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HIGH-RESOLUTION VERTICAL ELECTRICAL SOUNDING SURVEY: INVESTIGATION OF SUBSURFACE STRUCTURES AT DASHGIL´S MUD VOLCANO, AZERBAIJAN

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ABSTRACT

High-resolution electrical resistivity method was applied to investigate subsurface structure of Dashgil mud volcano in Azerbaijan. The field work performed on one profile with the use of four-electrode symmetrical installation AMNB. ERA-MAX electromagnetic prospecting equipment with an operating frequency of 4.88 Hz is used for the field measurements. A total of 21 VES using Schlumberger arrays were carried out along NW-SE oriented profile. Data processing was performed using inverse modeling. True resistivity values of the subsurface model are determined by curve matching with the curve of apparent resistivity values. Data interpretation is performed to estimate subsurface lithology and rock layers that are identified as the layer of hot groundwater aquifers. The sections of apparent resistivity and geoelectrical section based on the values of specific electrical resistance were composed, which were then converted to a litho-geophysical section. It is found that the specific electrical resistance of rocks composing the geological environment changes in the range of 0,1-35 Ohm-m. It is assumed that the eruption times of Dashgil volcano can be roughly determined based on the number of layers obtained from resistivity sections. In this study we determined it to be 5-8 times, which is consistent with the noted data in the catalogue of mud volcanoes eruptions of Azerbaijan.

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INTRODUCTION

Mud volcanism is a global phenomenon usually associated with compressional tectonics that favours extrusion of fluid- and clay mineral-rich sediment both on land and offshore. Methane, the dominant gas phase, is emitted at variable rates during and after emplacement of the mud domes. In case of continental mud volcanoes, the gas is directly released into the atmosphere, thereby contributing to global warming. Azerbaijan is one of the countries with one of the highest abundances of mud domes globally. One of the most prominent mud volcanoes, Dashgil, has been chosen for a case study because of its historic record of violent eruptions, continued activity, and well-documented regional geology in the Caucasus orogenic wedge adjacent to the Caspian Sea.

Since 2003, gas flux has quantitatively measured at one of the two crater lakes and is characterized by valve-type behaviour and episodically violent degassing. In 2007, the large crater lake was additionally equipped with methane fluxmeters as well as an in situ pore-pressure probe into the conduit (Yakubov *et al*., 1971; Aliyev *et al*., 2015; Guliyev I.S. and Feizullayev A.A., 1997). Manifestations of mud volcanism, or mud diapirs, are widespread in Azerbaijan. The number of mud volcanoes located on land and at sea exceeds 250. Many mud volcanoes are active at the present time. From all of mud volcanoes of Azerbaijan the Lokbatan mud volcano is the most active (Rakhmanov, 1987). Its first recorded eruption took place in 1864. Its last eruption occurred on October 24, 2001, and the release of gases and their combustion have continued ever since.

During the eruption, a loud boom and explosion were accompanied by the ignition of gas jets ejected at the Earth's surface. The study of the mechanism responsible for the formation and activation of mud volcanoes is still a topical problem. Repeated high-precision gravity, geodetic, and geothermal measurements in the occurrence areas of mud volcanoes is indispensable for constructing a model of their deep structure and studying the dynamics of processes associated with their activation. Unfortunately, although mud volcanoes of Azerbaijan have been investigated for a long time, their detailed geophysical studies have not been conducted, which hinders the development of models describing the formation and activation of mud volcanoes. The study of the deep structure of the mud volcano is interesting from the other side in terms of viewpoint of negative pressure effect on such volcanoes. This, in its turn, is relevant to geo-liquids and metastability. Most of the geo-liquids are „dirty", therefore the heterogeneous nucleation is the limit for the negative pressure. In mud volcanoes the negative pressure wave generates boiling, which also attracts the interest for the study (Veliev and Guliyev, 2014; Imre, Veliyev and Guliyev, 2009).

Several research studies conducted to more clearly understand the deep structure and activity of mud volcanoes in Azerbaijan. The most recent of them is electromagnetic methods to study the inner structure of mud volcanoes in Perekishkul mud volcano (Haroon *et al*., 2015). There are also numbers of studies conducted in other regions such as in the Northern Apennines based on a remote sensing techniques (Bonini, 2012). The results of these applications are promising to give more insight and valuable information regarding activity and formation of mud volcanoes. This work presents results of high-resolution electrical resistivity tomography survey in the Dashgil mud volcano area, Azerbaijan.

Dashgil Mud Volcano

The location of the studied volcano is shown in the Figure 1. Morphologically, it is a rather flat and latitudinally elongated upland with relative altitude of 100 m above the surrounding area (Yakubov *et al*., 1971; Guliyev and Feizullayev, 1997; Hovland *et al*., 1997).

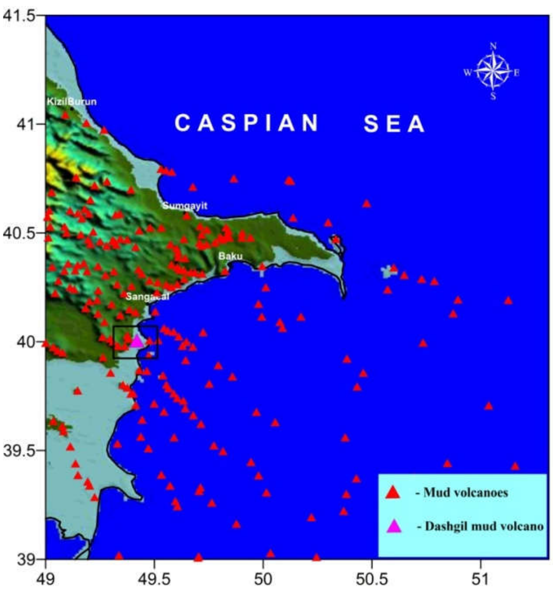

Figure 1. Mud volcano distribution in Azerbaijan and location of the Dashgil volcano

Its crateral field hosts numerous active and a number of extinct bald peaks, salsas and gryphons that vigorously liberate gas and small amount of mud with thick oil films. Volcano bald peaks and salsas have many cones, with relative height varying within 0.5-2 m. Salsas bubble over, excreting large amount of gas, and every 3-5 min eject turbid water at the height of 1-1.5 m. According to calculations, one gryphon evolves about 600-700 m^2 gas per day, and this gas creates whitish steam around the peak, which is well seen at a distance, The volcano crateral rampart diameter is 200-220 m. Eruption products ejected by the volcano form a wide and long flow (Figure 2).

Figure 2. Fanciful tongues of mud volcano Dashgil

Figure 3. Crateral field of Dashgil eruption

Prominent among the volcano breccia are gray fine-grained, occasionally oil-bearing sandstones, gray shale clays, solid marls, etc. (Yakubov *et al*., 1971; Hovland *et al*., 1997). Two large salsas are found in the crateral field central and eastern parts (Figure 3). One of them, of above 15 m diameter, vigorously excretes gas and muddy water. Southward of it, a range of burnt mud volcano breccia of the 1926 eruption can be traced. Overall volume of volcano-drifted breccia is 253 mln.m^3, its average thickness is 55 m, and breccia cover area is 460 hectares in all, 6 eruptions have been recorded for the volcano: in 1882, 1886, 1908, 1926, 1958 and 2001 (Aliev *et al*., 2009). Sand collectors of the productive strata are potential oil and gas targets. The Miocene deposits are also of certain interest. There are widespread mud volcanic brecciaas on the surface of the study area.

As a result of the eruption of Dashgil volcano numerous gryphons were formed, which in turn formed a real relief of the study area.

DATA COLLECTION

The field geophysical work performed on one profile with the use of four-electrode symmetrical installation AMNB. For the field measurements ERA-MAX electromagnetic prospecting equipment (http://www.era-max.com) with an operating frequency of 4.88 Hz is used. A total of 21 VES using Schlumberger arrays were carried out along selected profile. Profile direction of NW-SE cuts suspected gryphon sources within the area of study (Figure 4).

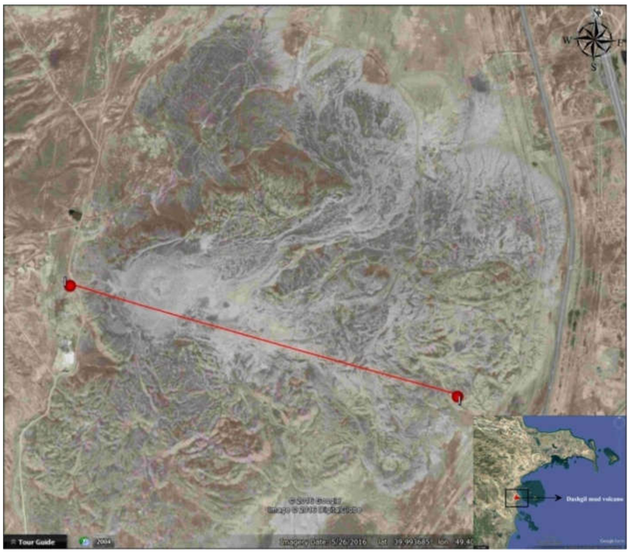

Figure 4. Location of vertical electrical sounding (VES) profile in Google Earth map

The length of profile is 1994 m, and step changes in interval of 60-128 m. Global Positioning System were used to record the geographic coordinates and the altitude of the VES stations. As it is known, the modern theory of VES is a mathematical model of Schlumberger, which allows to calculating the apparent resistivity ρ_a of multilayer medium with horizontal boundaries depending on the electrical resistivity and thickness of the various layers, as well as the size of the VES measurement configuration.

However, the use of this model eliminates the possibility of a unique solution of the inverse problem - determination on aggregate ρ_a values obtained from measurements with different settings, the depth of the horizontal section boundaries and an apparent electrical resistance of individual layers. This goal can be achieved by constructing a new model based on the introduction of the following simplifying assumptions about the characteristics of the current distribution in a horizontally layered medium with the placement of the electrodes on the surface:

- ρ_a measured values characterizes the section to a certain depth H, wholly determined by the relation between the size of MN and current AB lines, and when MN<< AB the value of H is AB/2 (practically MN almost should be no more than 0.1 AB);
- ρ_a value is only determined by the vertical component of the current density, i.e., represents some averaged electrical characteristic of the medium in the vertical direction, depending on the apparent electric resistance ρ_i of each layer, the "contribution" to the ρ_a value of each ρ_i depends on the thickness of h_i layer.

Assumptions allow constructing the following simple formula, which establishes the correspondence between the set of values (ρ_i, h_i) n – layered section and the value of ρ_a:

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

Where, $\sum_{i=1}^{n} h_i$, m = H_i , m – is a depth of n`s –layer foot. Since, according to the accepted assumptions, H_i value is completely determined by the ratio between the MN and AB, and hence it is known, the formula (1) can be used to solve the inverse problem - determination of geoelectric section parameters with the set of ρ_a values obtained in different sizes of measuring configuration. Indeed, having a series of consecutive values of ρ_{ai} and H_i (i = 1, 2, ... n), it is possible to consistently identify h_i and ρ_i, i.e., the thickness and the apparent resistivity of each layer.

So for each i-th layer

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

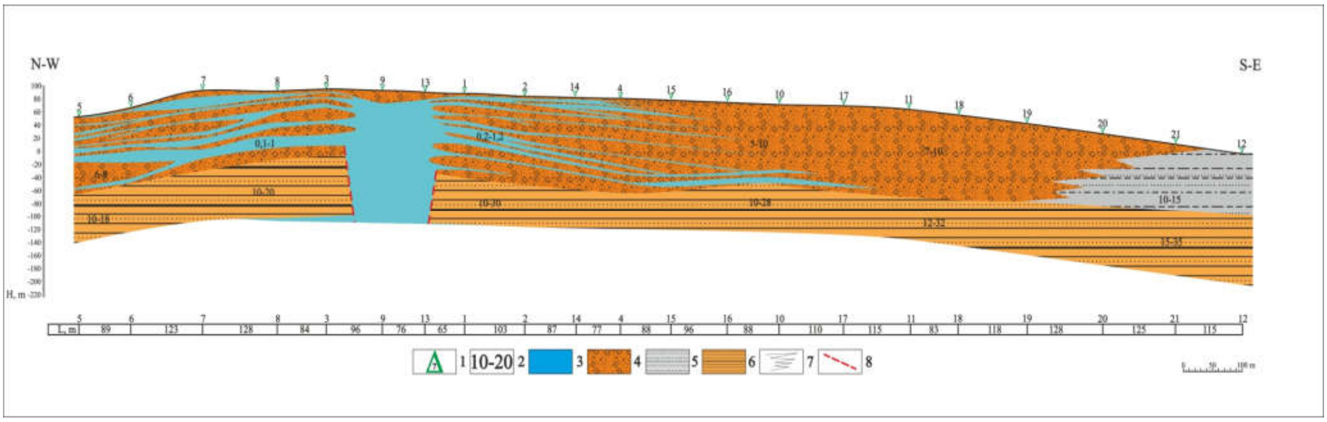

Figure. 5. Geophysical section made according to VES 1 - number of VES points; 2 - specific electrical resistance of the rocks composing the geological section; 3 - mud volcano deposits in the liquid phase; 4 - mud volcanic breccias; 5 - clay with layers of fine-grained and poorly cemented sands; 6 - presumably bedrock composed of clay alternating coarse poorly cemented sands; 7 - litho facial border; 8 - supposed faults identified according to VES

The formula is used to calculate the ρ_a apparent resistivity:

$$\rho_{ai} = K_{VES} \times \frac{\Delta UmV}{ImA} \quad (3)$$

Where, K – is the geometric factor (K), which can be precisely derived from the array geometry based on the law of electrical field distribution. Using the Laplace equation in polar coordinates the electrical potential functions around the source (A and B) and measuring (M and N) electrodes was derived. The geometric factor K can be obtained for four-electrode array of AMNB configuration as

$$K = \frac{2\pi}{\frac{1}{[AM]} - \frac{1}{[BM]} - \frac{1}{[AN]} + \frac{1}{[BN]}} \quad (4)$$

Formula (5) is used to determine the apparent electrical resistivity of individual layers, when $\rho_i > \rho_{i-1}$

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

In the $\rho_{i-1} > \rho_i$ case, the formula (6) is used:

$$\rho_i = \{[\left(\frac{AB}{2}\right)_i - \left(\frac{AB}{2}\right)_{i-1}] \times \rho_{ai-1} \times \rho_{ai}\}/[\rho_{ai-1} \times \left(\frac{AB}{2}\right)_i - \rho_{ai} \times \left(\frac{AB}{2}\right)_{i-1}] \quad (6)$$

Expressions (2), (3) and (5) are the main calculation formulas in the proposed method to determine parameters of geoelectric section according to VES data with MN<<AB configuration.
As follows from the formulas (2), (5) and (6) the use of the proposed model enables determination of thickness and apparent electrical resistivity of any layer independently of the settings of the overlying strata. The VES array consists of a series of the electrode combinations AMNB with gradually increasing distances among the electrodes for consequent combinations. The depth of sounding increases with the distance between A and B electrodes. The electrical resistivity measured with the method is shown to be related with salinity, texture and structure, porosity, bulk density, saturation, and hydrological conductivity of the soil. Thus, the VES profiles can provide information on the geological structures, soil properties, and hydrological conditions in a study area.

Taking into account the above stated with the purpose of a detailed dismemberment of the section and for more accurate determination of the depth of individual lithological variations, as a result of experimental measurement using method VES, the modified configuration of AB/2 and MN/2, respectively are the following: AB/2 =1; 2; 3; 4; 5; 6; 7; 8; 9; 10, 12, 14; 16; 18; 20; 22; 24, 26; 28; 30; 32; 34; 36, 38, 40, 42; 44; 46; 48; 50, 52; 54; 56; 58; 60; 63; 66; 69; 72, 75, 78; 81; 84; 87; 90, 93; 96; 99; 102; 105; 108; 111; 114; 117; 120; 125, 130, 135, 140; 145; 150; 155; 160; 165; 170; 175; 180; 185; 190; 195; 200 and MN/2=0,3; 1; 2; 3; 5; 7; 9; 12 and 15.
The concurrent MN electrodes are placed symmetrically within the center of AB (Popov *et al.*, 1990). Data processing was performed using inverse modeling. True resistivity values of the subsurface model are determined by curve matching with the curve of apparent resistivity values (Bobachev *et al*, 2001). The basic principle of processing is to use a linear least squares inversion with early model iteratively modified to obtain a response model that fits the observed data. In this case, the apparent resistivity is a model response while the true resistivity, thickness and depth below the surface layer are 1D model parameters to be determined.

Data interpretation is performed to estimate subsurface lithology and rock layers that are identified as the layer of hot groundwater aquifers. The resistivity of rocks, minerals, soil and chemical elements in general have been obtained through a variety of measurements that have been done. They can be used as a reference for the process to convert resistivity values to water containing lithologic layers of rock (Telford *et al*, 1990; Reynolds, 1987, Ward and Stanley, 1990). This interpretation is also based on the condition of lithology or rock types in the study area.

RESULTS

As a result of geophysical research studies along the profile I-I using VES method the sections of apparent resistivity and geoelectrical section based on the values of specific electrical resistance were composed, which were then converted to a litho-geophysical section. As a result of the VES data interpretation it is found that the specific electrical resistance of rocks composing the geological environment, changes in the range of 0,1-35 Ohm-m. There can be traced three layers in the lithological and geophysical sections, whose thickness ranges from 3.0 to 132 m (Figure 5). The thickness of mud deposits on the area varies in the range of 15-135 m, and of apparent electrical resistivity about 5-10 Ohm-m. There are fragments of different lithological varieties in their composition, such as sandstone, gravel and others. These deposits alternate with liquid phases of volcanic products which have apparent electrical resistivity of 0.1-1.2 Ohm-m.

It is assumed that the eruption times of Dashgil volcano can be roughly determined based on the number of layers obtained from resistivity sections. In this study we determined it to be 5-8 times, which is consistent with the noted data in the catalogue (Aliev *et al.*, 2009). In the foot of volcanic breccias can be traced the layer with a thickness of 56-110 m and apparent electrical resistivity of 10-35 Ohm-m. It is assumed that this layer is composed of bedrock, and from lithological point it is composed of clay alternating with coarse poorly cemented sands. There is an observed layer on the surface with thickness of 40-95 m and apparent electrical resistivity of 10-15 Ohm-m in the south-eastern part of the study area (VES number 21-12). This layer is made up of clay with layers of fine-grained and poorly cemented sands.

The expected steeply dipping, faults has been revealed along the profile in the range of VES number 3-9 and 1-13. In the interval of VES numbers 3-1 actively operating volcano gryphons, as well as in the range of 9-13 VES number, within the limit of study depths the apparent electrical resistivity of geological environment is about 0.2-1.3 Ohm-m. In the north-western part of the fault, bottom of the layer which is presumably composed of bedrock deposits can be traced at a depth of -10 m from sea level, the bottom of the same layer in the south-eastern part of the fault can be traced to a depth of -32 m from sea level. In other words, the amplitude of lowering of one part of the layer relative to another is 22 m. Taking into account the presence of faults and a sharp decrease of the electrical resistivity of the geological environment within the range of VES numbers 9-13 this part of a profile is presumably taken as a crater of the Dashgil volcano. The rest of the gryphons associated with this area and any intensification in the crater is reflected in the activation of gryphons. The capability of high-resolution electrical resistivity method shows that it can be applied to investigate other mud volcanoes located in the region.

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