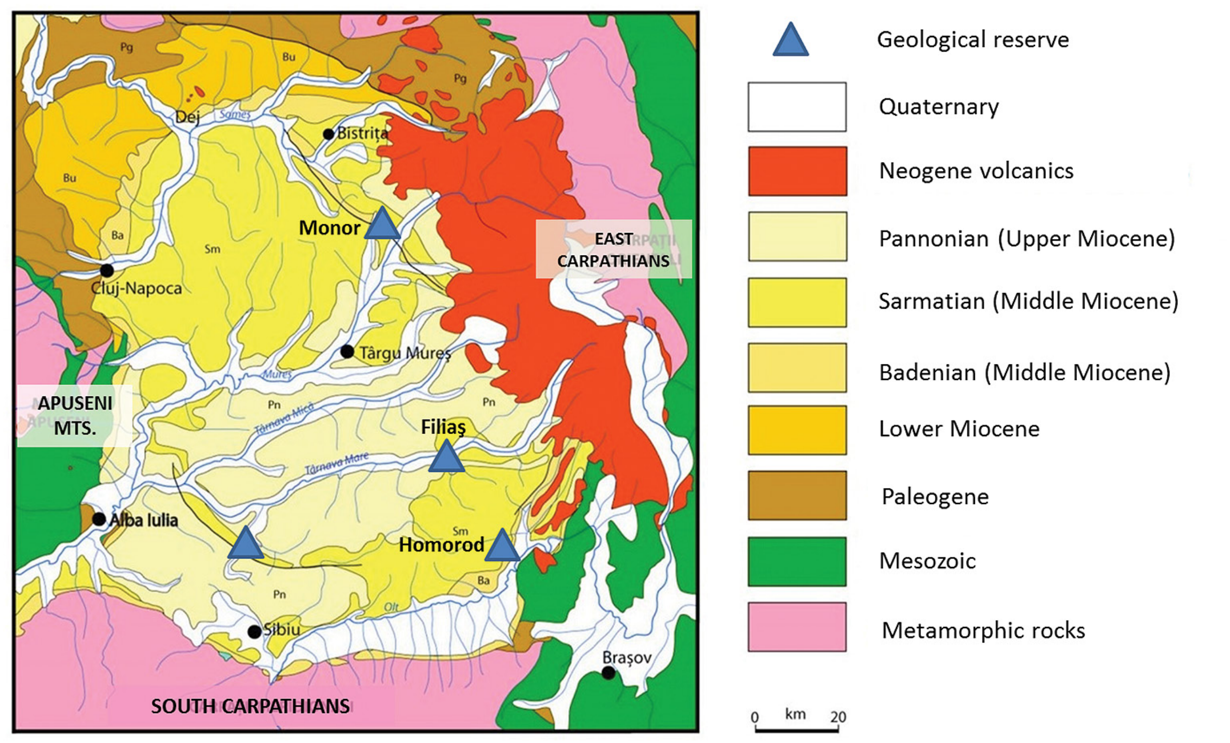

Fig. 1. Location of the geological reserves with mud volcanoes on a simplified geological map of the Transylvanian Basin (modified after Filipescu, 2001).

et al., 2002). Molasse sedimentation continued at lower rates into the Pannonian, with local unconformities between the Sarmatian and Pannonian successions. The present day configuration of the Transylvanian basin originated since the Miocene, as earlier suggested (Ciupagea *et al.,* 1970; Săndulescu, 1988), and confirmed by apatite fission track studies (Sanders *et al.*, 2002).

The main late Miocene and Neogene structures in the Transylvanian Basin are folds and salt diapirs (Mrazec, 1907; Paucă, 1969; Ciulavu *et al.*, 2000; Krézsek and Bally, 2006). Salt diapirism is related to the ongoing tectonics in the Carpathians, while location of salt diapirs is controlled by reactivation of inherited faults (Mrazec, 1907; Paucă, 1969; Visarion *et al.*, 1976; Ciulavu *et al.*, 2000).

Ludovic Mrazec played an important role in the discovery of gas domes in the Transylvanian depression (Ciupagea, 1991). The Miocene gas system is connected to the Badenian – upper Miocene source rocks (Popescu, 1995) and structural and stratigraphic traps (Ciupagea *et al.*, 1970). The Transylvanian basin is the main gas-producing province in Romania, as well as in Central and Eastern Europe, with a reserve in place of over 34 tcf (Popescu, 1995). Methane emissions are produced by smaller mud volcanoes and dry-seeps (sometimes as everlasting fires). Two main seepage areas are Sărmăşel and Homorod (Baciu *et al.*, 2007).

3. DESCRIPTION OF THE GEOLOGICAL RESERVES

3.1. The mud volcanoes at Băile Homorod

This geological reserve, designated as IV IUCN category, occupies an area of 2.78 ha south-east of Băile Homorod (coordinates: 46º01’56,5”N, 25º17’36,2”E), situated at the foothills of Perșani Mountains, Brașov county.

Access to the geological reserve is made from the national road DN13 Braşov-Sighişoara. At the sign to Gara Rupea railway station, the route goes right, following DC31 northward about 2 km to Homorod. Here, the road goes to the right on DJ132 about 1 km. At the intersection between DJ132 with the last street on the right, the road goes 500 m south, to the point where it crosses Homorod stream, and after 600 m the road enters the geological reserve (Fig. 2). The entrance is marked by an explanatory board (Fig. 3).

The object of protection is a swampy area in the Zeifăn valley meadow (one of the left tributaries of Homorod stream). The area includes mud volcanoes, mud flows and gas emissions and contains halophytic vegetation. The geological reserve was established in 1980 as a protected area of national interest, and declared as such by law 5/2000.

Fig. 2. Location of the Mud volcanoes Băile Homorod reserve on a Google Earth image from 2014.

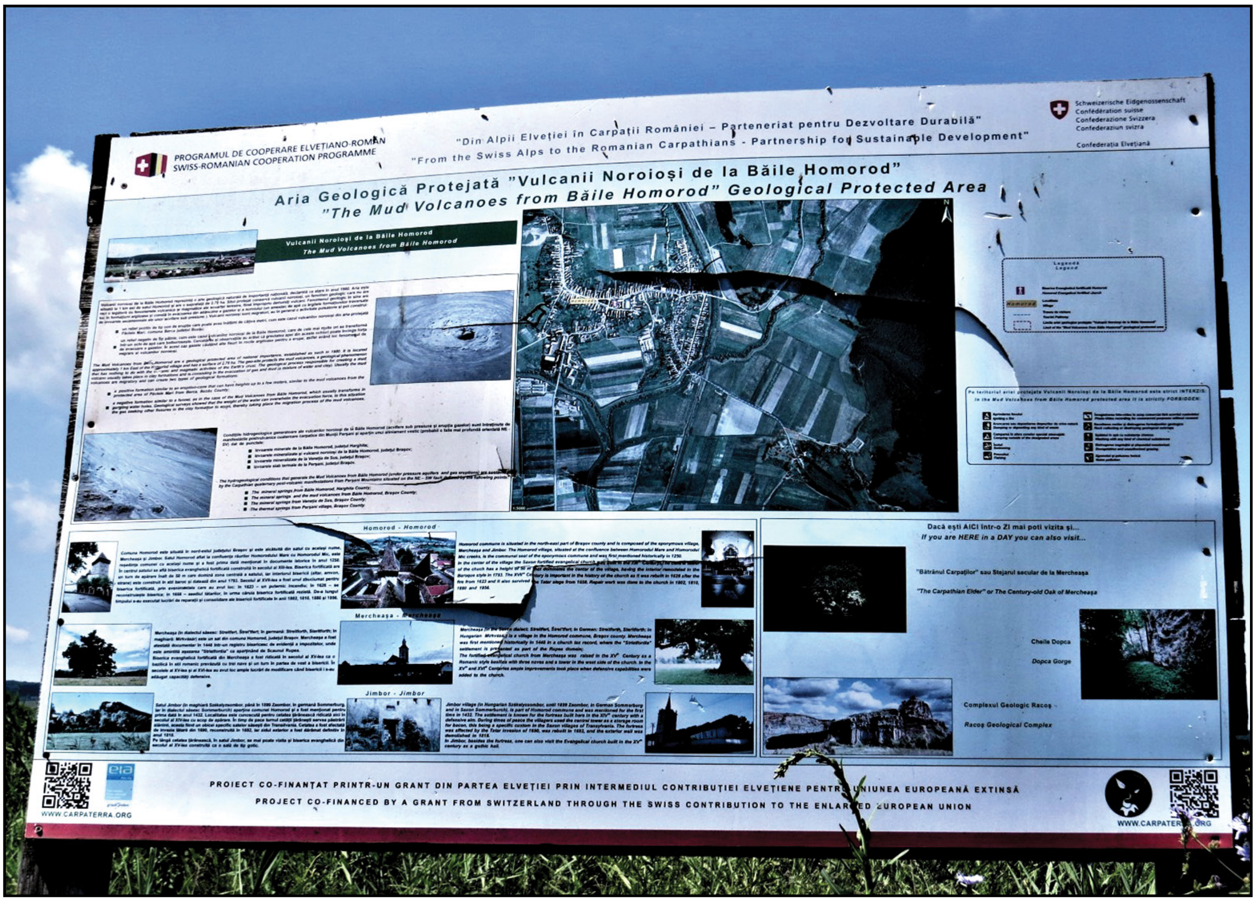

Fig. 3. Explanatory board placed at the entrance in the geological reserve, containing information about the mud volcanoes from Homorod and about other natural and cultural objectives in the area. (*Photo Silviu Rădan*)

The mud volcanoes occur on the limb of Rupea-Homorod anticline, oriented N-S, then NE (Vancea, 1960).

At the end of July 2020, when we visited the site, on the west side of the road crossing the reserve, there was a large pond with gas seeps, bubbling pools (40-60 cm diameter) (Fig. 4) and reed vegetation. On the road itself, there were tiny areas with gas bubbles and mud spills (Fig. 5).

A cone of an active mud volcano of gryphon type (height less than 3 m) is built 20-25 m southward, about 5-6 m east of the road. The cone was about 80 cm high, 3-4 m in diameter, with 6-7 m long mudflows flowing towards the valley situated to the north (Fig. 6). Mud volcanoes in this area were described as funnel-type, with a negative relief, often turning into a bubbling water pool. Because the weight of the water in the bubbling puddles can surpass the force of gas evacuation, the gases are seeking new fissures to be released from the host rocks, resulting in the migration of the volcanoes. The hydrogeological conditions favoring the formation of mud volcanoes (pressurized aquifers and gas eruptions) are maintained by the Quaternary post volcanic activity in the East Carpathians and Perşani Mountains, and belong to a western alignment (probably a more deep-seated NE-SV fault, marked by the tectonic lineament with mineral waters from Homorod Baths, mineralized springs and mud volcanoes from Homorod, mineralized springs from Veneția de Sus and mild thermal springs from Perşani) (Dessila-Codarcea *et al.*, 1967; Ciupagea *et al.*, 1970).

Investigations for methane seepage from the soil, gas flux into the atmosphere, gas composition and its origin, concluded that the Homorod mud volcanoes represent an unusual N_2-dominated mud volcano area (Baciu *et al.*, 2007). According to the authors, at the time of investigation, the geological reserve consisted of a small mud volcano with an inactive cone and four bubbling pools. Also, the number, size and frequency of the bubble trains were recorded in all the pools and gryphons. The results obtained by the authors indicated that gases released in a pool and shallow well are N_2-dominant (93%), with CH_4 <0.5%. The Helium content was also extremely high (1.4%). The highest Helium isotopic signature, R=0.4 Ra, was also measured in the Homorod gas, and the measured 4He/20Ne ratio was higher than 10.000, showing a negligible contribution from the air. The Homorod area shows a lower degree of methane degassing, also because the discharged gas has very low CH_4 concentrations.

Fig. 4. Mud and water pool (salse) with gas bubbles rising from the depth. (*Photo Silviu Rădan*)

Fig. 5. Swampy pool by the road crossing the reserve, with small mud mounds and a tiny bubbling crater right on the road, with mud spills flowing into the pool. (*Photo Silviu Rădan*)

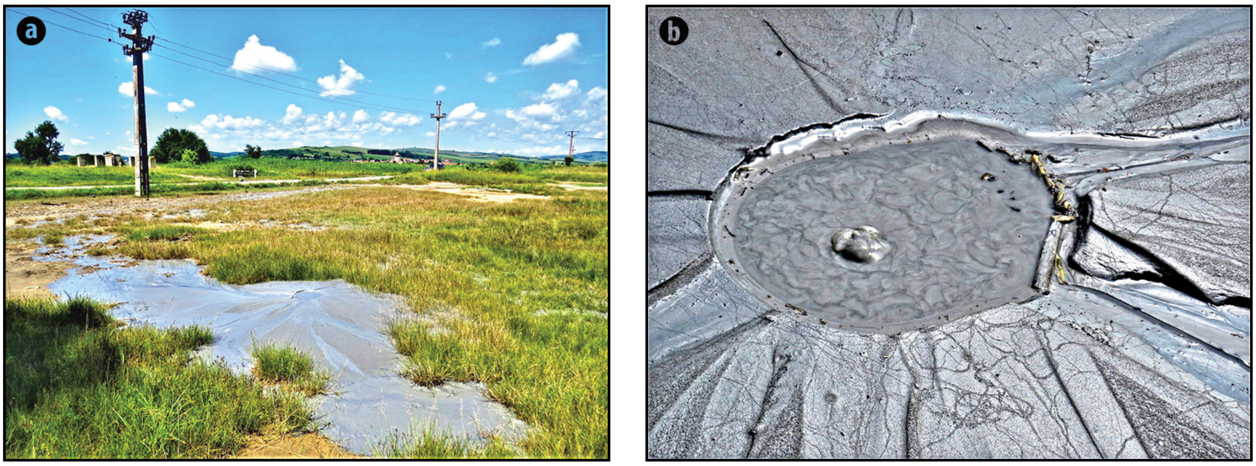

Fig. 6. Active mud volcano at Homorod, with a well-expressed flat cone, small crater and mudflows; (**a**) general view; (**b**) detail of the cone. (*Photo Silviu Rădan*)

A conclusion of the study was that the N_2-rich gas composition of Homorod mud volcano is completely different from other Romanian CH_4-dominated seeps. According to the authors, the Homorod mud volcano seems to be the richest N_2-mud volcano in the world. Also, it's unusual helium concentration (>1%) was never reported in the gas seeps literature. High Helium content and 3He/4He ratio of gas seeps indicate a contribution of mantle-derived helium, suggesting that fluid transfer through the crust was facilitated by deep tectonic discontinuities in Homorod area. The highest methane fluxes (103-105 mg CH_4 m^{-2} day^{-1}) were recorded in June 2009, after a rainy period, from a mud pool with vigorous bubbling (Spulber *et al.*, 2010).

Current situation of the geological reserve. There are no road signs indicating the geological reserve neither on the national road, nor on the country roads or in Homorod. At the entrance in the reserve there is an explanatory panel made by *Carpaterra Foundation* from Braşov, through the project „From Swiss Alps to Romanian Carpathians – Partnership for sustainable development", co-financed by Switzerland in the Swiss-Romanian cooperation programme. Unfortunately, the panel has lost its colors and is already broken in several places (Fig. 3).

Other objectives. Cultural sites in the area include the XIII-th century fortified church from Homorod (with an XVIII-th century baroque defensive tower), Rupea Fortress, as well as several Saxon fortified churches in the area (ex. Viscri – UNESCO monument, Criț etc.). Nature reserves include the geological complex from Racoşul de Jos, the basaltic cliff at Rupea, the Hoghiz basalt microcanyon, Dopca Gorges. The area is part of the Aspiring Carpaterra Geopark, former Perşani Geopark Project.

3.2. MUD VOLCANOES „LA GLODURI" MONOR

This nature monument in Eastern Transylvania (III IUCN category) extends on 2 ha (coordinates: 46°56'36,9"N 24°41'23,2"E) south of Monor commune, Bistrița-Năsăud County (Fig. 7). The nature reserve was established in 1976, and declared by law 5/2000.

Access. The geological reserve is situated on the hill, at the junction between Pârgului and Luțului streams, the latter, a tributary of Mures River, in the vicinity of its junction with the Bîrgăului stream. From Reghin, the route to the reserve follows DJ154 to Monor. Once in Monor, the route follows a street which goes to the right (east) from DJ154, crossing the Luțului stream. After about 300 m on the street, the route continues left through a yard (of a private house) to the northern margin of the geological reserve (Fig. 7).

The Monor mud volcanoes represent a marshy area, where partly extinct and partly active mud volcanoes were studied in detail by Chintăuan and Rusu (1975). The presence of mud volcanoes in this area was reported earlier by Szalai (1950), who gave a map of the area, but did not investigate the phenomenon. The volcanoes are formed in connection with the Pannonian marls from the hinge of a gas-bearing structure (Peahă, 1965). The mud spills created cones (Figs. 8, 9), as well as a marshy area with specific vegetation, from which locals name as "La Gloduri" (muds) or „răsuflatori" (vents or air holes).

The geological constitution of the area includes Miocene and Pliocene clastic - clays, marls, sandstones, sands and conglomerates. The structure of the region consists of a series of anticlines and synclines, some being gas-bearing structures. The gas structures from Reghin – Tg. Mureş area continue northward to Monor, the closest gas-bearing structure being Lunca brachianticline. Once the erosion level attains the faults and fractures of a gas-bearing structure, the gas escapes, and on its way to the surface, it draws the superficial waters infiltrated at depth, which soften the marls into a fluid mud. Consequently, mud volcanoes appear as accompanying phenomena of gas emissions.

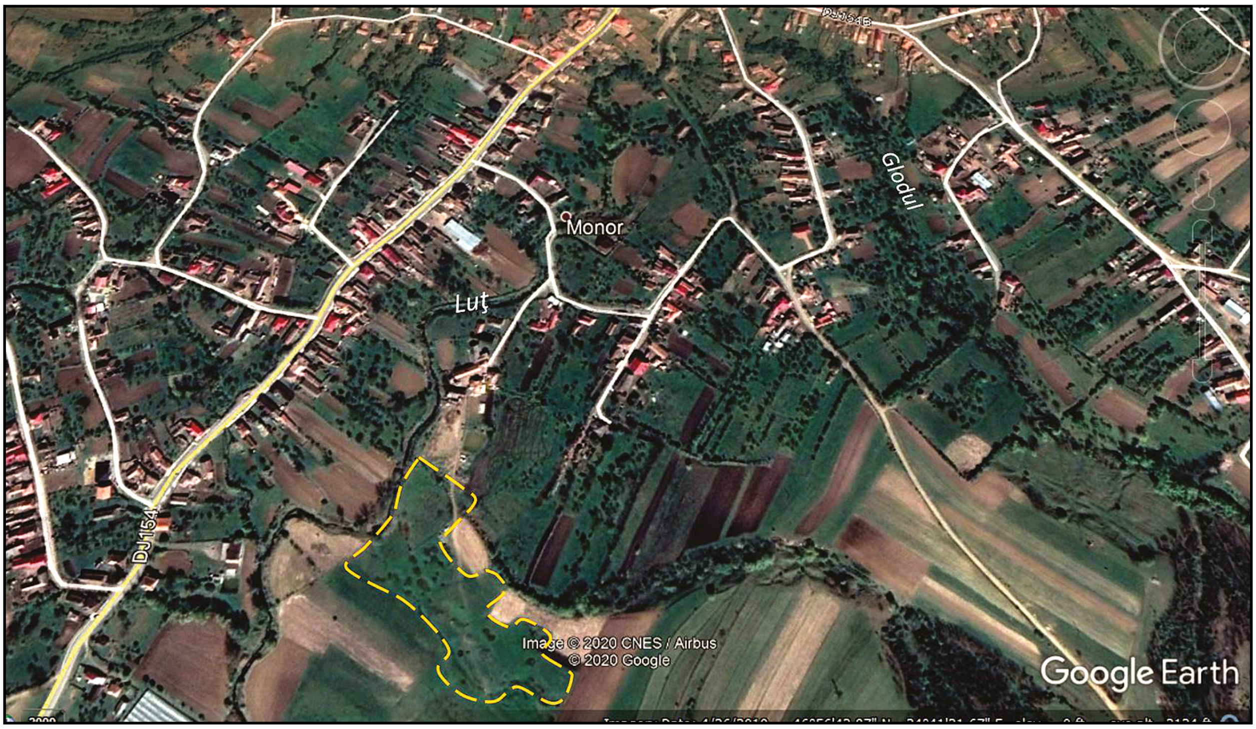

Fig. 7. Location of the Mud volcanoes „la Gloduri" Monor on a Google Earth satellite image from 2009. Dashed yellow line is the outline of the geological reserve. Dark green spots within the reserve are mud volcanoes, aligned on NW-SE or NNV-SSE directions.

Fig. 8. Alignment of four flat toped cones of mud volcanoes at Monor, covered by grassy vegetation. Currently the area is a pasture for cattle amidst farmland. (*Photo Antoneta Seghedi*)

The mud volcanoes at Monor have built their cones on top of gravelly and sandy deposits of the Quaternary terrace. Although these mud volcanoes use to expel a large variety of sediments (marly shale, sand, sandstone, tuff, sometimes salt), their main products are water and mud flows (Chintăuan and Rusu 1975; Spulber, 2010). Their activity at Monor transformed the surrounding area into a marshy surface, dotted with small mud cones. During periods of inactivity and aridity, the area around volcanoes is characterized by desiccation cracks and thin, dry mud plates.

A detailed description of the mud volcanoes from this area was given by Chintăuan and Rusu (1975), who noticed their distribution on two alignments. Developing their own classification, the cited authors described five morphological types of mud volcanoes, according to the shape of cones and of their crater tops, usually filled with mud (convex, convex-concave, convex plane, plane convex and convex elongated).

In 1975, the northern alignment was reported to include 18 partly active mud volcanoes and cones (maximum 1.50 m high) covered with vegetation. Most volcanoes looked like low swellings of plane- convex type, with a very low cone, slightly raised from the ground surface (maximum 25 cm high) and with a plane crater up to 1.5-2 m in diameter, filled with mud. Such muddy craters, with diameters of 0.50-2 m and filled with mud and water, almost continuously eliminated fluid mud.

In the central-east sector of this alignment, between two craters filled with fluid mud, there was a 20m long/15 m deep crack, with fluid mud and eruption centers (of concave-elongated type). The western part of the alignment was more active, but volcanoes were lower (of plane-convex type) and closely spaced. According to locals, during 1945-1950, when all these "vents" were in full activity, almost the entire area was covered in mud and only partly occupied by vegetation, and the whole area was an impermeable surface.

The southern alignment included an extinct and two partly active mud volcanoes, covered by vegetation. The eastern volcano, 1 m high, was extinct, with a small crater (10 cm in diameter) filled with dry mud. The western volcano, 1.5 m high, had a muddy crater (2 m in diameter), covered by vegetation. When pressed, this crater was pouring fluid mud. The middle volcano was the highest on this alignment and its base was 3 m in diameter. It had a consolidated crater, with mud and water flowing from a small secondary crater on its northern flank.

As mentioned by Chintăuan and Rusu (1975), the mud volcanoes from Monor were already on the verge of extinction 45 years ago. Active mud volcanoes also existed downstream of the place called "La Gloduri", on the left side of Luţului stream, toward Batoş, but these were already extinct in 1975. The consolidation (slow extinction) of the volcanoes from Monor is closely related to the gradual decrease of the gas discharge from the accumulation at depth.

Fig. 9. Three extinct mud cones at Monor, covered by grass. (*Photo Silviu Rădan*)

Fig. 10. Explanatory painted metal panel in front of a volcano cone at Monor, fallen from its initial support. (*Photo Silviu Rădan*)

Ten years ago, 20 cones and bubbling pools were still identified on an area of 2 ha at Monor (Spulber *et al.*, 2010). Mud flows, about 8-9 m long and rapidly overgrown with grass, were observed by the cited authors, who estimated a total output of at least 16 t CH_4 year^{-1} from a surface of about 2000 m^2.

Current situation. In the hot, dry summer of July 2020, the mud volcanoes from Monor seemed to be extinct, or at least inactive. Some cones could still be recognized and they still formed alignments (Figs. 8, 9), but the flat cones were almost completely covered by vegetation, sometimes excepting the top of the crater, where patches of mud with desiccation cracks still could be observed in places. In July 2020 there was a board with the name of the geological reserve, but this metallic board was scratched and the paint partly swollen (Fig. 10). The panel itself has fallen from its initial support and placed directly on grass, close to one of the volcanic cones. Currently, the area is a pasture for cattle.

Other objective in the area is the literary and memorial museum Todor Tanco in Monor. The mud spilled from the mud volcano craters was used by locals to treat certain rheumatic diseases.

3.3. Filiaş Mud volcanoes

This nature monument from southern Transylvania (III IUCN category) occupies 1 ha west of village Filiaş in Harghita county (coordinates: 46°32’30.8”N 25°07’11.3”). The geological reserve was established in 1980, and declared through law 5/2000.

Access. From DN13C in Cristuru Secuiesc, the route follows DC43 southward, to Filiaş. The reserve is located about 2.5 km SW of Filiaş, and it can be reached through a trail going south from the DC43, along a small stream (Fig. 11).

Known by locals as „Gurglers” (“colcăitori” in Romanian), the mud volcanoes represent a swampy area with four mud volcano cones of gryphon type (less than 3 m high). One of these cones has a permanent (but low) activity, consisting of gas emissions and mud spills. The area has a vegetation sometimes typical to wetlands.

The geological reserve is situated on the north-western slope of the Cristur gas dome, where the Pontian deposits are dipping 5-7°NW or W (Fig. 12). According to Vancea (1960), the oldest deposits in the area belong to the Sarmatian, which consist of compact sands, cemented in 1-2 m thick banks, with large concretions, and overlain by marls with fine sandstone and sand interbeds. A thin layer of dacitic tuff is interbeded in the marls, overlain by Sarmatian

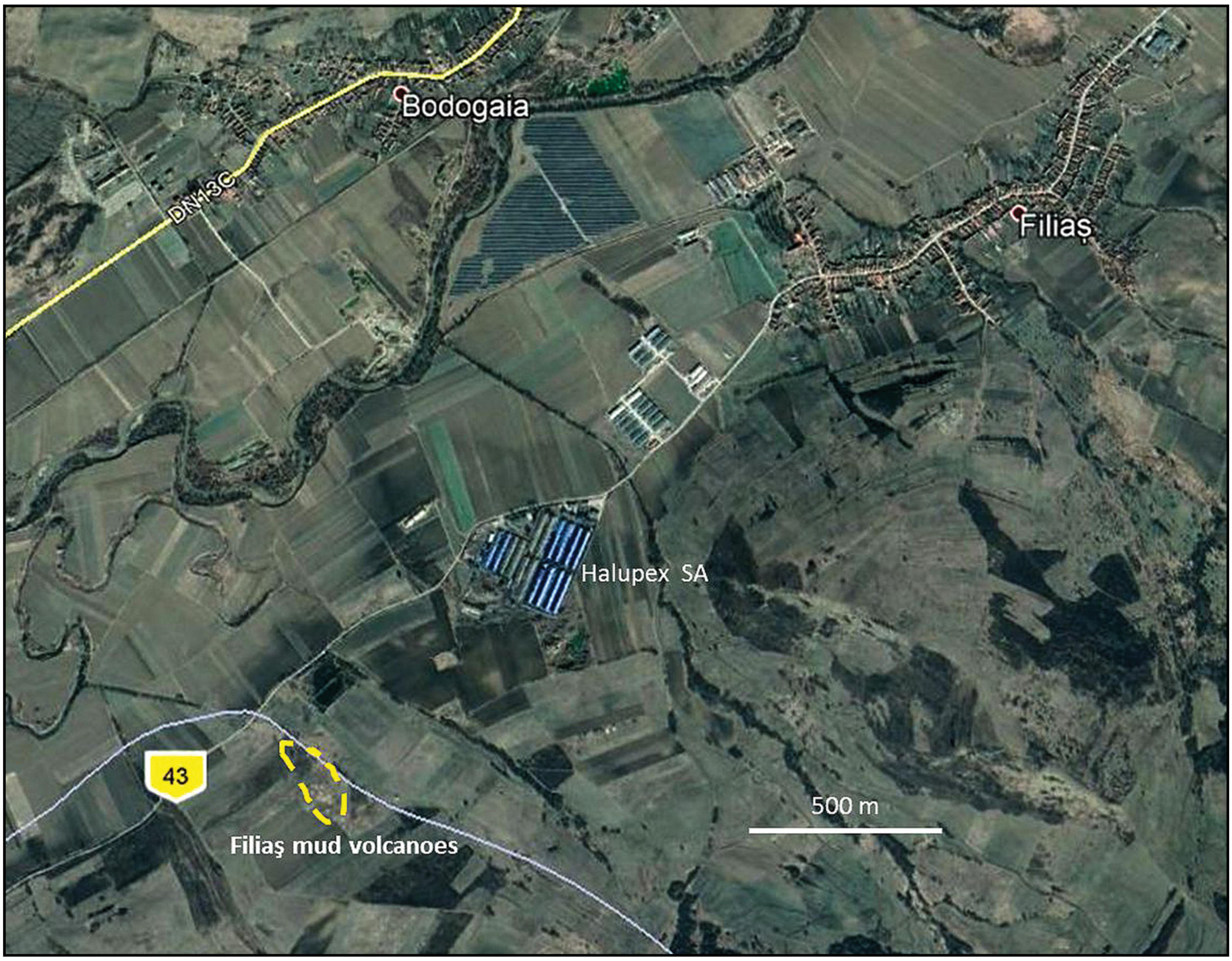

Fig. 11. The field of the Filiaş Mud volcanoes, shown with yellow dashed line on a Google Earth image from 2019.

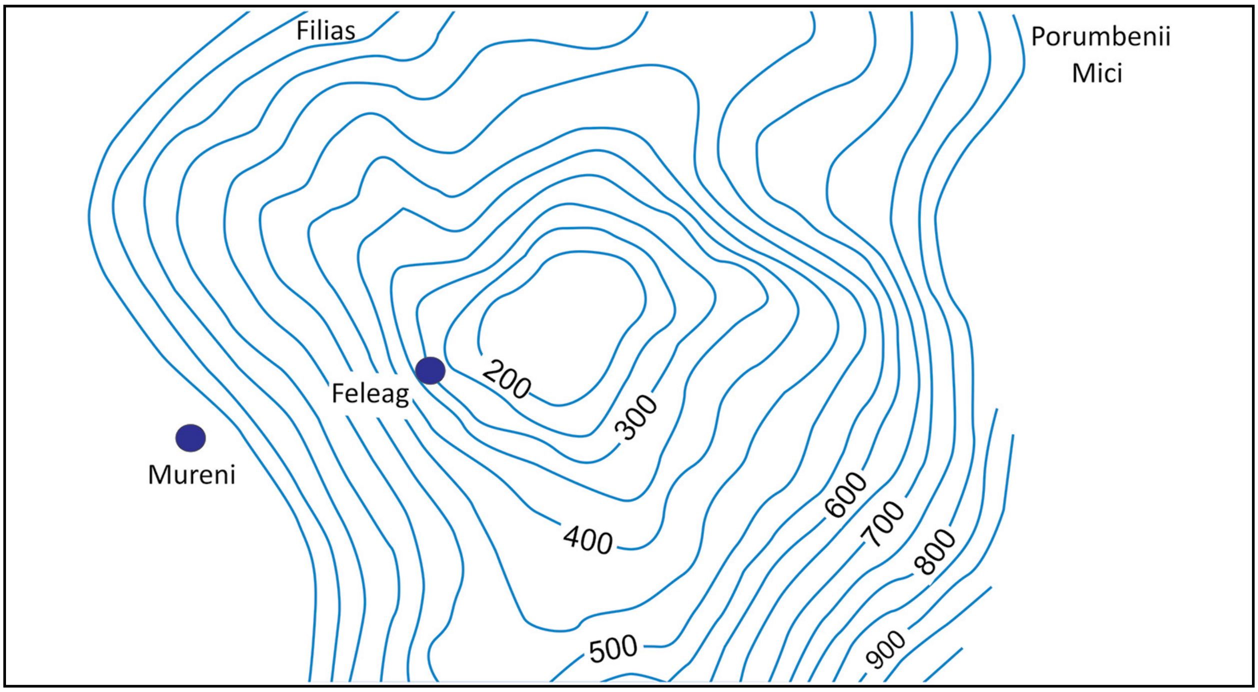

Fig. 12. Seismic sketch of the Cristur dome (redrawn and simplified after Palcu and Constantinescu, in Vancea, 1960).

limestones. South of Filiaş, the Sarmatian consists of a marly-sandy complex with blackish marls at the top, overlain by transgressive Pliocene conglomerates, containing locally bivalves and gastropods. Where conglomerates are missing, the sandy marls contain *Planorbis ponticus*, *Pisidium* sp. and various Cardiacea, Lymnaea and ostracods.

The Cristur brachianticline is formed of two secondary structures, the Cristur-Filiaş and Feleag domes (Oltean, 1970, in Ciupagea *et al.*, 1970). Seismic prospections in 1953 confirmed the presence of a NW-SE trending anticline fold, suggesting a perfectly closed dome (Fig. 12). Gas was found in all three Miocene series, and some accumulations were degraded through erosion, as indicated by natural emissions, muds and salt springs within the basin (Vancea, 1960).

According to Oltean, 1970 (in Ciupagea *et al.*, 1970), secondary migration of gas from the Sarmatian created gas accumulations in the Pliocene. Sometimes, the gas continues to migrate towards the surface due to the lack of tightness of cover sediments. The Cristur dome is such an example, where structural differences between gas accumulations (10-80m) are larger than the reservoir thickness.

The four mud cones from Filiaş, over 3 m high, represent the highest mud volcanic structures in Transylvania, but with a very low and seasonally variable activity (Spulber *et al.*, 2010). The authors estimated total CH_4 emissions up to 0.39 t/year for an area of 50 m^2 including all mud cones. In July 2020, the cones were covered by vegetation (Fig. 13, 14a). Mud crusts showing desiccation cracks could be seen on the flat tops of such cones (Fig. 14b). The reserve is now used as pasture for cows, and the area between the mud cones is plowed and cultivated (Fig. 13).

Fig. 13. Mud cones at Filiaş, overgrown by vegetation. (*Photo Silviu Rădan*)

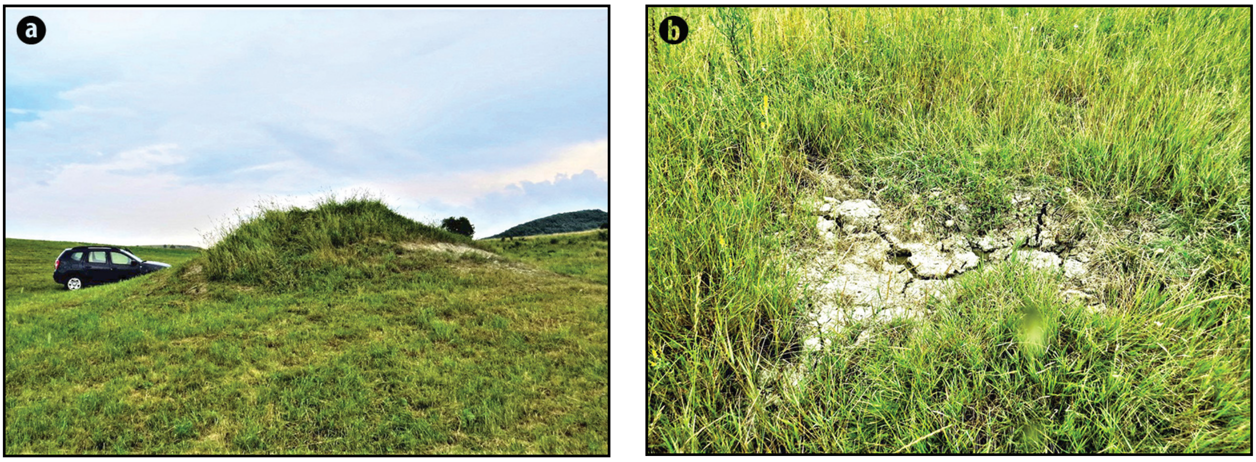

Fig. 14. (**a**) Mud volcano at Filiaş, covered by vegetation, with a small, dried mud patch still visible on the side of the cone; (**b**) Desiccation cracks on the mud from top of a mud volcano at Filiaş. (*Photo Silviu Rădan*)

Current situation. There are no road signs or explanatory panels for the Filiaş mud volcanoes. It is not easy to find them, only a few locals still know the area. This area is dryer than that at Monor, and volcanic cones can be difficult to recognize for an untrained eye.

Cultural objectives. There are several important cultural objectives in Cristuru Secuiesc, about 4 km from Filiaş. The Roman-Catholic Church was built in the XIIIth century as a Romanesque church. Following several restorations in the XIVth and XVth centuries, in the XVIth century the church was renovated in Gothic style. Traces of the medieval parish house form a complex next to the enclosure wall. The Unitarian Church still preserves architectural elements from the XIth century. Other objectives include Dr. Molnár István Museum, Gyárfás Mansion and the statue of the romantic Hungarian poet Petőfi Sándor, executed by sculptor Márkos Sándor.

3.4. HĂŞAG MUD VOLCANOES

The first studies and scientific observations on these mud volcanoes date back to 1853, but the nature reserve was declared by law 5/2000. According to this law, the geological reserve is a natural monument (III IUCN category) with an area of 1 ha in Sibiu county (coordinates: 45°58'03,1"N, 24°06'14,5"E).

Access to the geological reserve is possible on DJ106B from Ocna Sibiului, going North up to Mândra village, then the route continues along DC106B from the western side of Visa stream toward Hăşag. The first field of mud volcanoes is situated 3.5-4 km to the North, in the eastern alluvial plain of Visa stream (Bleahu *et al.*, 1976). The second field lies 1.5 km northward, on the western part of the alluvial plain, across the Hăşag railway station (about 300 m west of it) (Fig. 15).

According to Bleahu *et al.* (1976), the geological reserve includes three mud cones in the thalweg of the Visa stream, the largest cone showing a 50m diameter and 8m height. A typical salty soil vegetation surrounds the volcanoes.

The volcanoes are located between two areas with diapir folds: the outcropping Presaca – Ocna Sibiului salt anticline in the south (Vancea, 1960), and a zone with diapirs at depth, where salt deformation determined the uplift of Sarmatian deposits along a NW-SE reverse fault, bringing them to the level of Pannonian deposits (Fig. 15) (Săndulescu *et al.,* 1978). Parallel to this, another fault, also controlled by salt tectonics, develops south of Hăşag. Between these two faults, the natural gas released from the folded structures affected by brittle deformation is rising toward the surface. On its way, the gas mobilizes various amounts of salt water, which turn the Pannonian marls into a very fine mud.

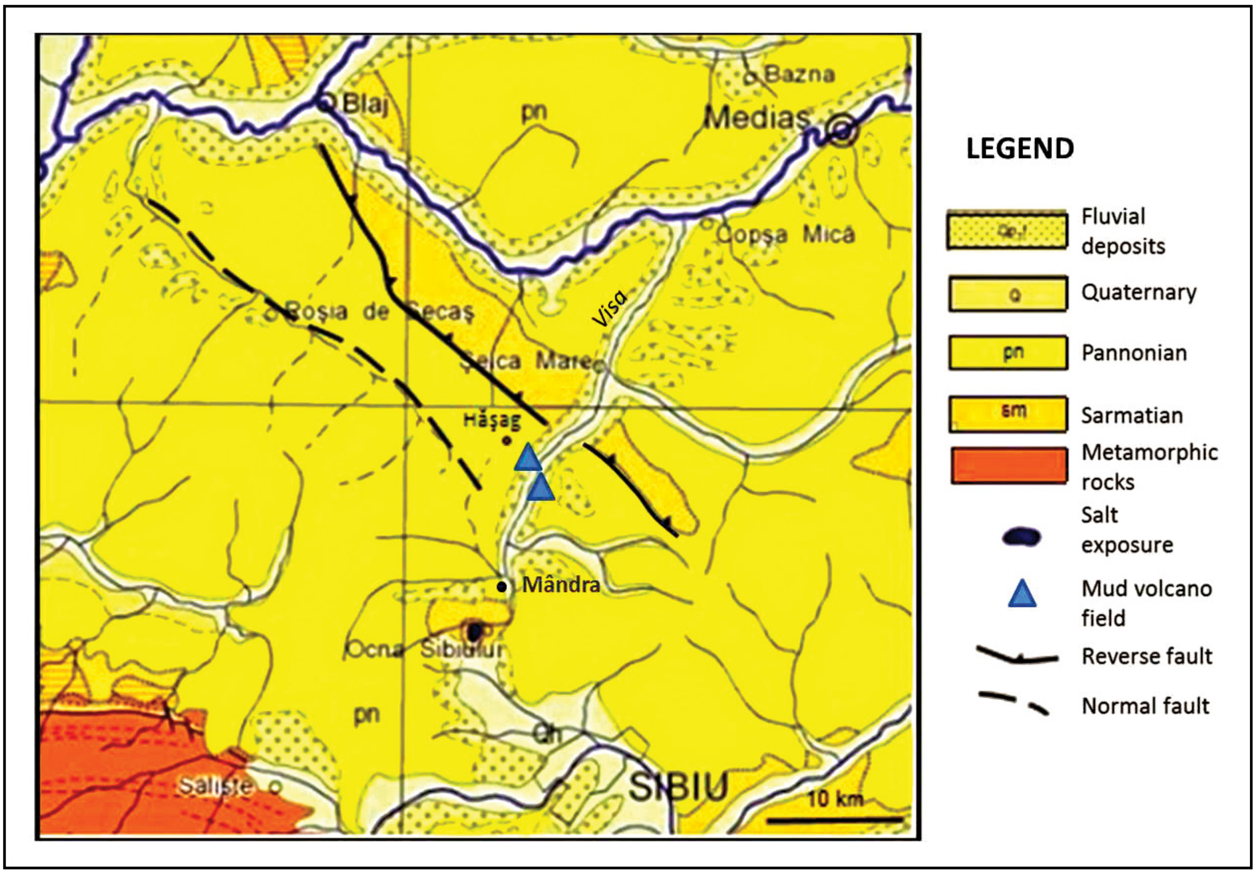

Fig. 15. Geological map of Hăşag area, showing the location of the mud volcanoes (excerpt from the geological map of Romania sc. 1:1,000,000, Săndulescu *et al.*, 1978, with modifications).

The mud is spilled at the surface as mud-flows, which in time may create cones with small craters, some of which are active and bubbling. In time, gas escape routes may become clogged, and volcanoes become inactive (or fossilized) (Bleahu *et al.*, 1976). At Hăşag, the area with mud volcanoes is affected by landslides, and volcanoes migrate, appearing or disappearing here and there, in the cultivated fields of the locals.

Current situation. First mentioned in 1853, then in 1911-1913 and 1942 (Vancea, 1942), the Hăşag volcanoes were still active for more than 100 years, with no significant changes (Bleahu *et al.*, 1976).

Spulber *et al.* (2010) reported a 1.5 m high cone, 20 m in diameter and no visible crater, with a gas flux of 893 mg m^{-2} day^{-1} detected only on the top of the structure. The authors measured gas fluxes ranging between 1.36 x 10^3 and 1.8 x 106 mg CH_4 m^{-2} day^{-1}, and estimated a total output of minimum 16 t CH_4 $year^{-1}$, from a surface of about 2000 m^2. In the summer of 2020, the cones in the riverbed were no longer observed, and only an area with dried mud holes and eroded mud cones could be noticed on the river bank (Figs. 16-18). The volcanoes seemed almost inactive. Even so, they still represent a geologic and geomorphologic phenomenon of scientific interest. Their landscape, touristic or educational values are given by the pseudo volcanic relief remodeled in time. Despite the blogs and articles found on the internet, there are no road signs or explanatory panels related to the geological reserve.

Other objectives. In the vicinity there are other sites of interest for tourists, like the ruins of Stolzemburg castle in Slimnic, Ocna Sibiului resort, with its spa complex and the Bottomless Lake (geological reserve).

4. GEODIVERSITY, GEOHERITAGE AND GEOCONSERVATION

When speaking about geological reserves, three terms have to be defined: geodiversity, geoheritage and geoconservation. One of the first definitions of geodiversity is „the diversity of geological (rocks, minerals, fossils), geomorphological (relief forms and processes) and pedological (soils), natural elements, including their properties and relationships" (Gray, 2001). A recent definition (Crofts *et al.*, 2020) specifies that „geodiversity is the totality of abiotic nature, of which some elements have significant value requiring conservation, termed Geoheritage, which is managed in geosites that are either formally protected areas or are „conserved areas", under the generic label geoconservation".

Fig. 16. Mud volcanoes from Hăşag, general view. (*Photo Silviu Rădan*)

Fig. 17. Flat mud volcano at Hăşag, with craters looking like puddles with dried mud, devoid of vegetation. (*Photo Silviu Rădan*)

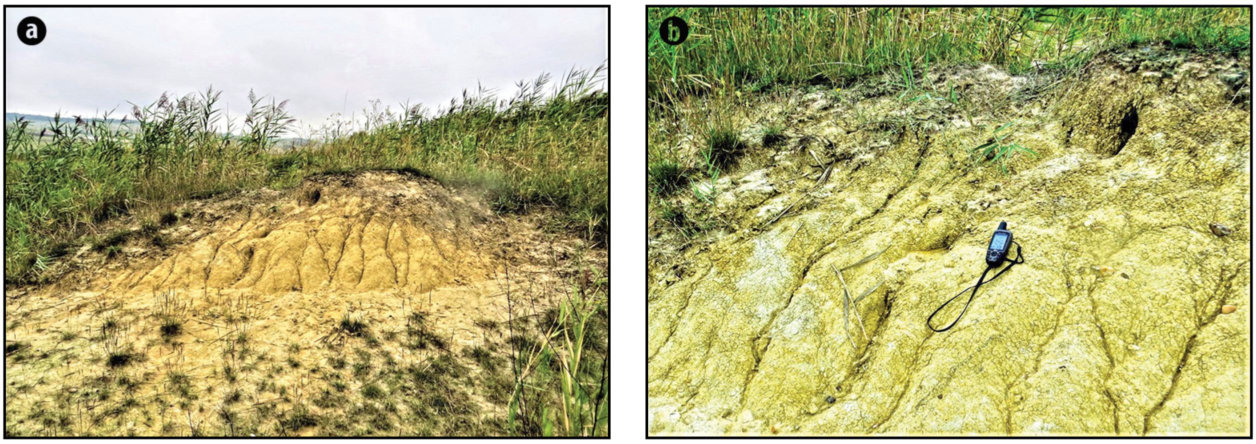

Fig. 18. Mud volcano at Hăşag; (**a**) Partially eroded mud cone at Hăşag; (**b**) Detail of the mud on the cone, in which the ravines formed by the erosion of the cone and a fine stratification given by the succession of the old mud flows are observed. (*Photo Silviu Rădan*).

According to Sharples (2002), geodiversity is „the natural quality we want to protect, geoconservation is our efforts in the endeavor to protect geodiversity, while geoheritage represents concrete examples of the significance of our efforts to conserve geodiversity". A geological reserve is a part of the geoheritage of a region or country and sometimes its exceptional value and unicity determine its international relevance.

The main values of geodiversity are intrinsic, scientific, cultural, aesthetic, economic and functional (Gray, 2004). Connected to the scientific importance is the educational value, there is a spiritual dimension of the cultural value, and there is also an ecological value of geoheritage, as it supports biodiversity and ecosystem functioning (Crofts *et al.*, 2020). A reserve might have also a touristic value, when it can be used in a geoconservation strategy.

In order to assess the importance of a geological reserve or of the local and regional geoheritage, these values have to be assessed and the use of the reserve or protected area to be established. Some reserves have merely scientific value, and need to be used for educating future generations of specialists. Others include several, or all the values briefly presented above.

The mud volcanoes from the Transylvanian Basin, declared geological reserves, have definitely an intrinsic value, given by their mere existence. They also have a scientific value, as they are places where we can study active or inactive mud volcanoes, in various stages of activity or extinction. As indicators of gas accumulations at depth and gas seepages to the surface, due to erosion of tectonized geological structures, the mud volcanoes also have an educational value.

In case of established geological reserves, conservation can be ensured by site assessment, management and monitoring (Crofts *et al.*, 2020). Risk assessment is an essential component of site management, as site vulnerability and resilience to natural changes or human pressure have to be assessed, as well as the inevitability of natural changes. In the case of mud volcanoes, the site vulnerability to natural changes is obvious, and so is the influence of climate change (which controls the availability of water). Some features of the sites can be partly or totally lost, due to the natural evolution of processes generating the mud volcano fields, like exhaustion of gas accumulation. In such cases, even the site boundaries need to be altered, and sometimes the protection status can no longer be justified (Proser *et al.*, 2010). In Romania, this applies to situations where sites were completely erased, due to their location in an active quarry, or to encroachment of construction works on fragile, sandy sites within a locality (Seghedi *et al.*, 2020).

5. QUANTITATIVE ASSESSMENT OF MUD VOLCANO GEOLOGICAL RESERVES

Qualitative assessment of the main values is not enough for a successful site management. It is necessary to distinguish between various geosites or geological reserves by applying a quantitative assessment, in order to understand how to use a reserve to ensure its conservation and protection.

There are many criteria used on national and regional scale, and they are often contradictory (Reynard *et al.*, 2007; Pereira and Pereira, 2010; Fassoulas *et al.*, 2012; Brilha, 2016).

For a quantitative assessment of the four mud volcano sites from Transylvania, the approach proposed by Brilha (2016) was chosen. The author proposed an assessment of geosites calculating four parameters: scientific value (SV), potential educational use (PEU), potential touristic use (PTU) and degradation risk (DR).

The scientific value is calculated based on seven criteria: representativeness, key locality, scientific knowledge, integrity, geological diversity, and rarity and use limitations), with different weights according to the relative importance of the diverse criteria.

The potential educational use is based on 12 criteria: vulnerability, accessibility, use limitations, safety, logistics, and density of population, association with other values, scenery, uniqueness, observation conditions, didactic potential, and geological diversity.

The potential touristic use is calculated on the basis of 13 criteria, 10 common with those used for the educational value, and adding interpretative potential, economic level and proximity of recreational areas.

The degradation risk (DR) is calculated using five criteria: deterioration of geological elements, proximity to areas/activities with potential to cause degradation, legal protection, accessibility and density of population.

The three main values and the degradation risk calculated for the four mud volcanoes reserves from Transylvania are presented in Table 1. For comparison, the same parameters were calculated for the Pâclele Mici geological reserve from Berca, in the Carpathians Bend Zone, which is one of the most important geosites with mud volcanoes in Romania (Andrăşanu, 2007; Baciu *et al.*, 2007; Brustur *et al.*, 2015; Melinte *et al.*, 2017; Briceag *et al.*, 2019). The highest scientific value of Transylvanian mud volcanoes is shown by the Băile Homorod site, which is quite close to the value obtained for Pâclele Mici. The other three, almost extinct mud volcanoes, have a significantly lower scientific value. The latter also show highest values for degradation risk, as they are mostly inactive. But degradation is of natural causes, as probably the gas in the subsurface gas-bearing structures is gradually depleted, causing extinction of mud volcanoes. Another possible cause might be global warming, as a much warmer and drier summers and mild winters were recorded in Romania lately, influencing the water availability.

Table 1. Values calculated for the geological reserves with mud volcanoes

Geological reserve	Scientific Value	Educational value	Touristic value	Degradation risk
Băile Homorod	3.3	2.25	2.47	2.1
La Gloduri Monor	1.6	2.15	1.75	2.5
Filiaş	1.6	1.9	1.85	2.5
Hăşag	1.6	1.75	1.85	2.65
Pâclele Mici	3.4	3.15	3.5	1.8

The Băile Homorod volcanoes also show highest educational and touristic values, as compared to the other three sites, and these values are significantly lower than those calculated for Pâclele Mici. This can be explained by accessibility issues (longer walks from the paved road, difficulties to find the site in the absence of any road signs), lack of safety facilities, lack of logistics in close vicinity and no special landscape value. Moreover, access to Monor reserve is possible only through a path crossing a private property.

6. CONCLUSIONS

Geological information on the four geological reserves in the Transylvanian Basin show the main features and evolution in time of mud volcanoes, which constitute a dynamic and unstable phenomenon, as well as indicators of damaged gas-bearing structures at depth. An account of their evolution in time is given by information from geological literature. Three such nature monuments „La Gloduri" Monor, Filiaş and Hăşag, are geological reserves with very slow or inactive volcanoes on the brink of extinction. As such, they have a scientific value, as documenting the final stages of evolution of mud volcanoes connected to gas structures, when the gas source becomes exhausted. However, due to accessibility, safety facilities and logistics issues, their educational and touristic values are low. The only site with currently active mud volcanoes is at Băile Homorod, which shows an active cone and crater, and a few gurgling pools in the nearby pond. This reserve is also interesting because of the gas composition, dominated by N_2 and relatively high Helium content, with mantle origin, suggesting deep fractures as access ways. The educational and touristic potential of this site is higher than of the other three, and the degradation risk is lower.

Although not as spectacular and much less studied than the mud volcanoes related to oil and gas structures from the East Carpathians bend zone, mud volcanoes from the Transylvanian basin show a scientific value related to the structures created by salt diapirism and brittle deformation of gas-bearing structures at depths.

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