ANAS Transactions **Earth Sciences** **1 / 2023**

http://www.journalesgia.com

ELECTRICAL RESISTIVITY TOMOGRAPHY OF LOKBATAN MUD VOLCANO: INNER STRUCTURE AND FORMATION MECHANISM

Salamov A.M., Mammadov V.A., Rashidov T.M., Zamanova A.G., Gasimov E.E.

Ministry of Science and Education of the Republic of Azerbaijan, Institute of Geology and Geophysics, Azerbaijan
119, H. Javid ave., Baku: vmamed@rambler.ru

Keywords: *geophysics, mud volcano, electrical sounding, microelements, fracture, 3D model, gases*

Summary. The paper deals with the genesis, structure, geochemical and geophysical studies in the vicinity of Lokbatan mud volcano, situated in the SW of Absheron peninsula (Azerbaijan) and characterized by the very intensive mud volcanic activity.

Along with the earlier-stated ideas regarding the process of the mud volcano formation as well as the theory based on the properties of non-newtonian fluid, we had proposed own hypothesis. Here the water has a leading role in formation of the mud volcano: it discharges as a result of geodynamic pressure upon the terrigenous-clayey bed, forming the substances (breccia) with the lowest density respectively the surrounded lithological differences. Breccia is under the great pressures and tends to the day surface along the newly formed conduit, shaping a mud volcano.

The prevailing microcomponents in mud breccia are boron, mercury, manganese, barium, strontium, lithium. Their content is several times over the bulk earth values for the sedimentary rocks.

Using the field data of the vertical electrical sounding on 9 geophysical lines in 19 physical points within Lokbatan mud volcano, 3D models of the area of study had been compiled such as complete, random section, along X, Y and Z axes, and the morphological structure of the ground part of the described volcano.

Introduction

The geological features, mostly described in literature as “mud volcanoes” are distributed worldwide. The main part of these natural objects is corresponded to the oil-and-gas provinces, and their number is assessed as 2500+ (Рашидов, 2017).

The phenomenon of mud volcanism itself represents a rise and emission of clayey masses (of different consistence) and rock fragments to the day surface that form the mud volcanic edifice (Алиев и др., 2015). The driving-forces are mainly the hydrocarbon gases and the rise occurs along the conduits. But the issue of “triggering mechanism” is still open. There are various hypotheses including the earthquakes, dislocations and even the drilling operations (Sawolo et al., 2009; Zoporowski, Miller, 2009).

The study of mud volcanoes is closely related with solution of various problematic theoretical and practical issues in geology, geochemistry, geophysics and some other natural sciences; definition of the deep horizons structure and the physical-chemical processes occurring there. For a total, it is necessary to identify the role of the mud volcanoes in formation of the petroleum system of the region as well as the assessment of oil-and-gas content of the great depths, etc. (Алиев и др., 2015; Рахманов, 1987).

As it was mentioned above, the area of the described natural phenomenon is wide enough. There is a clear regularity in mud volcanoes’ spatial distribution: most of them have a development within the Alpine-Himalayan (Mediterranean) and Pacific folded belts.

Besides it, the areas of mud volcanism development are also corresponded to the zones of accretionary prisms. The mud volcanism with non-accretional conditions includes the areas of the Black Sea, the Alboran Sea, and the Gulf of Mexico (Louisianian coast) (Алиев и др., 2015; Robertson, Kopf, 1998). The recent investigations with application of up-to-date tools and techniques allow identifying new volcanoes, especially in those places that were not considered as the traditional ones (e.g. Nile Delta) (Feseker et al., 2010). As a result, the total number of world mud volcanoes grows.

The territory of the East Azerbaijan and the adjacent water area of the South Caspian is characterized by the most intensity of the mud volcanism manifestation. This territory is the host for over 350 mud volcanoes (including 156 offshore) that occupy the total area of 60,000 km^2. It is well known that the mud volcanoes are mainly developed in the submontane and intermontane troughs where the thick series of the terrigenous-clayey Cenozoic sediments accumulate. Both East Azerbaijan and South Caspian basin (including the territory of the SW Turkmenistan) are the elements of the South Caspian oil-and-gas bearing basin, which is also characterized by the thick (over 25 km) sedimentary series.

Unlike the other regions, in Azerbaijan and the adjacent water area of the Caspian Sea the present natural phenomenon can be observed in all of its forms: acting, extinct, buried, island, submarine, oil-seeping mud volcanoes. From a morphology point of view, there are cone-, dome-, ridge- and plateau-like mud volcanoes. The craters can be of conical, plane-convex, shield, deeply-seated and caldera shape. About 40 mud volcanic manifestations are characterized by the abundant oil seepage. According to a number of mud volcanoes, their variety and activity this region is without equal. Thus, Azerbaijan is deservingly considered as the "motherland of mud volcanoes" (Martinelli, Ferrari, 1991; Алиев и др., 2001; 2015; Rashidov, 2014; Rashidov et al., 2019).

The major part of the mud volcanoes in Azerbaijan make the mud volcanic groups both onshore and the adjacent water area of the Caspian Sea (Baku archipelago, deep-water part of the Caspian Sea). Onshore (Absheron peninsula, SW Gobustan and Lower Kura region) there had been mapped over 220 mud volcanic structures, related with the anticlinal highs, tectonic faults, sometimes complicating the large oil and gas fields.

The individual mud volcanoes in Azerbaijan can reach 400-450 m in height with a crater field to 1000 m^2; the total volume of the hard ejects during the eruption can exceed hundred million cubic metres.

On theory of formation mechanism of the mud volcanoes

In spite of more than two-hundred-year history of study of the mud volcanoes in Azerbaijan, the problem of inner structure as well as the formation mechanism is still among the debatable issues (Baghzendani et al., 2015; Evans, 2007; Evans et al., 2008; Milkov, 2000; Zoporowski, Miller, 2009; Саламов и др., 2019).

The discussion of the theory of the mud volcanoes formation (origin) generated, as a rule, the various schools of thought and the expressed hypotheses consequently. Thus, some researchers like E.P.Shteber, S.A.Kovalevski, V.A.Gorin, N.A.Kudryavtsev, P.N.Kropotkin, B.M.Valyaev, Sh.F.Mekhtiyev, S.D.Gemp, Z.A.Buniyat-zadeh, C.Wilson et al. developed the early-cited ideas of Hermann W.Abich. The mentioned scientists held the theory of the endogenic, magmatic genesis of the mud volcanoes and drew attention to the individual, sometimes hard-to-explain features of the present phenomenon.

The tectonic explanation of the mud volcanism phenomenon and geodynamics contribution in the form of development of diapir folds, low-angle thrusts or deep faults had been proposed by academician A.D.Arkhangelski and, partly M.I. Gubkin. Further, it was supported by such geologists like N.S.Shatski, M.M.Zhukov, E.V.Milanovski, V.E.Ruzhentsev, S.Zuber, V.A.Gorin, S.F.Fedorov, Z.A.Buniyat-zadeh, V.G.Bondarchuk, A.L.Putkaradze, Ch.A.Zeynalov, M.M.Sirika, N.Yu.Khalilov, A.A.Kerimov, A.N.Pilchin, L.N.Elanski, M.L.Kopp, etc.

The theory, elaborated by the petroleum geologists M.K.Kalinko, A.A.Yakubov, M.M.Zeynalov, Z.A.Buniyat-zadeh, R.R.Rakhmanov, E.F.Shnukov, et al. turned out to be the most popular. Based on the earlier-cited opinions of V.N.Veber, K.P.Kalitski, V.D.Golubtanikov, and M.I.Gubkin the present theory connects the mud volcanism genesis with formation and destruction of oil and gas fields. The extra pressure, that appears in the oil fields and promotes the break of the mud volcanic breccia to the day surface through the eruptive channels, is explained by the excessive pressure of the hydrocarbon gases concentrated at the depths (Холодов, 2012).

Yusubov and Guliyev (2022) have proposed quite new mechanism of the mud volcanism formation, basically proved by the 3D seismic survey outcomes. The following idea had been suggested: the Maykopian clayey units exhibit properties of the non-newtonian fluid and locate under the geological system, consisting of the alternating beds of clays and sands. Because of the Rayleigh–Taylor instability (gravity instability) these units created the intrusions in the overlying environment. As a result, the eruptive channels of the mud volcanoes had formed. In other words, the mud volcanism had been developed.

To our opinion, plenty of water discharges as a result of the lateral, vertical pressures, geodynamic and geothermal processes in the terrigenous-clayey series.

The heated water, released as a result of the geothermal process, dissolves and wets a part of the clayey rocks, creating the new geological environments consequently.

As a result of swelling, the wet part of the clayey rocks decompacts and breaks the overlaying beds and creates the discharge (eruptive) channels, and sometimes the intermediate chambers at the definite depths. As a result, the substance with lowest density relatively the surrounding lithological varieties, is formed. The formed substance – breccia, is under the great pressure and gravitate to the day surface along the newly-formed eruptive channel. As a result the mud volcano is forming (Fig. 1).

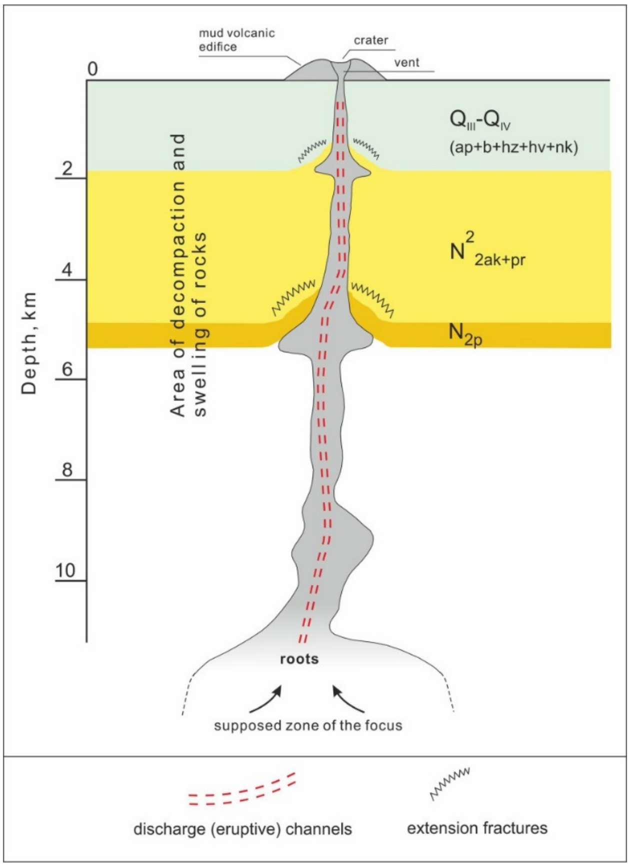

Fig. 1. Scheme of formation mechanism of the mud volcano

Besides it, Ad.A. Aliyev (Алиев, 2003) mentions that the formation of mud volcanic breccia doesn't take place in the volcanic focus itself. The stepped, somewhat stage-by-stage process of its formation is proposed. The fluids move upward along the conduit and the process finally ends at the definite depth, close to the day surface. In the course of paroxysm of eruption when pressure releases, the mud volcanic breccia is portionwise ejected from the volcano vent, filling the crater or flowing down the volcano slopes.

Geological setting

Lokbatan mud volcano (40°18'15.98"N; 49°42'32.61"E) stands out against the rest volcanoes in Azerbaijan. It is the most active and has the clear relation with oil-and-gas content of the structure where it locates. Fig. 2 illustrates a placement of Lokbatan mud volcano within Absheron peninsula.

The sediments of the Absheronian, Akchagilian stages and the Productive Series (Upper and Middle Pliocene) of the Cenozoic take part in the geological structure of Lokbatan fold. These rocks expose as the ridges in the volcano vicinity. The deep drilling had reached the sediments underlying the Productive Series – the Pontian (Lower Pliocene) and the Miocene tops. Generally, the roots of the majority of mud volcanoes in Azerbaijan are related with the Cretaceous and Paleogene-Miocene sediments. But towards the center of the South-Caspian depression these sediments transform into younger Pliocene-Quaternary sediments (Якубов и др., 1971).

Fig. 2. The placement of Lokbatan mud volcano within Absheron peninsula

Tectonically, the mud volcano locates at the crest of asymmetric anticline of latitudinal strike and steep angles of dip at the south side (45-50°) and gentle at the north ones (33-35°). The fold is complicated by faults running in different ways respectively the axis. There is a large displacement of the overthrust type on its top.

The studied mud volcano represents a dome-shaped rise with two humps on top and relative elevation of 86 m, the base 2.5 x 2.3 km and volcanic edifice volume estimated as 98.76 million m^3. Its cone is composed of the mud breccia, formed as a result of the numerous eruptions. The great number of fragments of various rocks are scattered over the volcano vicinity. The volcano crater is represented by subsidence caldera and has an oval shape of ~25 m across. The hard ejects from mud volcano take the area of ~ 400 ha, the average thickness of breccia cover is ~ 40 m, and to 150 m near the crater. The most extended flows of breccia are traced westward for ~700 m and have the width to 300 m (Рашидов, 2017). The hard ejects of Lokbatan mud volcano are corresponded to the Paleogene-Miocene complex and represented by the sandstones, siltstones, clays, marls, limestones and dolomites. The bitumen content is 0.03 to 0.8%, rarely exceeding the values of 1.56%. The increased content (0.8-1.56%) is related with the bitumen presence in non-scattered state but due to rocks enrichment by the epigenetic bitumens accumulated here due to their migration. The quantity varies 0.01 to 1.05%, in rocks strongly saturated with oil the value reaches to 1.83% (Якубов и др., 1976).

According to chemical composition the gases from Lokbatan mud volcano are hydrocarbonic; they consist of methane (92%), heavy hydrocarbons (~2%) and carbon dioxide (~2.5%). The volume of gas emanated during the eruption in 1972 was about 9 million m^3.

Among the rock-forming combinations, SiO_2 (55.35%) and Al_2O_3 (15.51%) prevail in the chemical composition of the breccia (by field works in 2012), and a row of clarkes of concentration for microelements had the following expression:

$$\frac{Cd}{14.7} > \frac{As}{2.9} > \frac{Cr}{2.0} > \frac{Mo}{1.6} > \frac{Cu, Zn}{1.2} >$$
$$> \frac{Ni}{0.9} > \frac{Ba, Sr}{0.6} > \frac{Rb, V}{0.5} > \frac{Co, Pb, Ga}{0.2}$$

Parameters of the present row are corresponded to the nearly all mud volcanoes of Absheron region.

The main morphological elements of the relief of Lokbatan mud volcano are the breccia flows and crater field, but the main destructive factors – the physical and chemical erosion.

Observations for the great number of eruptions of various mud volcanoes in Azerbaijan show that difference between them is mainly in frequency and intensity of eruptions. But they are very similar in respect to the external effect of paroxysm manifestation and products of activity. It is clearly seen on the example of Lokbatan mud volcano being one of the most active (from viewpoint of eruption). Since 1829 till 2017 there had been recorded 25 eruptions, i.e. one eruption every 7.5 year in an average. The strongest eruptions with intensive eject of breccia, gas ignition with further burning fire were observed in 1887, 1923, 1935, 1954, 2001, 2012 and 2017 (Якубов и др., 1971; Aliyev et al., 2002; Рашидов, 2017).

The intensity of eruptions and closeness to the settlements make this volcano quite easy to perform the various geologic-geophysical studies. So, a month after the eruption in September 20, 2012, the short-term field works had been performed within Lokbatan mud volcano (Figs. 3-5). Gas emissions were observed mainly in the north-western part of the crater field. In some places there were newly-formed mud springs as well as the fragments of mud volcanic breccia experienced the thermal impact because of gas ignition (Fig. 6).

As it was mentioned above, Lokbatan mud volcano locates within the oil-and-gas bearing structure of the same name. It is quite important to point out that a gusher of oil had been obtained for the first time from the IV horizon of the Productive Series (Middle Pliocene) in 1935, from well #45 located eastward of the crater. For the less than 50 years ~ 30 million tons of oil and ~ 1 milliard m^3 of natural gas had been produced in Lokbatan oil field for a total (Якубов и др., 1971).

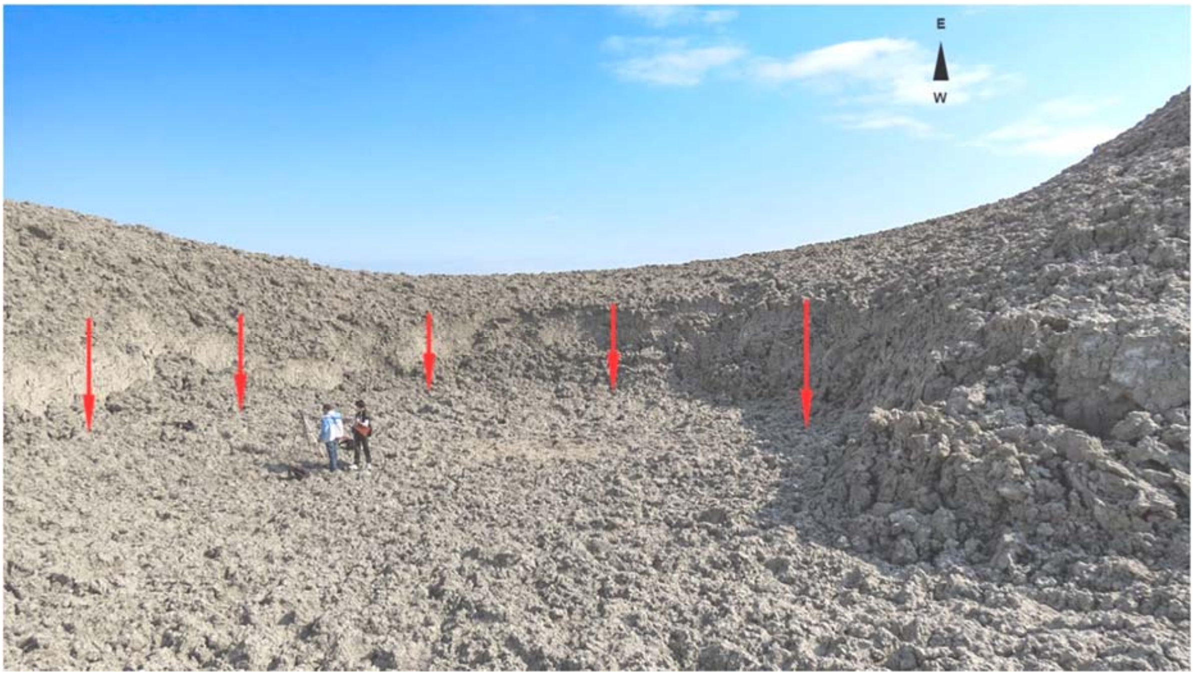

Fig. 3. Crater of Lokbatan mud volcano after eruption in September 20, 2012. The red arrows indicate the border of crater subsidence after the event

Fig. 4. Mud breccia flow cut the crater in the western direction. Two mountains locally called as "Baku ears" in the back ground (on the left)

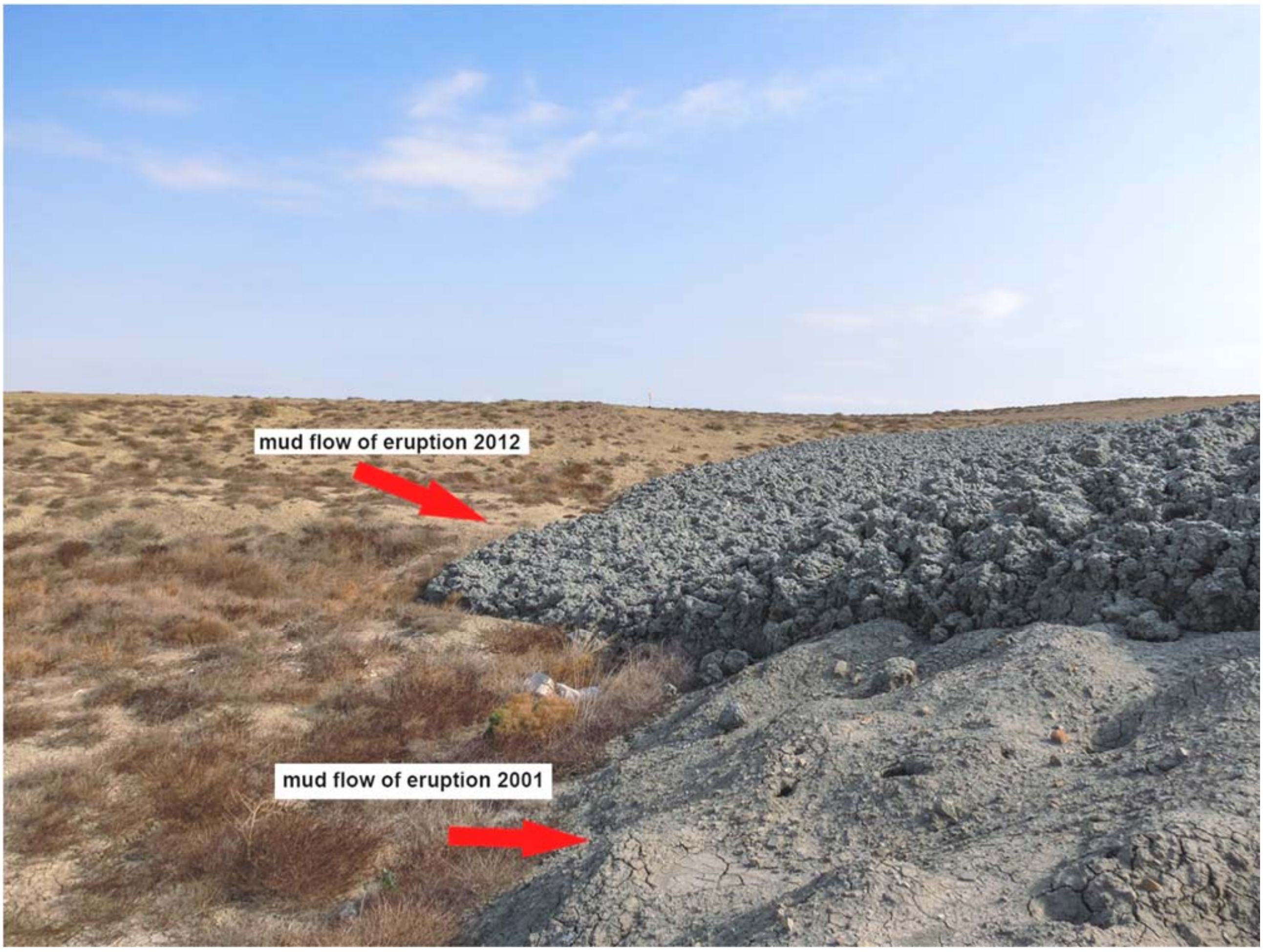

Fig. 5. Fresh mud flows, overlying the previously erupted, eroded flows

a) *b)*

Fig. 6. Gas emission from newly-born mud spring (A) and fragment of mud volcanic breccia after the thermal impact (b)

Methodology and technique of the field works for Vertical Electrical Sounding in Lokbatan mud volcano

The aims to carry out the geophysical studies using the Vertical Electrical Sounding (VES) within Lokbatan mud volcano were:

- the detail dissection of the geological section to 200 m in depth;
- definition of the morphological structure of the above-surface part of the mud volcano;
- definition of the proposed thickness of the mud volcanic breccia and depth of occurrence of the primary deposits top;
- definition of the inferred dislocations;
- definition of the inferred structure of the underground part of the mud volcano.

The field works using EVS had been carried out for the first time in 2018 around the volcanic vent and the adjacent areas to solve the set tasks as well as the detail study of the geological section.

The field geophysical activities using AMNB quadripole had been performed in 9 geophysical lines of total length of 3195 running metres and in 19 physical points. The observation points coordinates had been defined using GPS (Fig. 7).

As it is known, the VES modern theory is based on the Schlumberger mathematical model. It allows calculating the apparent resistivity ρk of the horizontally layered medium depending upon the electrical resistivity and thickness of the individual layers as well as the sizes of the VES measuring equipment.

The usage of the mentioned model excludes the possibility of the single-valued solution of the inverse problem – definitions on totality of the values ρk, obtained when measuring with different equipment, as well as the depths of occurrence of horizontal boundaries and electrical resistivity of individual layers.

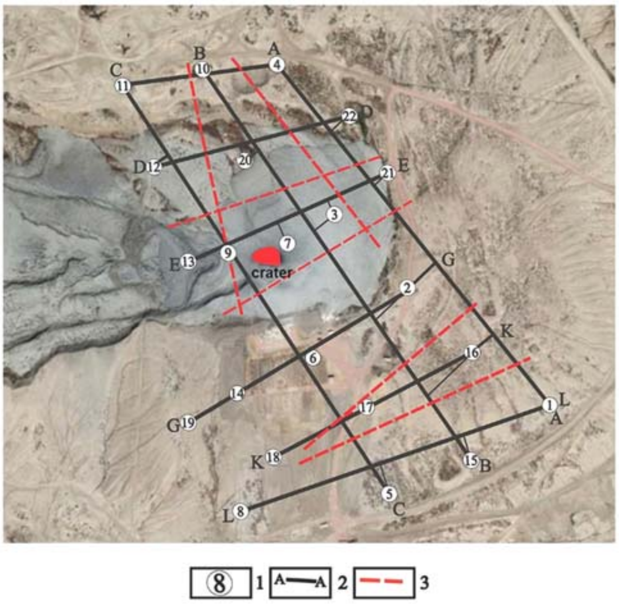

Fig. 7. Scheme of geophysical lines near Lokbatan mud volcano: 1 – VES points; 2 – geophysical lines; 3 – inferred dislocations revealed by VES data

The present aim can be generally reached by compiling a new model, based on the introduction of the following simplifying approximations regarding the nature of current distribution in the horizontally layered medium under electrodes' distribution on the day surface:

– the measured value ρ_k describes the section up to some depth *H*, entirely defined by correlation between the dimensions (*MN*) and transmitting (*AB*) lines; moreover, under $MN \ll AB$ the *H* value makes *AB/2* (actually *MN* should be not more than 0.1 *AB*);

– the value ρ_k is defined only by the vertical component of current density, i.e. represents some kind of averaged electrical characteristics of the medium in vertical direction, depending upon the electrical resistivities ρ_i of each layer; moreover, the "contribution" of every ρ_i into the value ρ_k depends upon the thickness of the present layer h_i. The made assumptions allow designing the following simple equation that defines the relation between the values (ρ_i, h_i) of n–layer section and the value ρ_k:

$$\rho_k = \frac{\rho_1 h_1 + \rho_2 h_2 + \cdots + \rho_i h_i}{h_1 + h_2 + \cdots + h_i} = \sum_{i=1}^{n} h_i \rho_i / \sum_{i=1}^{n} h_i \quad (1)$$

where $\sum_{i=1}^{n} h_i$, $m = H_i$, m – the depth of occurrence of the bottom of n–layer.

Since, according to assumption, the value H_i is completely defined by the relation between *MN* and *AB* and, consequently, is the known one, the Equation (1) can be used to solve the inverse problem – definition of parameters of the electrical model on totality of values ρ_k, obtained under various dimensions of the measuring equipment. Indeed, having a set of the successive values ρ_{ki} and H_i (i=1, 2, ... n), one can consistently define h_i and ρ_i, i.e. the thickness and resistivity of every layer.

So, for any i–layer

$$h_i = H_i - H_{i-1} \text{ or } h_i = (AB/2)_i - (AB/2)_{i-1} \quad (2)$$

Equation

$$\rho_{ki} = K_{ves} * \frac{\Delta U_{\text{мВ}}}{I_{\text{мА}}} \quad (3)$$

was used to calculate the apparent resistivity ρ_k.

Equation (4) is used to define the electrical resistivity of individual layers when $\rho_i > \rho_{i-1}$

$$\rho_i = [\rho_{ki} * (AB/2)_i - \rho_{ki-1} * (AB/2)_{i-1}] \, / \, / \, [(AB/2)_i - (AB/2)_{i-1}] \quad (4)$$

but in case $\rho_{i-1} > \rho_i$ Equation (5) was used:

$$\rho_i = \{[(AB/2)_i - (AB/2)_{i-1}] * \rho_{ki-1} * \rho_{ki}\} \, / \, / \, [\rho_{ki-1} * (AB/2)_i - \rho_{ki} * (AB/2)_{i-1}] \quad (5)$$

The expressions (2), (3) and (4) are the basic calculation equations within the proposed method of defining the parameters of the electrical model by VES data for equipment with *MN*<<*AB*.

As it follows from Equations (2), (4) and (5), the usage of the proposed model provides the ability to define the thickness and electrical resistivity of any layer irrespective of the overlying series' properties.

Taking into account the above-mentioned, as a result of carried out actual measurements by VES method the following dimensions of transmitting *AB/2* and receiving *MN/2* lines had been accepted accordingly: *AB/2* =1; 2; 3; 4; 5; 6; 7; 8; 9; 10,10; 12,12; 14; 16; 18; 20; 22; 24,24; 26,26; 28; 30; 32; 34; 36,36; 38,38; 40,40; 42; 44; 46; 48; 50,50; 52; 54; 56; 58; 60; 63; 66; 69; 72,72; 75,75; 78; 81; 84; 87; 90,90; 93,93; 96; 99; 102; 105; 108; 111; 114; 117; 120; 125,125; 130,130; 135, 140; 145; 150; 155; 160; 165; 170; 175; 180; 185; 190; 195; 200, 200 and *MN/2*=0.3; 0.3; 0,3; 0.3; 0.3; 0.3; 0.3; 0.3; 0.3; 0.3;1; 0.3;1; 1; 1; 1; 1; 1; 1;2; 1;2; 2; 2; 2; 2; 2;3; 2;3; 2;3;3; 3; 3; 3; 3;5; 3;5; 5; 5; 5; 5; 5; 5; 5; 5;7; 5;7; 7; 7; 7; 7; 7;9; 7;9; 9; 9; 9; 9; 9; 9; 9; 9; 9; 9;12; 9;12; 12; 12; 12; 12; 12; 12; 12; 12; 12; 12; 12; 12; 12; 12;15.

The electrical resistivity values of the individual layers had been defined using the interpretation technique provided in the guidelines for the use of VES for the detailed dissection of the section in solving geological and engineering-geological problems. The present recommendation is developed on the new theory and based on the practical data obtained in different regions of the former USSR (Попов и др., 1990). The software Surfer 15, CorelDRAW X6 and ZOND were used to proceed the field geophysical data.

The electrical operational equipment "ЭРА-MAX" with operational frequency 4.88 Hz had been used for the field measurements. The measuring system is oriented northwest to southeast.

Outcomes and discussions

The vertical sections of the apparent resistivity of the rocks (ρ_k) on 9 lines as well as 3D models of sections by X, Y and Z axes of the plot area had been compiled as a result of the carried out geophysical studies by VES method.

The electrical models had been compiled by electrical resistivity values *(*ρ_y*)*, which had been subsequently transformed into the inferred lithologic-geophysical sections (Fig. 8).

The results of the carried out field works allowed stratifying the geological section up to 200 m depth. It had been determined that ρ_k of rocks with different thickness, composing the geological environment of the region of study, vary within 1-250, and ρ_y 1-300 Ohm×m.

Lithologically, on day surface these rocks are composed of the thin clayey drifts and volcanic breccia as well as the alternation of the thin layers of sands and clays.

Following the compiled lithologic-geophysical lines one can say that the volcano vent has approximately wavy shape and the chambers of the various size had been formed at different levels. The electrical resistivity (ρ_y) of the volcanic breccia, accumulated in the vent, varies 1-300 Ohm×m. It is proposed that the great (~ 200-300 Ohm×m) values of ρ_y are related with oil that penetrates into the volcano vent. This is indirectly proved by the dark color and slight oil smell of the volcanic breccia. The breccia thickness varies in the range of 1 to 40 m (VES ## 2, 9, 12, 13).

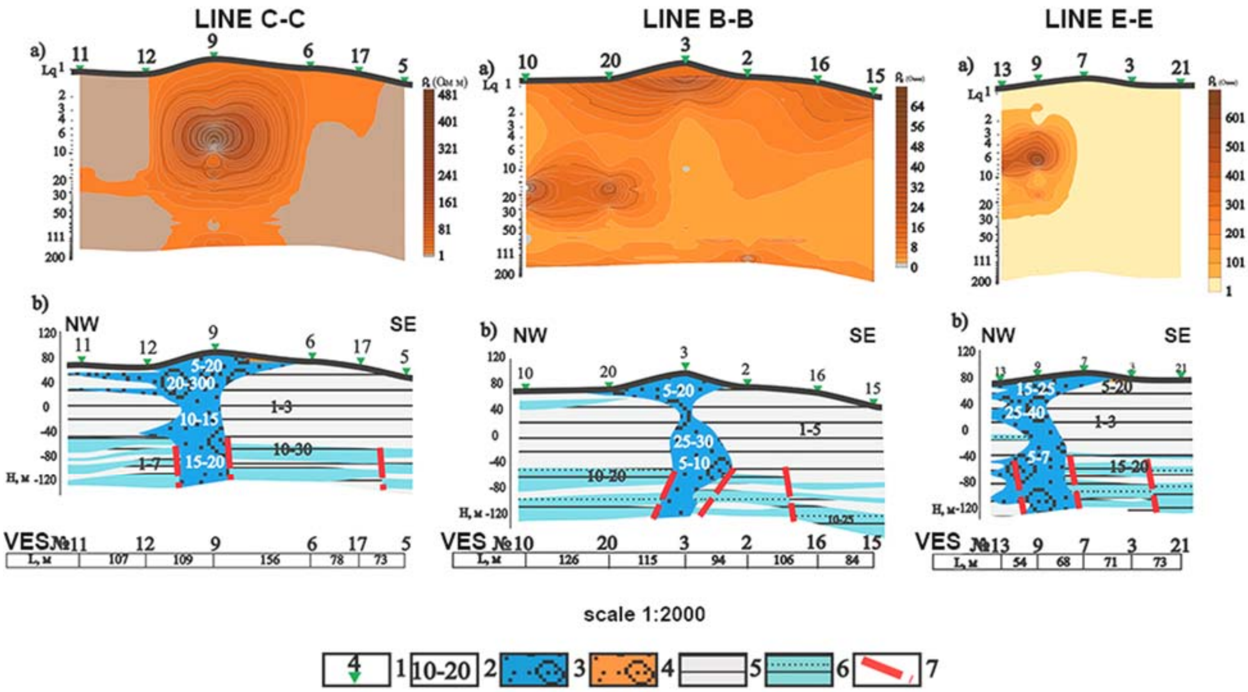

Fig. 8. Vertical sections of the apparent resistivity (A) and lithologic-geophysical sections (b) along the lines C-C, B-B and E-E: 1 – VES points and their numbers; 2 – electrical resistivity of the rocks; 3 – mud volcanic breccia; 4 – drifts; 5 – clays; 6 – alternation of the thin layers of sands with clays; 7 – inferred dislocations revealed by geophysical survey data

Some inferred dislocations had been revealed; they are probably related with activity of Lokbatan mud volcano.

Following the compiled 3D models it is seen that the apparent resistivity of the rocks, composing the geological section of the region of study, has quite variable nature (Fig. 9).

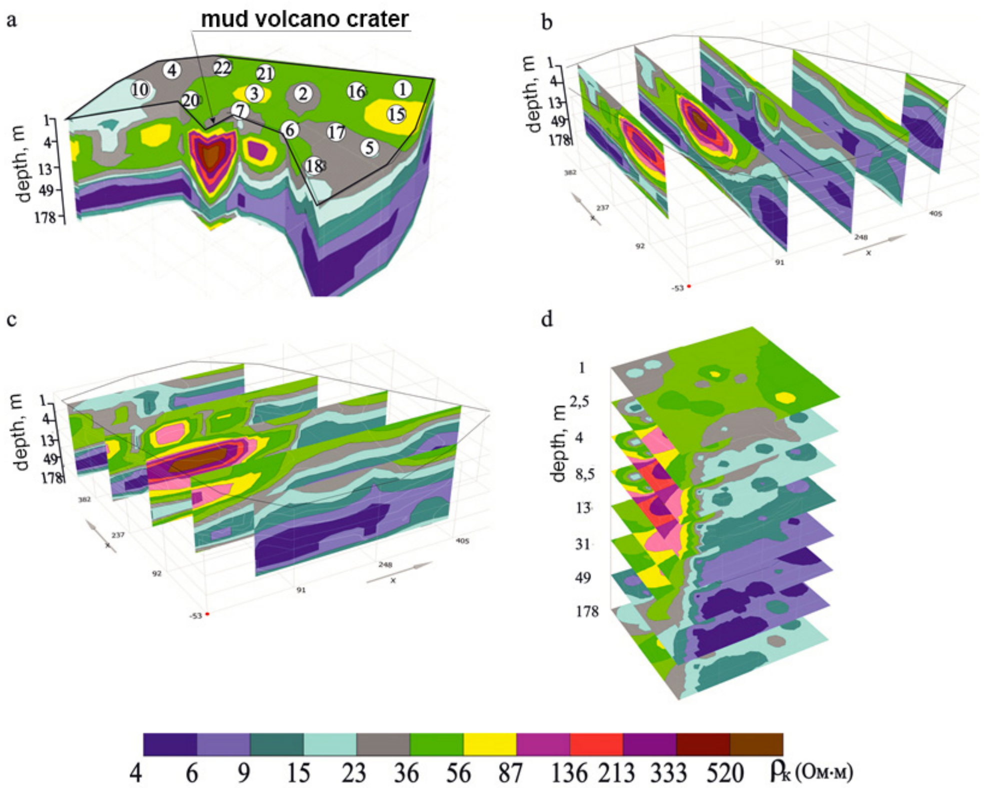

Fig. 9. 3D models of the territory of Lokbatan mud volcano (a) and the sections along the axes X (b), Y (c), Z (d)

In spite of the fact that within the region of study the geological section is generally composed of the sedimentary rocks, the layers are mainly in underformed state. But the upper part of the section is strongly deformed due to volcano's activity. Slightly deformed dip of the layers is traced with increase of their occurrence depths; to our opinion it is quite regular.

Conclusion

Analysis of the geologic-geophysical data for Lokbatan mud volcano allow drawing the following basic conclusions:

– it had been discovered that breccia with the lowest density respectively the surrounded lithological differences tends to the day surface along the newly formed fractures (conduits), shaping a new mud volcano.
– lithologically the area of study is mainly composed of the clays and clayey rocks; the supposed thickness of the mud volcanic breccia around the volcano varies 35-45 m to 150 m;
– some differently directed dislocations had been revealed in the area of study;
– the upper layers of the section are strongly deformed due to volcano activity;
– it had been revealed that the hydrocarbons are transported from the underlying Pliocene-Miocene sediments into the mud volcanic chambers via the discharge (eruptive) channels.

REFERENCES

Aliyev Ad.A. Mud volcanism of the South-Caspian oil-and-gas bearing basin. Proceedings of Geology Institute of Azerbaijan NAS, Nafta-Press, No. 31, 2003, pp. 21-47 (in Russian).

Aliyev Ad.A., Gasanov A.G., Bayramov A.A., Belov I.S. Earthquakes and activation of mud volcanic activity (casal link and interaction). Proceedings of Geology Institute of Azerbaijan NAS, Nafta-Press. No. 29, 2001, pp. 26-39 (in Russian).

Aliyev Ad.A., Guliyev I.S., Belov I.S. Catalogue of recorded eruptions of mud volcanoes of Azerbaijan for period of years 1810-2001. Nafta-Press. Baku, 2002, 88 p.

Aliyev Ad.A., Guliyev I.S., Dadashev F.G., Rakhmanov R.R. Atlas of the world mud volcanoes. Nafta-Press. Baku, 2015, 322 p. (in Russian).

Baghzendani H.R., Aghajani H., Solimani M. Subsurface modeling of mud volcanoes, using density model and analysis of seismic velocity. Journal of Mining & Environment, Vol. 6, No.1, 2015, pp. 31-39, DOI: 10.22044/jme.2015.383.

Evans R.J. The structure, evolution and geophysical expression of mud volcano systems from the South Caspian Basin. PhD Thesis, Cardiff University, 2007, 290 p., http://orca.cf.ac.uk/54906/1/U585295.pdf

Evans R.J., Stewart S.A., Davies R.J. The structure and formation of mud volcano summit calderas. Journal of the Geological Society, Vol. 165, No. 4, 2008, pp. 769-780, DOI: 10.1144/0016-76492007-118.

Feseker T., Brown K., Blanchet C., Scholz F., Nuzzo M. Active mud volcanoes on the upper slope of the western Nile deep-sea fan – first results from the P362/2 cruise of R/V Poseidon. Geo-Marine Letters, Vol. 30, No. 3-4, 2010, pp. 169-186.

Kholodov V.N. Mud volcanoes: Distribution and genesis. Geology and Mineral Resources of World Ocean, No. 4, 2012, pp. 5-25 (in Russian).

Martinelli G., Ferrari G. Earthquake forerunners in a selected area of Northern Italy: recent developments in automatic geochemical monitoring. Tectonophysics, Vol. 193, No. 4, 1991, pp. 397-410, DOI: 10.1016/0040-1951(91)90348-V.

Milkov A.V. Worldwide distribution of submarine mud volcanoes and associated gas hydrates. Marine Geology, Vol. 167, No.1-2, 2000, pp. 29-42, DOI: 10.1016/S0025-3227(00)00022-0.

Popov E.A., Ten K.M., Funtikov G.N., Selyakov V.I., Glushko S.P. Guidelines for the use of VES for the detailed dissection of the section in solving geological and engineering-geological problems. Rotaprint. Moscow, 1990, 52 p. (in Russian).

Rakhmanov R.R. Mud volcanoes and their significance in forecasting of oil-and-gas content of the depths. Nedra.

ЛИТЕРАТУРА

Алиев Ад.А. Грязевой вулканизм Южно-Каспийского нефтегазоносного бассейна. Тр. Института Геологии НАН Азербайджана, Nafta-Press, No. 31, 2003, с. 21-47.

Алиев Ад.А., Гасанов А.Г., Байрамов А.А., Белов И.С. Землетрясения и активизация грязевулканической деятельности (причинная связь и взаимодействие). Тр. Института Геологии АН Азербайджана, Nafta-Press, No. 29, 2001, с. 26-39.

Алиев Ад.А., Гулиев И.С., Дадашев Ф.Г., Рахманов Р.Р. Атлас грязевых вулканов мира. Nafta-Press. Баку, 2015, 322 с.

Попов Е.А., Тен К.М., Фунтиков Г.Н., Селяков В.И., Глушко С.П. Методические рекомендации по использованию ВЭЗ для детального расчленения разреза при решении геологических и инженерно-геологических задач. Ротапринт. Москва, 1990, 52 с.

Рахманов Р.Р. Грязевые вулканы и их значение в прогнозировании газонефтеносности недр. Недра. Москва, 1987, 174 с.

Рашидов Т.М. Морфоструктурные исследования грязевых вулканов Гобустана с использованием технологии GIS (в связи с нефтегазоностностью). Дис. на соиск.уч. степени доктора философии по наукам о Земле. Баку, 2017, 165 с.

Саламов А.М., Мухтаров А.Ш., Мамедов В.А. 3D геофизическая модель близповерхностной структуры грязевого вулкана Дашгиль. ANAS Transactions, Earth Sciences, No. 1, 2019, с. 32-40. DOI: 10.33677/ggianas20190100024.

Холодов В.Н. Грязевые вулканы: распространение и генезис. Геология и полезные ископаемые Мирового океана. No. 4, 2012, с. 5-25.

Юсубов Н.П., Гулиев И.С. Грязевой вулканизм и углеводородные системы Южно-Каспийской впадины (по новейшим данным геофизических и геохимических исследований). Элм. Баку, 2022, 168 с.

Якубов А.А., Али-заде А.А., Зейналов М.М. Атлас грязевых вулканов Азербайджанской ССР. Элм. Баку, 1971, 258 с.

Якубов А.А., Кастрюлин Н.С., Джавадов А.А. Грязевой вулканизм и нефтегазоносность Локбатана. Элм. Баку, 1976, 76 с.

Aliyev Ad.A., Guliyev I.S., Belov I.S. Catalogue of recorded eruptions of mud volcanoes of Azerbaijan for period of years 1810-2001. Nafta-Press. Baku, 2002, 88 p.

Baghzendani H.R., Aghajani H., Solimani M. Subsurface modeling of mud volcanoes, using density model and analysis of seismic velocity. Journal of Mining & Environment, Vol. 6, No. 1, 2015, p. 31-39. DOI: 10.22044/jme.2015.383.

Moscow, 1987, 174 p. (in Russian).

Rashidov T. The diversity of mud volcanoes in the landscape of Azerbaijan. EGU General Assembly Conference Abstracts. Vienna, 2014, 1610019R, DOI: 10.13140/RG.2.2.23100.74883.

Rashidov T., Kangarli I., Ibragimov V. The quaternary mud volcanism in Azerbaijan as the geological phenomenon of the Ponto-Caspian region of the Alpine-Himalayan folded belt. The Third Plenary Meeting and Field Trip of INQUA IFG 1709F POCAS. Tehran and Guilan Province, I.R. Iran, 2019, pp. 121-123.

Rashidov T.M. Morphostructural studies of the mud volcanoes in Gobustan using GIS technology (in connection with oil-and-gas content). PhD Dissertation. Baku, 2017, 165 p. (in Russian)

Robertson A.H.F., Kopf A. Tectonic settings and processes of mud volcanism on the Mediterranean ridge accretionary complex: evidence from LEG 160. Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 160, 1998.

Salamov A.M., Mukhtarov A.Sh., Mammadov V.A. 3D Geophysical model of near surface structure of the Dashgil mud volcano. ANAS Transactions, Earth Sciences, No. 1, 2019, pp. 32-40, DOI: 10.33677/ggianas20190100024 (in Russian).

Sawolo N., Sutriono E., Istadi B.P., Darmoyo Agung B. The LUSI mud volcano triggering controversy: Was it caused by drilling? Marine and Petroleum Geology, Vol. 26, No. 9, 2009, pp. 1766-1784, DOI: 10.1016/j.marpetgeo.2009.04.002.

Yakubov A.A., Ali-zadeh A.A., Zeynalov M.M. Mud volcanoes of Azerbaijan SSR. Atlas. Elm. Baku, 1971, 258 p. (in Russian).

Yakubov A.A., Kastryulin N.S., Dzhavadov A.A. Mud volcanism and oil-and-gas content of Lokbatan. Elm. Baku, 1976, 76 p. (in Russian).

Yusubov N.P., Guliyev I.S. Mud volcanism and the hydrocarbon systems of the South-Caspian depression (by most recent data of the geophysical and geochemical studies). Elm. Baku, 2022, 168 p. (in Russian).

Zoporowski A., Miller S.A. Modelling eruption cycles and decay of mud volcanoes. Marine and Petroleum Geology, Vol. 26, No. 9, 2009, pp. 1879-1887.

Evans R.J. The structure, evolution and geophysical expression of mud volcano systems from the South Caspian Basin. PhD Thesis, Cardiff University, 2007, 290 p. http://orca.cf.ac.uk/54906/1/U585295.pdf.

Evans R.J., Stewart S.A., Davies R.J. The structure and formation of mud volcano summit calderas. Journal of the Geological Society, Vol. 165, No. 4, 2008, pp. 769-780, DOI: 10.1144/0016-76492007-118.

Feseker T., Brown K., Blanchet C., Scholz F., Nuzzo M. Active mud volcanoes on the upper slope of the western Nile deep-sea fan – first results from the P362/2 cruise of R/V Poseidon. Geo-Marine Letters, Vol. 30, No. 3-4, 2010, pp. 169-186.

Martinelli G., Ferrari G. Earthquake forerunners in a selected area of Northern Italy: recent developments in automatic geochemical monitoring. Tectonophysics, Vol. 193, No. 4, 1991, pp. 397-410, DOI: 10.1016/0040-1951(91)90348-V.

Milkov A.V. Worldwide distribution of submarine mud volcanoes and associated gas hydrates. Marine Geology, Vol. 167, No.1-2, 2000, pp. 29-42, DOI: 10.1016/S0025-3227(00)00022-0.

Rashidov T. The diversity of mud volcanoes in the landscape of Azerbaijan. EGU General Assembly Conference Abstracts. Vienna, 2014, 1610019R, DOI: 10.13140/RG.2.2.23100.74883.

Rashidov T., Kangarli I., Ibragimov V. The quaternary mud volcanism in Azerbaijan as the geological phenomenon of the Ponto-Caspian region of the Alpine-Himalayan folded belt. The Third Plenary Meeting and Field Trip of INQUA IFG 1709F POCAS. Tehran and Guilan Province, I.R. Iran, 2019, pp. 121-123.

Robertson A.H.F., Kopf A. Tectonic settings and processes of mud volcanism on the Mediterranean ridge accretionary complex: evidence from LEG 160. Proceedings of the Ocean Drilling Program, Scientific Results, Vol. 160, 1998.

Sawolo N., Sutriono E., Istadi B.P., Darmoyo Agung B. The LUSI mud volcano triggering controversy: Was it caused by drilling? Marine and Petroleum Geology, Vol. 26, No. 9, 2009, pp. 1766-1784, DOI: 10.1016/j.marpetgeo.2009.04.002.

Zoporowski A., Miller S.A. Modelling eruption cycles and decay of mud volcanoes. Marine and Petroleum Geology, Vol. 26, No. 9, 2009, pp. 1879-1887.

ЭЛЕКТРОТОМОГРАФИЯ ГРЯЗЕВОГО ВУЛКАНА ЛОКБАТАН: ВНУТРЕННЕЕ СТРОЕНИЕ И МЕХАНИЗМ ФОРМИРОВАНИЯ

Саламов А.М., Мамедов В.А., Рашидов Т.М., Заманова А.Г., Гасымов Э.Э.
Министерство Науки и Образования Азербайджанской Республики,
Институт геологии и геофизики, Азербайджан
AZ1143, г. Баку, просп. Г.Джавида, 119: vmamed@rambler.ru

Резюме. В данной статье рассматриваются вопросы генезиса, строения, геохимических и геофизических исследований в районе грязевого вулкана Локбатан, расположенного в юго-западной части Абшеронского полуострова (Азербайджан), и отличающегося повышенной грязевулканической активностью. Наряду с ранее высказанными идеями о процессе формирования грязевого вулкана (магматическая, тектоническая, углеводородная и др.), авторами была предложена собственная гипотеза. В ней ведущая роль в формировании грязевого вулкана отводится воде, выделяющейся в результате геодинамического давления на терригенно-глинистую толщу. Данная вода увлажняет и насыщает глинистые породы, образовывая субстанции с наименьшей плотностью относительно окружающих литологических разностей, тем самым создавая выходные каналы и промежуточные камеры на определенных глубинах. Образовавшаяся субстанция – брекчия, находящаяся под большим давлением, по новообразованному эруптивному каналу стремится к выходу на дневную поверхность и в результате формируется грязевой вулкан.

С учетом новой гипотезы формирования грязевого вулкана была предложена схема механизма формирования грязевого вулкана с выделением промежуточных камер накопления грязевулканической брекчии. Было выявлено, что преобладающими микроэлементами грязевулканической брекчии являются бор, ртуть, марганец, барий, стронций, литий и др., содержание которых в несколько раз превышает кларковые значения для осадочных пород. Используя материалы полевых работ вертикального электрического зондирования по 9 профилям на 19 физических точках в пределах грязевого вулкана Локбатан, были построены 3D модели площади исследования: полные, в произвольном срезе, по осям X, Y, Z, а также морфологического строения наземной части описываемого вулкана.

Ключевые слова: *геофизика, грязевой вулкан, электроразведка, микроэлементы, разрыв, 3D модель, газы*

LÖKBATAN PALÇIQ VULKANININ ELEKTROTOMOQRAFİYASI: DAXİLİ QURULUŞ VƏ FORMALAŞMA MEXANİZMİ

Salamov A.M., Məmmədov V.A., Rəşidov T.M., Zamanova A.G., Qasımov E.E.
Azərbaycan Respublikası Elm və Təhsil Nazirliyi, Geologiya və Geofizika İnstitutu, Azərbaycan
AZ1143, Bakı, pr. H.Cavid, 119: vmamed@rambler.ru

Xülasə. Məqalədə Abşeron yarımadasının (Azərbaycan) cənub-qərb hissəsində yerləşən və palçıq vulkanizminin aktivliyi ilə səciyyələnən Lökbatan palçıq vulkanı ərazisinin genezisi, quruluşu, geokimyəvi və geofiziki məsələləri müzakirə olunur.

Palçıq vulkanının əmələ gəlməsi prosesi haqqında əvvəllər söylənilən (maqmatik, tektonik, karbohidrogen və s.) fikirlərlə yanaşı müəlliflər öz fərziyyələrini irəli sürmüşlər.

Onların fikrincə palçıq vulkanının əmələ gəlməsində aparıcı rol geodinamik təzyiq nəticəsində terrigen-gilli təbəqələrdən sıxışdırılıb çıxarılan sular gilli süxurları nəmləndirib doyuraraq, ətrafdakı litoloji fərqlərə nisbətən zəif sıxlığa malik olduğundan müəyyən dərinliklərdə çıxış kanalları və ara kameralar yaradır. Əsasən gilli süxurlardan təşkil olşunmuş brekçiya yüksək təzyiqlə yeni yaranmış püskürmə kanalı ilə yer səthinə çıxmağa meyillidir və nəticədə palçıq vulkanı formalaşır.

Palçıq vulkanının əmələ gəlməsi ilə bağlı yeni fərziyyəni nəzərə alaraq, oradakı brekçiyalarının toplanması üçün aralıq kameraların ayrılması ilə palçıq vulkanının əmələ gəlməsi mexanizminin sxemi təklif edilmişdir.

Müəyyən edilmişdir ki, palçıq vulkanı brekçiyalarında üstünlük təşkil edən mikroelementlər bor, civə, manqan, barium, stronsium, litium və s. olub onların miqdarı çökmə süxurlar üçün klark ədədindən bir neçə dəfə yüksəkdir.

Lökbatan palçıq vulkanı ərazisində 9 profil üzrə 19 fiziki nöqtədə şaquli elektrik zondlama işlərinin materiallarından istifadə edilərək tədqiqat sahəsinin tam, ixtiyari kəsiklə və X, Y, Z oxları boyunca, eləcə də vulkanın yerüstü hissəsinin morfoloji quruluşu 3D modelləri qurulmuşdur.

Açar sözlər: *geofizika, palçıq vulkanı, elektrik kəşfiyyatı, mikroelementlər, fasiləsizlik, 3D model, qazlar*