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GEOPHYSICS

Explosion Dynamics of the Andrusov Mud Vent (Bulganak Mud Volcano Area, Kerch Peninsula, Russia)

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Abstract—Based on comprehensive geophysical and hydrogeochemical study of mud volcanism within Bulganak center (Kerch Peninsula), periodicity of ejections of Andrusov mud volcano are defined during its activity.

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Gas emitting mud volcanism is regarded as a part of the global process of the Earth's degassing. Formation of mud volcanoes is complex combination of different processes, namely, sedimentogenesis, diagenesis, maturation of dispersed organic matter, crushing and grinding of rocks, transportation of material to the surface with different transporting agents (gas, loam pulp, water, etc.), and, finally, accumulation of eruptive products. The rapid uplift of gas-saturated and water-saturated soft mud masses is followed by eruptions, ranging from the quiet overflow of liquid rock to gas explosions [1–4].

Some of these processes have been studied thoroughly by now, while others have not been studied. Despite the fact that the external morphology of mud volcanoes has been studied well, data on their internal structure is extremely scarce [4]. In particular, the structural features of vents and feeding channels are unknown. In addition, there are no data about changes in their configurations before and after an eruption, the characteristics of shallow gas and saline water reservoirs feeding gryphons and small lakes (salsas), and their behavior before outflows. Due to an absence of techniques developed, researchers have still not had a chance to look in the internal part of an active mud volcano or to observe in detail the development of a mud volcano's eruption in time.

This work presents unique results of a full-scale geophysical investigation that, along with the measured hydrochemical parameters of mud volcanoes, can be used with success for the study of the geometry of feeding channels before and during an eruption.

The mud volcanoes being studied are located in the active Kerch-Taman mud volcano province [2, 5]. Based on the composition of fragments of the surrounding rocks (sandstone, limestone, marl, clayey-siderite nodules, siltstone, Neogene and Paleogene clays, and Kimmerian iron ore) that were brought to the surface, the root zones of Kerch mud volcanoes can be traced to the Maykop basal deposits and those of the Taman mud volcanoes, to Upper Cretaceous deposits [2, 6].

Geophysical investigations were carried out in the area of the Bulganak mud volcano, located on the southern flank of the Bondarenko anticline, 8–10 km north of Kerch (45°25′39″ N, 36°28′41″ E), in September 2013 (Fig. 1). The current level of activity of this volcano, the largest one on the Kerch Peninsula (4 km^2), corresponds to the passive gryphon-salsa stage, which is expressed in a quiet overflow of saline water and mud (about 5000 liter a day) and emission of hydrocarbon gases (about 100 m^3 a day). The composition of gases is as follows: methane 95–96%, CO_2 2–4% [2, 6]. The continuous emission of gas leads to pressure release in the underground chambers and release of excess pressure, thus preventing catastrophic eruptions. In the twentieth century only two relatively violent explosions of the Andrusov vent in 1926 and 1986 were registered. As a consequence, vents of the Bulganak mud volcano field are referred to the morphogenetic types of structures (small hills, gryphons, and salsas), which are formed during the eruption of water-saturated (low viscous) material. The main part of the caldera is occupied by salsas filled with saline

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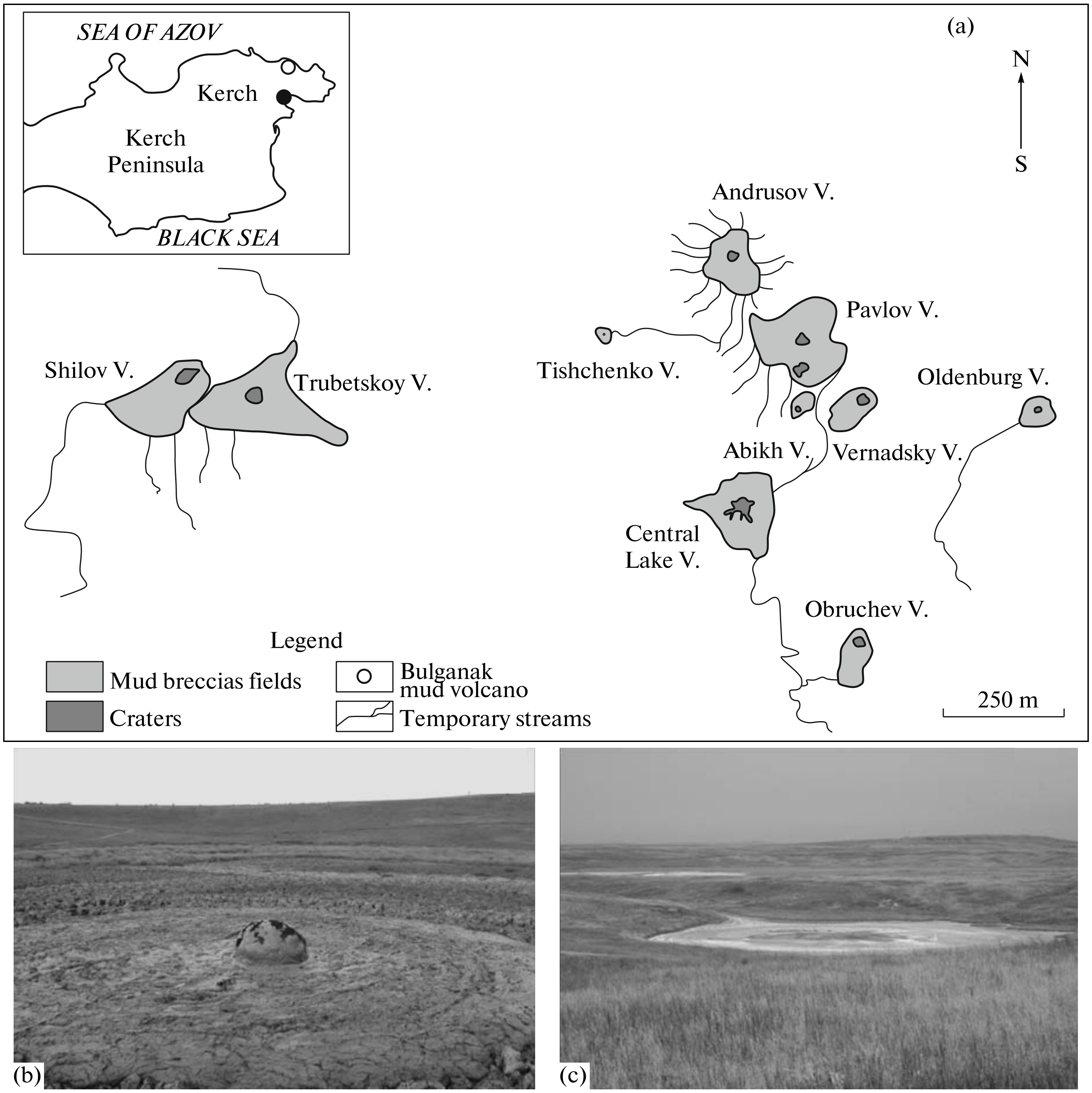

Fig. 1. (a) Scheme of location of vents within the Bulganak mud volcano area; (b) the Andrusov vent at the peak of activity (September 19, 2013); (c) the panoramic view of the Bulganak mud volcano (Central Lake vent, front view).

water, loamy pulp, and mud. The Andrusov, Pavlov, Tishchenko, Abikh, and Vernadsky vents are located in the north of the field; Obruchev and Central Lake—in the south, Trubetskoy and Shilov—in the west; Oldenburg—in the east (Fig. 1). The highest Andrusov vent rises 5–7 meters over the surface with a 300 m base and a 50 m crater.

In June 2012, we carried out hydrogeochemical sampling of gryphons and salsas in the Bulganak volcano mud area: the solution from the Andrusov vent, collected in a satellite crater where the proportion of the liquid phase was significantly greater than that of the solid phase, the Oldenburg vent, travertine sources, and the Obruchev vent. The samples collected were placed in plastic containers; pH, Eh, and electric conductivity were measured in situ. After detention the solution was filtered through blue ribbon filter paper and embedded into containers. The main anionic and cationic compositions of the solution were analyzed with titrimetric, turbidimetric, and photometric methods. The concentrations of trace elements in the solutions were determined by the ISP-AES method using an IRIS Advantage instrument (2000) in the Analytical Center of the Institute of Geology and Mineralogy, Siberian Branch, Russian Academy of Sciences (Novosibirsk).

In accordance with the pH values and the main ionic composition, the alkaline to highly alkaline

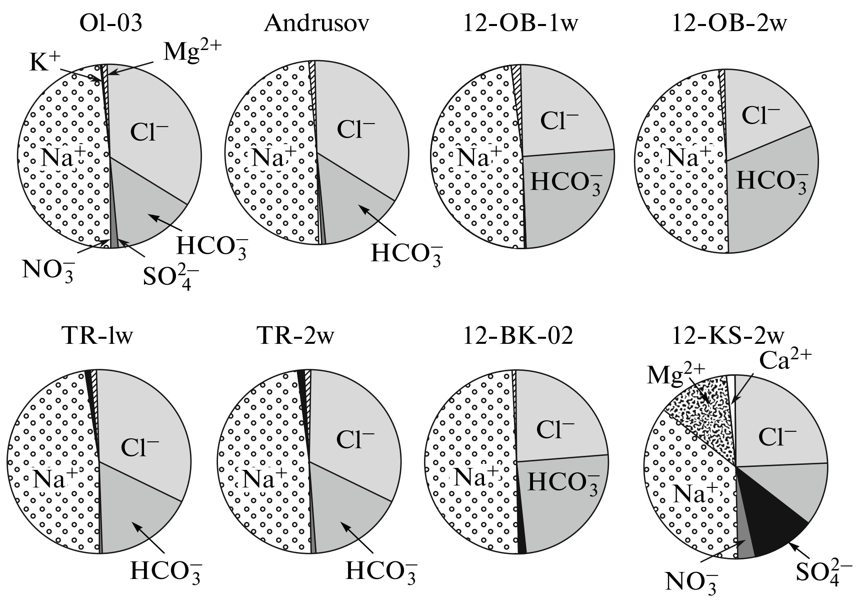

Fig. 2. The main ionic compositions of solutions of the following vents: Oldenburg (Ol-3), Andrusov, Obruchev (OB), travertine sources (TR), Bulganak (BK) and Kayaly-Sart (KS) sources, mg-equiv.%.

brackish to saline water of the sources is classified as chloride-bicarbonate or bicarbonate-chloride (Fig. 2). The type of water in all samples is sodium, which is evidence that buried and modern waters dominate in solutions of mud volcanoes. The level of mineralization and the microelement composition allow us to attribute them to Maykop (Oligocene) water-bearing clay complex [2].

The fluid generation temperatures estimated using a Mg–Li thermometer [7] and an oxygen thermometer ($\delta^{18}O$) [8] for modern travertines of the study area are 52–78 and 54–75°C. This corresponds to a depth interval of 2.5–3 km and the stratigraphic position of the Maykop stratum and supports S.V Al'bov's opinion [9] that in accordance with hydrogeochemical parameters deeply buried unwashed and poorly washed sediments with saline waters took part in the formation of the Bulganak mud volcano.

Indirect confirmation of the high salinity of pore fluids is mass crystallization of water-soluble salts at the evaporation barrier: halite (NaCl), tinkalkonite ($Na_2[B_4O_5(OH)_4] \cdot 3H_2O$), borax ($Na_2[B_4O_5(OH)_4] \cdot 8H_2O$), trona ($Na_3H(CO_3)_2 \cdot 2H_2O$), geylyussite ($Na_2Ca(CO_3)_2 \cdot 5H_2O$), nortupite ($Na_3Mg(CO_3)_2Cl$), and nitratine ($NaNO_3$).

Geophysical investigation of the internal structure of the Andrusov vent was carried out using a modified version of the vertical electrical sounding method (VES)—electrical resistivity tomography (ERT). Electrical resistivity tomography is referred to a set of geoelectric prospecting methods, based on variations in the electrical resistivity (ER) of rocks. Unlike the VES method, which is used for studying horizontal-bedding structures, the ERT technique is used to study complex two-dimensional and three-dimensional geological environments. Electrical resistivity tomography allows one to reveal the geoelectric structure of the near-surface space. The structural elements of the mud volcanic system are well differentiated with respect to ER values, which is a favorable factor to determine the depths and geometrical parameters of reservoirs, traps, and channels [10].

As salts dissolved in the pore fluid is the main carrier of electric conductivity, the electrical resistivity tomography allows one to identify with confidence the type of pore fluids (gas, water, brine) in rocks.

The activation of the Andrusov vent was noted from 9:00 to 13:00 on September 19, 2013. This made it possible to record changes in the geoelectric parameters of the near-surface space during the mud eruption for the first time. During the eruption, pulse emission of gases and outflows of water-saturated loamy mud ($T = 18–20°C$) were observed. The electrical resistivity tomography profile passes through the central part of the Andrusov vent, the profile center was over the vent where the mud exhausted A length of the profile was constrained by that of a 115 m standard electric prospecting cable with a distance between electrodes of 5 m. For measurements we used the SKALA-48 multielectrode geoelectric prospecting equipment designed at IPGG, Siberian Branch, Russian Academy of Sciences [11]. In order to measure the electrical resistivity, the Schlumberger array with daisy-chained electrodes was used. Due to the speed of the electric exploration equipment, we were able to measure the electrical resistivity every 7 minutes. Continuous observations over the Andrusov vent behavior conducted for 3 hours showed that at a low-intensity

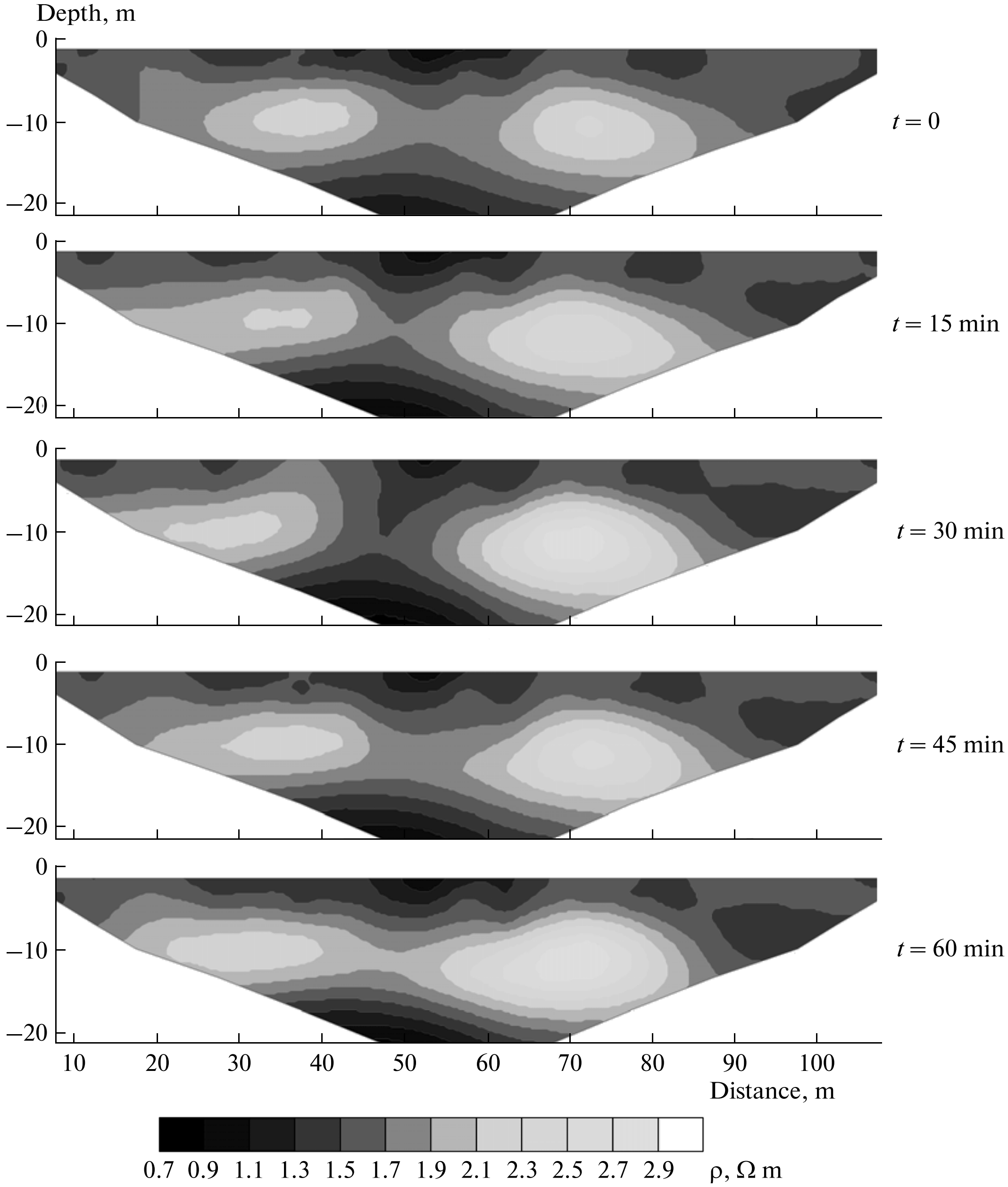

Fig. 3. Variations in geoelectric parameters during eruption of the Andrusov vent on September 19, 2013.

eruption of the Andrusov vent the intervals of pressure rise in the chamber, the eruption itself, and the relaxation period of the vent are comparable with the period of the ET measurement. This made it possible to monitor changes in the electrical resistivity in the near-surface space of a vent during the eruption. The resulting data set was processed with Res2Dinv software [12]. As a result, two-dimensional (2D) resistivity cross sections of the near-surface environment were constructed.

The geoelectric cross sections across the Andrusov vent show that the matter is characterized by a very low resistivity (0.7–3.0 Ω m, Fig. 3) due to the high salinity level in the pore fluid and the soil salinity. According to [13] such electrical resistivity is evidence that the salinity of pore fluid in loamy mud should be about 20 g/L, which is close to that measured during the laboratory analysis (18 g/L). The minimum ER (0.7–1.0 Ω m) is characteristic of very soft mud in a vent and mud in an intermediate chamber.

The vent breccias composing the mud volcano structure are characterized by a high resistivity (2–3 Ω m) due to the large volume of the sandy fraction and fragments of surrounding rocks. In the feeding channel, there is a narrowing in the high-resistivity layer. In general, the vent is a high-conductive structure with a distinct separation of the upper (crater) and lower (near-surface camera) parts, connected by a feeding channel bringing gas, mineralized water, and loamy pulp to the surface.

As is seen in a series of sections-shots illustrating the changes in the geoelectric section of the Andrusov vent during its eruption (Fig. 3), the ERT variations define the dynamics of the changes in the state of the environment, in other words, this is illustration of the process of the rising gas-saturated fluid (t = 0–15 min), the opening of a vent (t = 30 min), and then the sealing of the channel with soft loam (t = 45–60 min). Thus, the complete cycle of evolution of typical mud, including the opening of a channel, the uplift of decompressed gas–water–loamy pulp, a rapid outflow, and then the sealing of the channel walls as a result of gas pressure release, lasted 45 minutes. At the moment of the maximum opening of the feeding channel, the latter in the axial part was about 1 m in diameter increasing up to 10 m on the surface.

Observations over the dynamics of the electrical resistivity variations in a vent at a depth of 5 m during a 3-hour eruption allowed us to reveal the cycle of these variations with a period of about 6 hours, that is, about a half-period of semi-diurnal lunar tides (12 h 25 min). Based on such coincidences, one can suggest that pulse activation of the Andrusov vent is caused by tidal forces since there was full moon on September 19, 2013. The relationship between the catastrophic eruptions of mud volcanoes and cosmic cycles is justified [14]. It is likely that our data give new impetus to the development of this idea.

Thus, the following results were obtained.

Due to study of the Andrusov vent, analysis of the repeated measurements of active mud volcanoes with electrical resistivity tomography was developed. This method made it possible to identify the mechanism of the eruption and to study changes in the structure of the near-surface space caused by the uplift and eruption of gas-saturated mud.

The periodicity of eruptions of the Andrusov vent (about 45 minutes) is regulated by the uplift and concentration of gases in the near-surface chamber. When a chamber becomes overpressured, gas emission starts and gas-saturated loamy mud escapes to the surface to form a mud volcano. It is assumed that a mud volcano becomes active at the full moon when the diurnal period of activity is 6 hours.

The solid fraction is represented by water-saturated hydrothermally altered fragments of surrounding rocks, the porous space of which is filled with buried marine brine, diluted to varying degrees by meteoric water and gases.

The resistivity of the mud is 0.7–1.0 Ω m. Such low resistivity values indicate the high level of salinity (up to 20 g/L) of the liquid phase.

Based on the chemical composition of the liquid phase which outflows from volcanic vents, one can assume that buried marine water was the main source of solutions and emitting gases are enriched in some microelements (anionogenic As, Se, In, and metals Cu, Zn, Fe, Al, Ag, Sn, etc.), while the concentrations of macroelements (Ca, Mg, K, Na, Cl, S) are due to the fact that the marine water is diluted by more fresh near-surface or formation water.

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