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UNDERSTANDING THE DEEP UNDERGROUND STRUCTURE OF THE MOUNT KARABETOV MUD VOLCANO

The success of recently developed geological and geophysical methods and technologies for monitoring of mud volcanoes in the Kerch-Taman region is eventually based on the fundamental scientific results accumulated at the turn of the century under the overall leadership of the Academician E.F. Shnyukov. The results of geological and geophysical studies of the Mount Karabetov mud volcano (Taman Peninsula) featuring the passive seismoacoustic sounding method are presented. New data on the spatial configuration of subvertical fluid-saturated structures associated with the volcano's feeding system were obtained. Subsequent common interpretation of the geophysical data and the results of the structural-geomorphologic observations allowed one to formulate a consistent hypothesis on the possible deep mechanism of mud volcanic activity responsible for the mostly paroxysmal nature of eruptions of the Mount Karabetov..

Keywords: *mud volcanism, Mount Karabetov mud volcano, deep underground structure, fluid migration, surface waves, microseisms, Taman Peninsula.*

Mt. Karabetov mud volcano is a high plateau with a system of individual hills located at the top of a low-angle dome-shaped uplift (142 m asl, N 45.20°, E 36.794°). The volcanic edifice is com-posed of mud-volcanic breccias. Salses, gryphons, and small salt lakes are scattered on the flat surface of the uplift (Fig. 1). The mud volcano is confined to the eastern periclinal closure of the eponymous anticlinal ridge. The main core of the anticline is composed of rocks of the Chokrakian and Karaganian stages. In two places, the domal part of the anticline is intruded by intensely dislocated Maikopian clays. The Chokrakian and Karaganian layers around the fold core dip at 60—70°. Sarmatian rocks on the limbs rapidly flatten out. Thus, the anticline has a prominent diaper structure [11].

It is confirmed that paroxysmal eruptions are dated back in 1835, 1856, 1868, 1882, 1952 and 1982 [11]. The next explosive event in 2001 has covered nearly 2000 square meters of the volcanic edifice by fresh breccia (Fig. 1).

Crumpled and near-vertically solidified breccia layers accompanied by scattered bulky fragments of rocks, testify to the explosive nature of the 2001 eruption. Next sum-

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Fig. 1. Breccia deposits formed by the May 6, 2001 paroxysmal eruption of the Mount Karabetov mud volcano

Fig. 2. Seismic and hydro-acoustic observations in one of the mud eruptive centers of the Mount Karabetov carried out by the author and his colleague Dr. I.I. Naumenko-Bondarenko in 2002

mer it was the subject for the detailed study by the IPE RAS expedition (Fig. 2). Even the very first inspection of the eruption site located almost on top of the volcano has provided the clear indication of the scale of pa-roxysm. The mud volcanic dome was completely destroyed along with dramatically twisted and burnt steel construction of the geo-triangulation point on top of the mountain.

The geological study examination of consequences of the eruption started immediately after the outburst. As follows from the eyewitness description, strong rumbling, bursts of flame, and columns of smoke and dust (up to 100 m high) accompanied the paroxysm. The interpretation of large-scale aerial photographs allowed us to outline the ring structures of the crater field in the explosion center and the lineaments that intersect slopes and summit of the volcano. The eruption center is related to the ~1700-m-long lineament that extends in the northwestern direction. The next center of the volcanic outburst and the mud eruption forming a light breccia field is situated about 500 m away from the first center.

As a result of the paroxysmal eruption, the surface of the volcanic source zone was severely de-formed and crosscut by a dense network of fissures that served as conducts of dry gases. A rounded mud breccia massif, up to 500 m^2 in area and about 800 m^3 in volume, was formed in the outburst center. High temperature burning of the mud-volcanic gases has transformed the clayey rocks into brick-red scoria. Clayey volcanic bombs and lithified volcanic breccia were scattered by the outburst over an area of more than 24000 m^2.

In the course of field expedition next year we sampled the dry mud-volcanic gases from the Mt. Karabetov mud volcano in order to study their chemical composition and carbon isotopes. These studies were carried by the scientific team supervised by the famous geochemist G.I. Voitov [1].

The chemical composition of gases (CH_4 and its homologues, N_2, CO_2, H_2, and He) were ana-lyzed on a "Tsvet-500" chromatograph equipped with gas detectors based on measurements of the thermal conduction and ionization in the hydrogen flame. Low hydrocarbon concentrations were analyzed with ionization detectors in hydrogen flame. Uncertainty of the chromatographic analysis was ±2 % of the measured value and increased to ±30 % when the concentration of methane homo-logues dropped to 10^{-6} %. The uncertainty of chromatographic analysis of nonhydrocarbon gases and high CH_4 contents was ±3 % of the measured value (Table 1, 2).

The carbon isotopic composition of CO_2 and CH_4 was determined on an MI-1201 mass spec-trometer with an accuracy better than ±0.2 ‰. Analytical results are given in parts per thousand of $\delta^{13}C$ values referred to the PDB international standard.

For the explosive eruption in 2001, the scale of the release of carbonaceous gases in the paroxysmal stage has been clarified. The average quantity of gas ($\bar{q}$) consumed for

Table 1. **Chemical composition of hydrocarbons in dry gases from gryphons of the Karabetov mud volcano (September 5, 2002) [1]**

Sample no.	Concentration, %									
	CH_4	C_2H_6	C_2H_4	C_3H_8	C_3H_6	i-C_4H_{10}	n-C_4H_{10}	C_4H_8	i-C_5H_{12}	n-C_5H_{12}
N 3	57.78	Not analyzed								
N 4	64.35	0.53	Not found	0.2037	Not found	0.0502	0.0461	0.0024	0.0594	0.0278
N 5	70.20	0.61	Not found	0.2333	Not found	0.0614	0.0708	0.0021	0.0584	0.0282
N 6	74.17	Not analyzed								

Table 2. **Chemical composition of hydrocarbons and carbon isotopic composition in dry gases from gryphons of the Karabetov mud volcano (September 5, 2002) [1]**

Sample no.	Concentration, %					$\delta^{13}C$, ‰ PDB		
	CO_2	CH_4	He	H_2	N_2	CH_4	C_2+C_3	CO_2
N 3	14.16	38.45	0.005	n.fnd.	28.06	–31.7	n.a.	n.a.
N 4	14.21	48.55	0.004	n.fnd.	21.43	–31.5	–30.5	n.a.
N 5	14.87	66.9	0.007	0.002	14.92	–31.6	n.a.	n.a.
N 6	17.39	69.28	0.003	n.fnd.	8.45	–31.7	n.a.	–20.7

the discharge of unit breccia volume is determined as [5]:

$$\bar{q} = \int_{d_{\min}}^{d_{\max}} q f(x)\,dx, \qquad (1)$$

where $d_{\min}$ and $d_{\max}$ — are minimum and maximum diameters of fragments and $f(x)$ — is the differ-ential function of fragment size distribution. It is assumed that the fragment dimensions are uniformly distributed within a range from 0.001 to 0.1 m. Then the total quantity of gas ($\overline{Q}$) released during the eruption of the given breccia volume (800 m^3), can be estimated as $\overline{Q} = \bar{q}\,W$.

$$\bar{q} = \frac{3\rho_G \,.\, H}{(d_{\max} - d_{\min})}\left[\ \ln\frac{d_{\max}}{d_{\min}} + \frac{2}{\nu_0}\sqrt{\frac{4(g+a)(\rho_s - \rho_G)}{3\lambda\rho_G}}\ \sqrt{d_{\max}} - \sqrt{d_{\min}}\right], \qquad (2)$$

where: ρ_G is the density of gas at its outlet on the surface, $\lambda = 0.5$, $a = \nu_0^2/(2H)$, ρ_s is the density of fragments, g is the acceleration of gravity, and ν_0 is the initial velocity of fragment scattering (~10 m/s). If $\nu_0 = 10$ m/s и $H = 5$ km, $\bar{q} \approx 5 \cdot 10^6 \frac{m^3\ gas}{m^3\ breccia}$, $\overline{Q} \approx 4 \cdot 10^9$ m^3.

Let and be initial and current gas discharges, be the initial gas reserve, and, be the quantity of escaped gas. Then we have:

$$q = q_0\left(1 + \frac{k-1}{2} \cdot \frac{q_0}{Q_0}\ t\right)^{\frac{k+1}{k-1}},\ \ Q = Q_0\left(1 - \left(1 + \frac{k-1}{2} \cdot \frac{q_0}{Q_0}\,T\right)^{\frac{2}{k-1}}\right), \qquad (3)$$

where $k = 1.3$ is the adiabatic exponent, t is the current time, and T — is the eruption period in the free outflow regime. The initial discharge $q_0 = \nu_G \cdot \rho_G \cdot s$, where s is the total section of all con-duits (~1 % of the total area of mud occurrence equal to $2.4 \cdot 10^4$ m^2). If we assume $\nu_G \approx 400$ м/с, $\rho_G = 3$ kg/m^3, then $q_0 \approx 1 \cdot 10^6$ m^3/s. Taking into account that the eruption lasted about 50 min, then $Q_0 \approx 3 \cdot 10^9$ m^3 (Fig. 3).

Thus, according to our estimates, the total volume of carbonaceous gases released in the paroxysmal stage of the eruption of the Mt. Karabetova mud volcano was $Q_0 \approx 3 \times 10^9$ m^3 in 50 minutes [1].

The chemically dry gases of the Mt. Karabetov mud volcano are represented by mixtures of hydrocarbons of the methane series, homologues (isopentanes, normal pentanes, and hexanes), nitrogen, carbon dioxide, helium, and occasional molecular hydrogen. The helium content corresponds to natural mixtures genetically related to the metasedimentary or granitic basement rocks. Mentioned gases remain chemically unstable during a year or more after the mud volcanic outburst; i.e., processes of permanent generation and ascent of oil-series gases from their source to the surface troposphere are accompanied by appreciable changes of their chemical composition.

Methane and nitrogen contents are variable while concentrations of methane homologues are more stable (see Table 1). The carbon isotopic composition of methane is also rather uniform (see Table 2) and varies only within analytical uncertainties (0.1 ‰ of δ^{13}C PDB). This testifies either to the limited dimensions or the uniqueness of methane source with δ^{13}C 10 ‰ higher than the average carbon isotopic composition of methane from the catagenesis zone of organic matter in sedimentary rocks [14]. As an alternative, it may be assumed that the source of methane beneath the Karabetov mud volcano resides in Paleozoic rocks. Gas and fragments of highgrade metamorphic rocks are

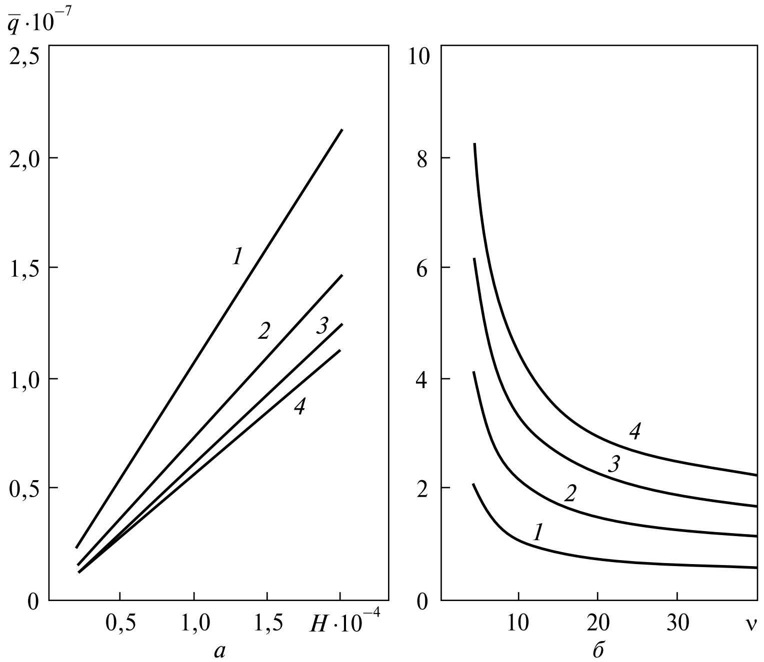

Fig. 3. Average quantity of gas consumed for breccia exhumation depending on: *a* — source depth (H), and *b* — outflow velocity (V). V values (m/s): (*1*) — 10, (*2*) — 20, (*3*) — 30, (*4*) — 40. H values (km): (*1*) — 10, (*2*) — 20, (*3*) — 30, (*4)* — 40 [1]

exhumed to the surface during the paroxysmal eruption. Similar fragments were repeatedly found in the mud-volcanic breccia from the Taman province [9].

Later on the detailed geological-geomorphological mapping of Mt. Karabetov mud volcano was carried out and supplemented by remote sensing data. As a result, it became possible to trace the tectonic deformations of young forms of topography and various manifestations of exogenous geo-logical processes in the studied region (Fig. 4).

Clear structural-geological regularities are observed in the arrangement of topographic forms. Gryphons and salses are usually confined to the domes of anticlinal folds or tectonic fractures. The major part of anticlines remains active up to the present time. This is indicated by deeply intended ravine valleys, which cut the folds, and by landslides on the slopes of the valley. The westernmost anticline, which is almost invisible in the anomalous development of exogenous processes, is an exception. In general, the anticlinal ridge is characterized by an asymmetric structure: its northern flank is flatter than the southern one. Therefore, we can suppose that the ridge is located near a fault. Individual folds in the ridge are characterized by the properties typical for the major part of diapirs in the Taman Peninsula. The core of the folds is intruded by folded plastic clays of the Maikop Group (see Fig. 4).

Thus, we can suppose that the formation of the Mt. Karabetov mud volcano and the eponymous anticline is related to the conditions of subhorizontal extension along the fracture in the fold axis. In this case, the extension is oriented in the sublatitudinal direction, while contraction is in the subme-ridional direction. This anticline is characterized by a NNE orientation, which is atypical for normal NE-oriented diapirs of the ridge, and the deep location (1 km) of the Maikopian diaper core. We can suppose that

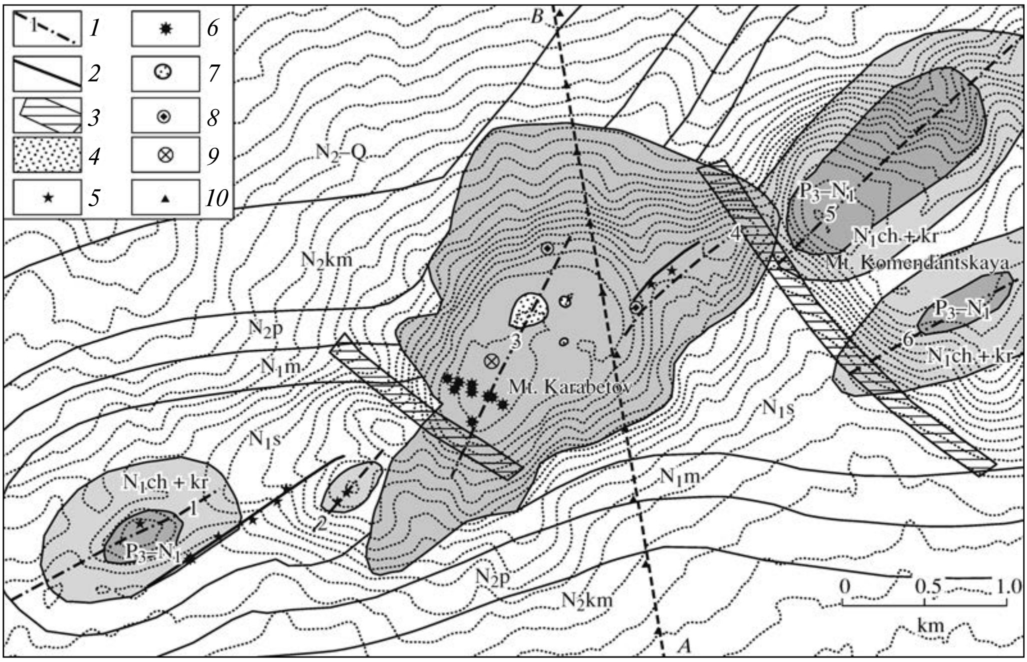

Fig. 4. Geological schematic map of the Mt. Karabetov mud volcano. Horizontal contour lines are shown with an interval of 5 m: *1* — axes of anticline folds and their numbers; *2* — proven fractures; *3* — fractures based on the structural-geomorphological indicators; *4* — Mud-volcanic breccia cover on the Mt. Karabetov mud volcano; *5* — active gryphons; *6* — inactive gryphons; *7* — salses; *8* — large conic gryphons up to a few meters high; *9* — center of explosive eruption on May 6, 2001; *10* — points of microseismic survey profile. (P_3_N_1) Maikop Group (clays); (N_1ch+kr) Chokrakian and Karaganian stages (dark gray clays with marl and limestone layers); (N1s) Sarmaian stage (greenish gray clays with numerous porous marl and limestone layers); (N_1m) Meotian stage (dark clays with marl and limestone layers); (N_2p) Pontian stage (dark gray and black clays with loose limestone, marl, and sandstone interlayers); (N_2km) Kimmerian stage (clays and sands with oolitic iron ore interlayers and lenses in the lower part); (N_2_Q) clays, sandy loams, sands, and a reddish brown clay layer in the upper part [12]

this orientation caused maximal concentration of extension stresses and the most favorable conditions for fluid pressure discharge. Therefore, the diapir core piercing was not exposed.

In 2007—2009 the IPE RAS has initiated a series of expeditions in order to implement the new geophysical method [4] to study the subvertical fluid-permeable mud feeding system under the Mt. Karabetov. It should be noted that seismic prospecting techniques based on the use of surface waves have proved to allow rather quick acquisition of a qualitative idea of the internal structure of the crustal layers via relatively easy procedures used in field work and for data processing. To study mud volcanoes with a predominantly sub-vertical structure of low-velocity inhomogeneities it seems natural to go for passive amplitude methods based on microseismic surface waves as on a sounding signal. The key assumption is based on an experimental fact that underground inhomogeneities affect the amplitude of surface waves, namely: buried high-velocity inhomogeneities cause a decrease in the amplitude of microseismic noise registered on the surface over them and vice versa. So the increase or decrease in the amplitude of micro-

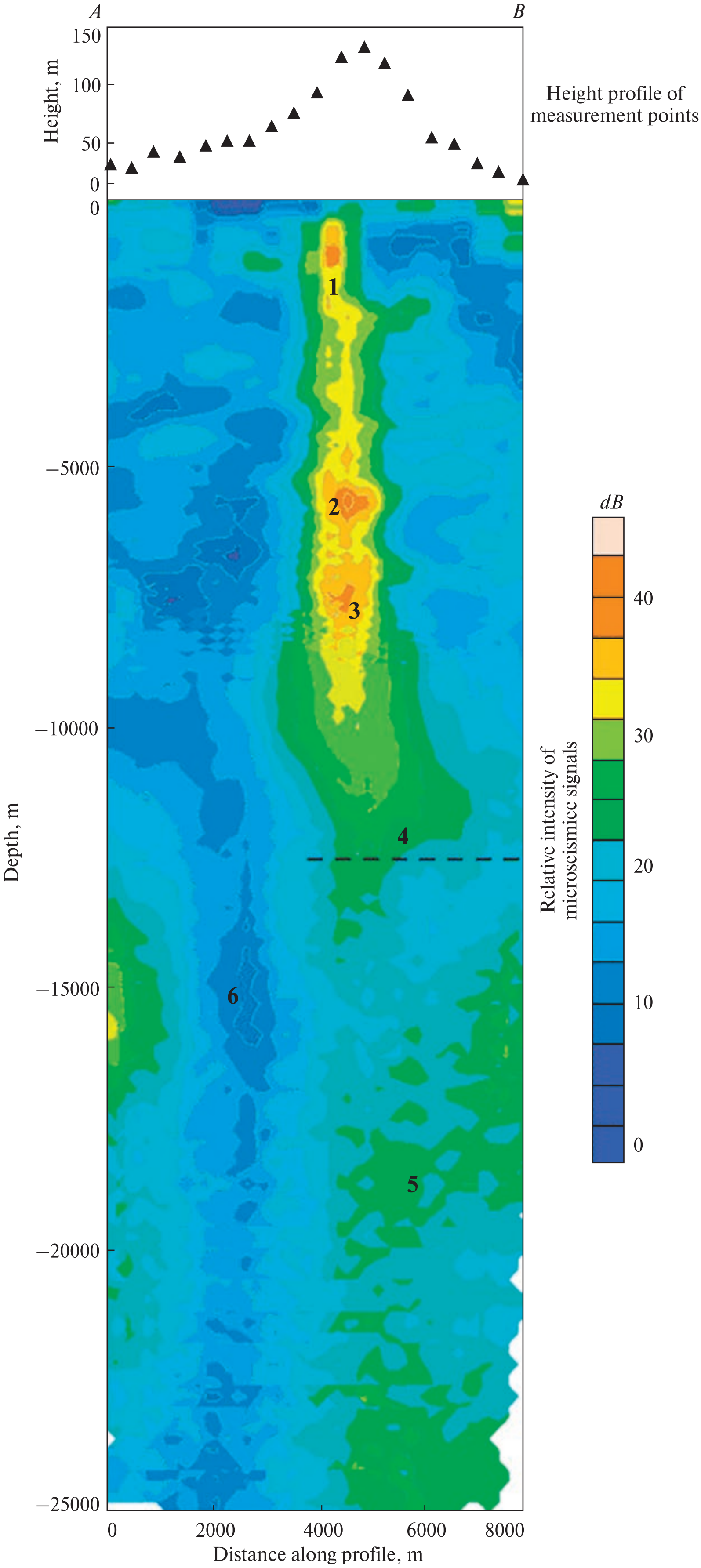

Fig. 5. Vertical cross-section along the low-frequency microseismic sounding geophysical profile (line AB in Fig. 4): *1* — subsurface mud volcanic reservoir; *2,3* — deep mud reservoirs; *4* — domain of transition to consolidated basement; *5* — deep fluid-permeable structures; *6* — solid rocks. Color scale indicates values of ratio of spectral amplitudes of S-wave vertical component in microseismic noise measured along the profile relatively to base station. Low-velocity subsurface inhomogeneities cause increase of the ratio (warmer colors) and vice versa [12]

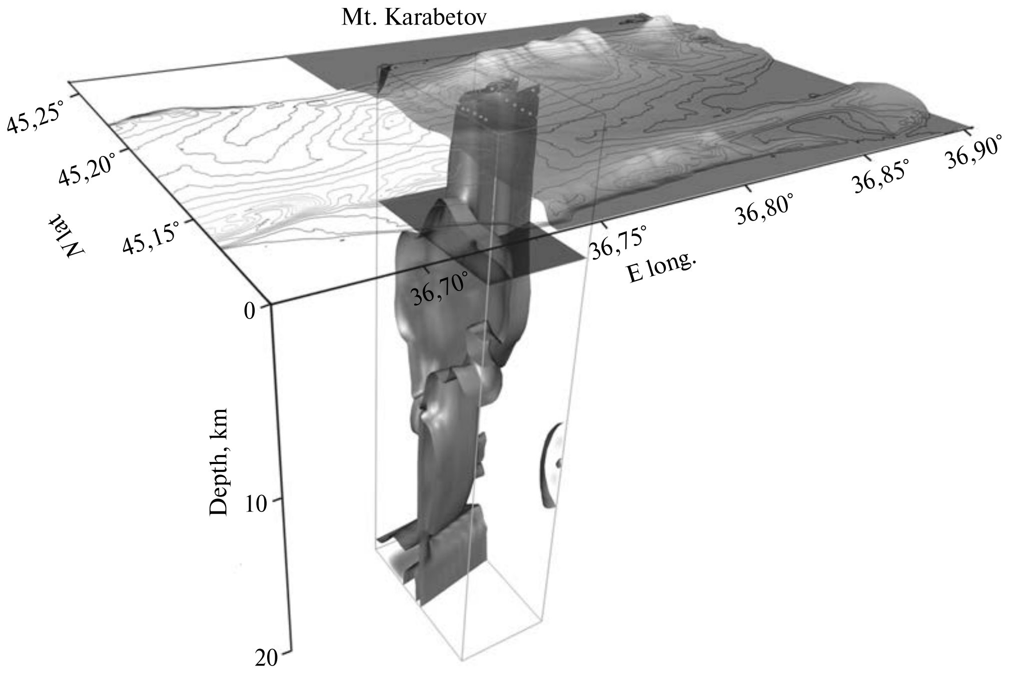

Fig. 6. Three-dimensional representation of the fluid-saturated feeding system of the Mt. Karabetov mud volcano based on processing of data acquired along several geophysical profiles [8]

seismic noise is mainly related to wavelengths equal to approximately twice the depth of the inhomogeneity in question.

First geophysical profile [12] studied by means of the low-frequency microseismic sounding technology is shown in Fig. 4 (line AB) and the vertical cross section along it is shown in Fig. 5.

A relatively narrow vertical low-velocity zone associated with the fluid-saturated conduit was distinguished from the results of microseismic sounding beneath the Mt. Karabetov. Based on the experimental data, the recharge zone for conduit is located at a depth of 4.5—9 km (see Fig. 5). In the deeper zone, the contrasts of seismic velocities of S waves are not so clear. However, the anomaly associated with the recharge zone can possibly continue to a depth greater than 15 km. Hence, the core of Karabetov diapir anticline composed of Maikopian clays and the mud volcano can be interpreted as products of deep processes — pressure of fluids penetrating along a relatively narrow zone from greater depth and leading to decompaction and flow of the Maikop Group clays along the fractures [13].

The crumpling of the Neogene-Quaternary sediments into the anticlinal fold is in this case unre-lated to regional compression but is associated with the response of the sediments overlying the Maikop Formation to the pressure of the softened mobile masses penetrating from the deep.

Theoretical studies of processes of outflow of viscous gas-saturated mud breccia for various scenarios of mud volcano eruption [17], as well as the common interpretation of the results of experimental geophysical studies, isotope and hydrochemical geothermometry followed by the subsequent mathematical modeling, allows one to obtain comprehensive estimates for the spatial location of the buried mud reservoir [2] and propose the following working hypothesis to explain the mechanisms of the Mt. Karabetova mud volcanic activity.

Let us consider Fig. 6, which shows the data processing results for three geophysical profiles intersecting the anticlinal structure and the corresponding volcanic edifice in the meridional direction. In the three vertical geophysical cross sections, by the values of seismic velocity contrasts delineating the fluid-permeable rocks, we draw the isosurface which gives an idea of the spatial configuration of the feeding system of a mud volcano. At depths from 25 to 12 km, a rather narrow feeding channel can be seen, which at the shallower depths passes into the area of the intermediate accumulation of mud breccia. Further upwards, this area again transforms into the subvertical channel through which the erupted products are directly transported to the surface. The conditional boundary between the accumulation domain and the near-surface feeding channel can be attributed to a depth of ~5 km (shown in Fig. 6 by the horizontal section of a 3D model).

It is hypothesized that from the domain of intermediate accumulation the fluid-saturated clayey masses are nonuniformly supplied to the feeding channel during the preparation and eruption of a mud volcano, which can be accompanied, inter alia, by the tectonic displacements on the fault. This structural peculiarity in the deep structure of the Mt. Karabetov mud volcano largely determines the explosive pattern of its activity. At the same time, separate elements of the feeding system are present in the southeastern part of the volcanic edifice; they act almost permanently in the regime of the free outflow of liquid breccia [8].

Thus, the roots of the Mt. Karabetov mud volcano are stretched almost vertically down to the large depths where they penetrate the Mesozoic formations and even deeper. Volatile component of the deep origin in the Taman Peninsula is demonstrated by the Fontalovskoe gas field. It is located in the region of the relatively shallow occurrence of the Mesozoic rocks, in the Pre-Azov uplift where it is confined to the fractured Upper Cretaceous limestones within the Fontalovskaya anticlinal chain at a depth of 40 km and even. The oil-and-gas and oil occurrences gravitate to the younger rocks at the Oligocene-Miocene stratigraphic level. Another probable source of hydrocarbons is the Lower Cretaceous shelf deposits which, according to the geophysical data, are located at a depth of 8 to 15 km [7]. Let us consider for now, that the dramatic changes in eruptive style of the Mt. Karabetov mud volcano from paroxysmal eruptions to steady outflow of breccia are to be determined mostly by combination of tectonic processes and the generation variability of the deep gaseous component [15, 16]. Supplementary geological and geophysical field studies including instrumental observations of the gas and temperature regimes in mud-volcanic products may either confirm, clarify, or even reject the proposed hypothesis.

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РОЗВИТОК УЯВЛЕНЬ ПРО ГЛИБИННУ БУДОВУ ГРЯЗЬОВОГО ВУЛКАНА ГОРИ КАРАБЕТОВА

Нові геолого-геофізичні методи і технології моніторингу грязьових вулканів Керченсько-Таманської області представляються природним продовженням основоположних наукових робіт, виконаних на рубежі століть під керівництвом академіка НАН України Є.Ф. Шнюкова.

Представлені результати комплексних геолого-геофізичних досліджень грязьового вулкана гори Карабетова (Таманський півострів), в тому числі із застосуванням пасивних сейсмоакустических методів, отримані нові дані щодо просторової конфігурації субвертикальних флюїдопровідних структур живильної системи вулкану. Подальша спільна інтерпретація даних польових геофізичних і струтурно-геоморфологічних спостережень дозволила сформулювати несуперечливу гіпотезу про можливий механізм грязевулканічної діяльності об'єкта, що вивчався, і в значній мірі визначає пароксизмальний характер вивержень.

Ключові слова: *грязьовий вулканізм, гора Карабетова, глибинна будова, кореневі структури, флюїдна активність, поверхневі хвилі, мікросейсмічний шум, Таманський півострів.*