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Original paper

Eruption of the mud volcano "Lokbatan"

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Abstract: Relevance. Mud volcanoes are the main mechanism that creates the process of migration of hydrocarbons in a three-dimensional geological environment. At the same time, eruptive channels of mud volcanoes and tensile cracks created by the process of formation of diapiric structures serve as migration channels. If we take into account that almost all oil fields located in the territory of mud volcanism development are complicated by eruptive channels of mud volcanoes associated with Maikop deposits, then the mechanism of filling reservoirs of the productive stratum due to vertical migration of hydrocarbons is proved very convincingly, which is relevant for our country. **The aim** of this article was to study the eruptions of the Lokbatan Mud Volcano – which is one of the most famous mud volcanoes in the world due to its frequent fiery eruptions. **Methods.** Due to the high resolution of digital seismic equipment manufactured by Kinemetrics (USA) of the Republican Seismic Survey Center at ANAS (RSSC), records of mud volcano eruptions were recorded and analyzed. In addition, in 2022, within the framework of the international project "Expansion of the seismic network in the Caucasus and Central Asia", 22 seismic stations manufactured by Nanometrics (Canada) were installed in Azerbaijan. For the first time in the world, in order to study the dynamics of mud volcanoes, 12 such stations were installed around the mud volcanoes Lokbatan and Otman-Bozdag**. Results.** Thus, it was found that the eruption of the Lokbatan volcano in 2012 during the day was characterized by 3 periods of activation. The first one occurred in the morning at 04:59:17.7 (eruption duration 7 minutes, focus depth 5 km, $E=0.64\times10^7$ J), the next ones at 09:14:40 (eruption duration 4 minutes, focus depth 5.5 km, $E= 0.70\times10^7$ J) and at 09:23:00 (duration of eruption 12 minutes, focus depth 1.2 km, $E=3.15\times10^7$ J).

Keywords: Lokbatanmud volcano, Otman-Bozdagmud volcano, digital seismic stations.

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ГЕОТЕКТОНИКА И ГЕОДИНАМИКА

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Оригинальная статья

Извержение грязевого вулкана «Локбатан»

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Резюме: Актуальность работы. Грязевые вулканы являются основным механизмом, создающим процесс миграции углеводородов в трехмерной геологической среде. При этом каналами миграции служат эруптивные каналы грязевых вулканов и трещины растяжения, созданные процессом формирования диапировых структур. Если принять во внимание, что практически все нефтяные месторождения, расположенные на территории развития грязевого вулканизма, осложнены эруптивными каналами грязевых вулканов, связанных с майкопскими отложениями, то механизм заполнения резервуаров продуктивной толщи за счет вертикальной миграции углеводородов доказывается весьма убедительно, что является актуальным для нашей страны. **Целью** данной статьи являлось изучение извержений грязевого вулкана Локбатан, являющегося одним из самых известных грязевых вулканов во всем мире из-за его частых огненных извержений. **Методы работы.** Благодаря высокой разрешающей способности цифровой сейсмической аппаратуры производства «Кинеметрикс» (США) Республиканского центра сейсмологической службы при НАНА (РЦСС) были зарегистрированы и проанализированы записи извержений грязевых вулканов. Кроме того, в 2022 г. в рамках международного проекта «Расширение сейсмической сети на Кавказе и в Центральной Азии» на территории Азербайджана были установлены 22 сейсмических станций производства Nanometrics (Канада). Впервые в мире с целью исследования динамики грязевых вулканов 12 таких станций были установлены вокруг грязевых вулканов «Локбатан» и «Отман-Бождаг». **Результаты работы.** Таким образом, было установлено, что извержение вулкана Локбатан 2012 г. в течение дня характеризовалось тремя периодами активизации. Первый произошел утром в 04:59:17.7 (длительность извержения 7 минут, глубина очага 5 км, $E=0{,}64\times10^7$ Дж), последующие в 09:14:40 (длительность извержения 4 минуты, глубина очага 5,5 км, $E=0{,}70\times10^7$ Дж) и в 09:23:00 (длительность извержения 12 минут, глубина очага 1,2 км, $E=3{,}15\times10^7$ Дж). 2 мая 2017 г. 08:55:51 **произошло очередное сильные извержение** вулкана Локбатан. Длительность извержения составила 4 минуты, глубина очага 4 км. Выделившаяся энергия составила $E=1{,}12\times10^7$ Дж. Последнее извержение данного вулкана произошло 11 августа 2022 г. Толщина излившегося покрова грязи составила 80–90 см. Извержение началось утром в 09:36:35. Глубина извержения составила 3 км, а выделившаяся энергия $0{,}6\times10^7$ Дж. Очаги развития грязевых вулканов располагаются преимущественно на глубинах 1–5 км, т.е. развитие грязевых вулканов связано с активными внутренними процессами, протекающими преимущественно в осадочной толще земной коры.

Ключевые слова: Грязевой вулкан Локбатан, грязевой вулкан Отман-Бождаг, цифровые сейсмические станции.

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Introduction

Although studies of the nature of mud volcanoes in Azerbaijan have always been topical, the problems of their spatio-temporal relationship with seismicity have not been widely discussed. The first catalog of recorded eruptions of mud volcanoes in Azerbaijan for the period 1810-1974 was published 45 years ago. Then the data on the eruptions of mud volcanoes in Azerbaijan were summarized in the work of Rakhmanov R.R. In addition, information about the eruptions of mud volcanoes in the whole world in 1982 was also collected in the catalog given in the work of Rakhmanov R.R. (1987). In 2009, Aliyev A.A., Guliyev I.S. and Rakhmanov R.R. the catalog of eruptions of mud volcanoes of Azerbaijan for 1810-2007 was created. In 2015 Aliyev A.A., Guliyev I.S., Dadashev F.G. and Rakhmanov R.R. The Atlas of Mud Volcanoes of the World was published [Aliyev et al., 2009; Yusubov, Guliyev, 1971].

The works [Ahmedbeyli, 1975; Panahi, Rakhmanov, 1993; Aliyev et al., 2002] Aliyev 2004-2009, Guliyev, 2018, etc.) note the connection between mud volcanism and oil and gas accumulation processes, where it is indicated that the patterns of their distribution and structural localization are one of the important criteria for the selection of priority objects for prospecting and exploration for oil and gas in the depression zones of mobile belts. Hazardous processes are currently being investigated by a variety of methods [Zaalishvili et al., 2014a, b; 2016]. Obviously, this problem is of great scientific and practical importance. From a fundamental point of view, such studies are necessary to understand the conditions and mechanism of formation of mud volcanoes. From a practical point of view, they are of interest in connection with the problem of seismic hazard assessment, which includes general seismic zoning, detailed seismic zoning, and microzoning. This topic is of particular importance at the present stage, when the intensive development of oil and gas fields, the development of the agro-industrial complex and urban agglomerations of Azerbaijan are planned. Lokbatan is one of the settlements located not far from Baku. Since 1810, 26 eruptions have been recorded. One of its largest eruptions occurred in 1977. A strong emission of dirt and gas was observed. The eruption began in the early morning when the surroundings resounded with a roar. A powerful explosion soon followed. A column of fire 350 m high rose above the top of the volcano. This ignited a gas jet escaping from the depths of the earth. The volcano threw out a huge amount of volcanic mud that covered the surrounding area. Due to its size and activity, the volcano has been a candidate for inscription on the UNESCO World Heritage List since 1998. It is important to note that Azerbaijan ranks first in the world in terms of the number of mud volcanoes. However, it is the mud volcano Lokbatan that is closely associated with the oil industry.

Eruptions of mud volcanoes of Azerbaijan

Mud volcanoes in East Azerbaijan are located within 6 oil and gas regions: Caspian-Guba, Shamakhi-Gobustan, Absheron (including the Absheron Peninsula and the Absheron archipelago), Low Kura and in the Baku archipelago (fig. 1).

The highest intensity of mud volcanic activity, excluding events on marine mud volcanoes, was observed in the Shamakhi-Gobustan region, on the Absheron peninsula and the Baku archipelago, which is about 86% of the total number of recorded eruptions in Azerbaijan [Dadashev et al., 1995]. It should be noted that in these areas of development of mud volcanism, the thickness of Maikop deposits is more than 1000 meters (1000-2300 m).

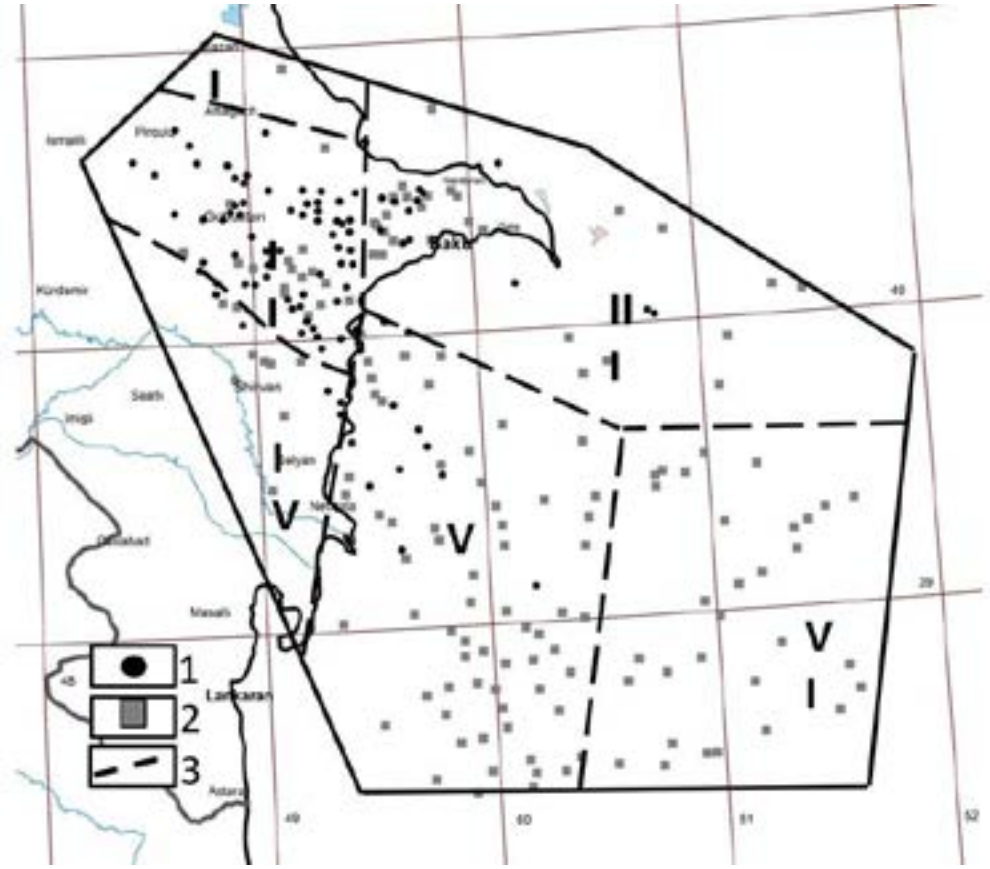

Fig. 1. Location map of mud volcanoes in Azerbaijan [Aliyev et al., 2015]: 1 – Identified volcanoes; 2 – Suspected volcanoes.
Oil and gas prospect zones: I – Caspian-Guba; II – Shamaxi-Gobustan; III – Absheron; IV – Low Kura; V – Baku archipelago; VI – Southe Caspian

Morphologically, mud volcanoes are hills of various heights, having a regular shape of a truncated cone. Volcanic manifestations are extremely diverse in size: from the largest hills hundreds of meters high with large fields of mud volcanic breccias, in some cases reaching 40-60 sq. km in area (Kelany, Akhtarma-Pashaly), to small ones, often not distinguished in the relief hill fields and represented by groups of griffins andsalz, with a total area of several hundred square meters. Otman-Bozdag (404 m) and Toragay (399 m) volcanoes located in the eastern part of Central Gobustan are the highest mud volcanoes in the world [Aliyev et al., 2009, 2015; Planke et al., 2006].

During the eruptions of mud volcanoes, an underground rumble or a thunderous roar is heard, after which an explosion occurs, the release of mud volcanic breccia to the surface and spontaneous combustion of hydrocarbon gases with the formation of a flame column up to 50-200 m high. The combustion temperature at this time reaches 1000-1200°. Around the small particles of rocks turn into slag. Periodically, as if in separate “portions”, along with fire high into the sky through the vent connecting the crater with the volcano, a huge amount of breccia is ejected. Having reached its apogee at a height of about 80-200 m, the entire mass of erupted breccia covers the crater of the volcano. If gases and water are able to make their way (when the volcano channel is not clogged with breccia), then over time, microforms appear – active gryphons and salses, mainly associated with the

apophyses of the volcano's vent. Similar structures are found on the Dashgilmud volcano [Kopf et al., 2010; Mazzini et al., 2009].

Fig. 2. Numerous griffins of the mud volcano Dashgil

Mud volcano "Lokbatan"

Lokbatan is one of the most famous mud volcanoes worldwide due to its frequent fiery eruptions. It is located about 30 km southwest of Baku in the Absheron region. It is located within the anticlinal structure of Lokbatan Put, which also hosts other mud volcanoes (including Shongar, Akhtarma, Kushkhana). Lokbatan has an elongated shape, coinciding with the direction of the anticline axis, and its mud breccia flows cover an area of about 5 km^2. For 199 years (1824-2022), 102 eruptions were recorded on 13 volcanoes on the Absheron Peninsula. At the same time, almost half of them fall on the Lokbatan and Keireki volcanoes. Since the beginning of recording the activity of mud volcanoes, about 25 of its eruptions have been recorded. In 1888, Yalmer Sjogren published the first information about the eruption of the mud volcano Lokbatan. According to [Aliyev et al., 2002, 2009, 2015; Mazzini et al., 2021], almost all of its eruptions are accompanied by the release of a large amount of mud volcanic breccia with a volume of about 250 thousand m^3 [Aliyev et al., 2009] onto the day surface, a powerful gas column with its subsequent ignition (fig. 3). The height of the flame is estimated at 100 to 300 m. Ejections of the mud volcano are mainly represented by clays of the Maikop series, fragments of overlying sandstones and limestones make up only 7-8% of the total volume of igneous rocks. Naturally, the mud volcanic breccia may contain fragments of rocks younger than the Oligocene age, because the vent is in contact with them along the entire height of the vent. The presence of rocks older than the Oligocene in the composition of the volcanic breccia is due to the removal of terrigenous material from the territories adjacent to the Maikop sedimentation basin, that is, they are allochthons.

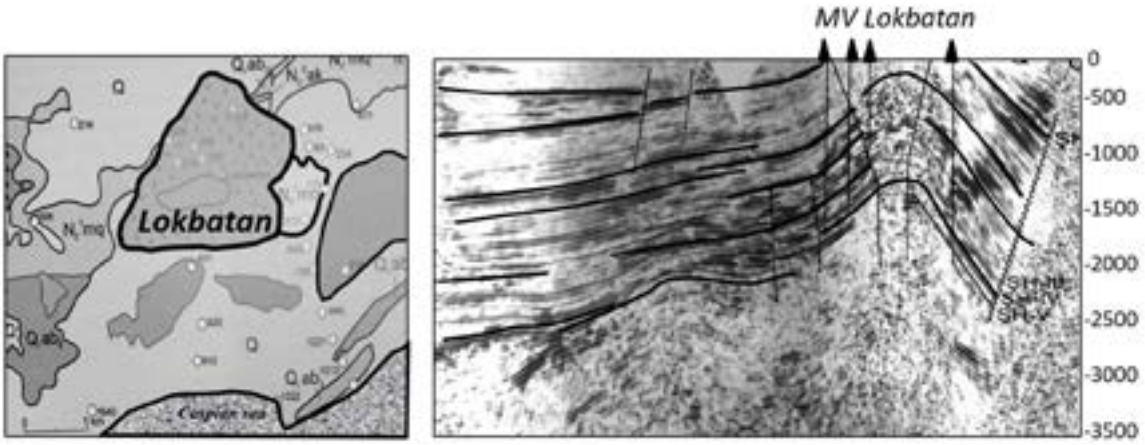

Fig. 3. Location of the mud volcano Lokbatanon the geological map and deep seismic section [Aliyev et al., 2015]

One of the most spectacular eruptions occurred on October 21, 2001 [Mukhtarov et al., 2003; Planke et al., 2006; Stogny et al., 2022] with a strong release of burning methane, followed by a massive mud breccia flow that covered the surface with an area of ~0.1 km^2. On the margins of the main crater, depressions several meters in scale were observed, which were interpreted as impacts of large mud breccias ejected during this latest eruption. Large fragments (up to 0.5 m in size) can be observed everywhere in mud-flows. The main flow extends to the NW and is framed by vertical displacement walls, the direction and orientation of which coincide with the direction and orientation of the axis of the anticline containing Lokbatan and other mud volcanoes. This tectonic control determines the elongated shape of the mud volcano [Bonini, 2012]. Huge blocks of mud breccia are also present within the stream. Planke et al. [Planke et al., 2006] also suggested that this collapse is tectonically controlled by fold orientation and volumetrically dependent on post-eruption deflation of the shallow chamber. Field observations indicated that this deflation was still ongoing in the crater between 2005 and 2006, as evidenced by signs of progressive collapse within the crater. After the 2001 eruption, burning methane vents and diffuse seepage were observed for several years [Etiope et al., 2004, 2009; Planke et al., 2003], but their intensity decreased over time. No burning vents were observed in 2005, and portable methane sensors did not register concentrated and corresponding gas plumes. Lokbatan is one of the most active MVs that periodically erupt with a cycle of ~5-8 years. The first documented eruption of Lokbatan dates back to 1829. Other major eruptions have been documented in 1829, 1864, 1887, 1890, 1900, 1904, 1915, 1918, 1923, 1926, 1933, 1935, 1938, 1941, 1954, 1959, 1972, 1977, 190,20,20 2012, 2017, 2018, 2022 [About the eruption of the mud volcano Lokbatan, 1938; New awakening of Lokbatan volcano…, 1978; Aliyev et al., 2015] (Fig. 4). The high rate of eruptions and the apparent absence of significant seeps suggest that Lokbatan is able to block the main overpressure that occurs at depth and promote a shorter and stronger eruption [Mazzini et al., 2021]. The eruption on September 20, 2012 was no exception for the volcano, and despite the fact that only 2 years have passed since its previous eruption (February 4, 2010), it surpassed it both in strength and power.

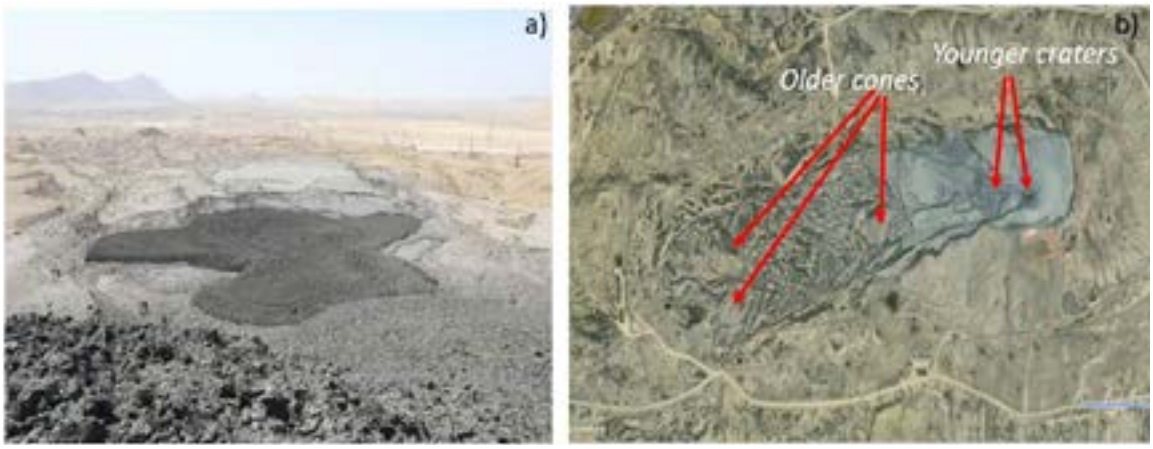

Fig. 4. Eruption of the mud volcano Lokbatana. (A) Eruption of mud volcanic breccia after the eruption on August 11, 2022. b) Google Earth image on October 22, 2022. Red arrows indicate fused fragments of older cones and young craters

The satellite image obtained by Google Earth shows an elongated shape with the last debris flow extending to the west (darker colored mud breccia). The elongated structure of the graben frames the mudflow with numerous production wells located in the environment. According to ArcGIS10.8.1. and Surfer10, a three-dimensional model of the Lokbatan mud volcano was built (Fig. 5). The volume of the mud volcanic structure of the Lokbatan mud volcano according to GIS data is 997-10^{-5} km^3.

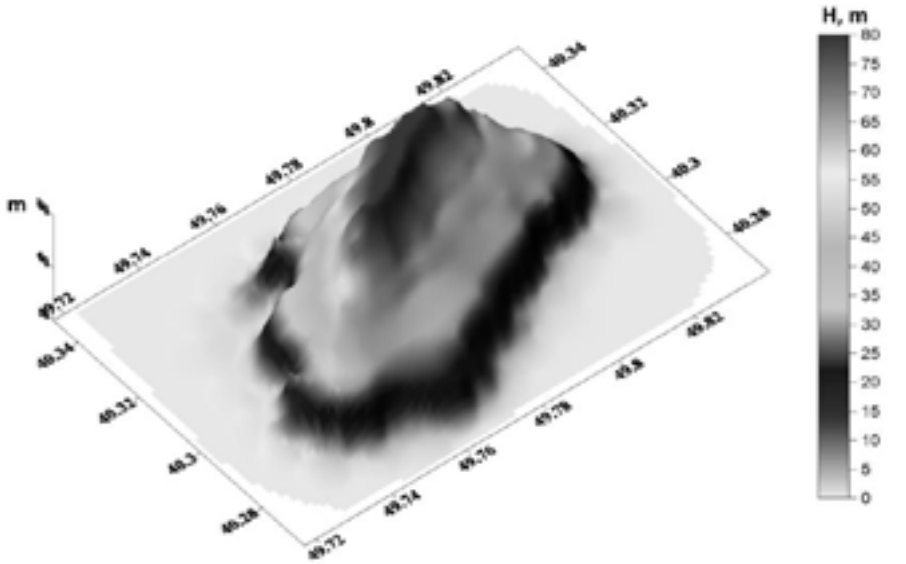

Fig. 5. Mud volcano Lokbatan 3D model

Field observations show the presence of large (up to ~50,000 m^3) layered blocks, which were originally part of a large crater cone. These blocks were fused > 1 km from the vent over mud breccia flows. [Koronovsky, 2018; Veliev, 2021; Mazzini et al., 2021]. The presence of large cohesive blocks is not unique to the Lokbatan Mud Volcano and has been documented in other large-scale structures both onshore and offshore.

Methods of determination of the parameters of the mud volcano Lokbatan

Along with the development of scientific and practical issues of mud volcanism, serious attention was paid to mud volcanic eruptions, their fixation, with the characteristics of the natural process, as well as the study of volcanic ejecta products (breccias, fluids). Each eruption of a mud volcano is new information, "news" about the processes taking place in the bowels. Unfortunately, due to the short duration of the process of mud volcanic eruption, it is practically not always possible to observe and trace the entire mechanism of this phenomenon from beginning to end. Usually, geologists find out about this with some delay and on the volcano, especially if it is located far from settlements, they come after the end of the eruption. And how this process took place is mainly described from the words of eyewitnesses.

Thanks to the high resolution of digital seismic equipment manufactured by Kinemetrics (USA) of the RSSC, since 2008 it has become possible to record and analyze records of mud volcano eruptions, namely, to determine the time and duration, the number of phases, and the focus depth and the energy of a mud volcano eruption. To date, there are 35 digital seismic stations on-line in Azerbaijan and 10 strong motion stations located within the Absheron Peninsula.

In addition, 17 new digital seismic stations were installed in 2017 as part of a joint international project of the RSSC, the University of Missouri (USA) and the Ukrainian Scientific and Technical Center "Caucasus Transect" to study the velocity inhomogeneities of the earth's crust.

In addition, in 2022, within the framework of the international project "Expansion of the seismic network in the Caucasus and Central Asia", implemented with the support of the Ukrainian Scientific and Technical Center, 22 seismic stations manufactured by Nanometrics (Canada) were installed in Azerbaijan. For the first time in the world, in order to study the dynamics of mud volcanoes, 12 such stations were installed around the mud volcanoes Lokbatan and Otman-Bozdag (Fig. 6).

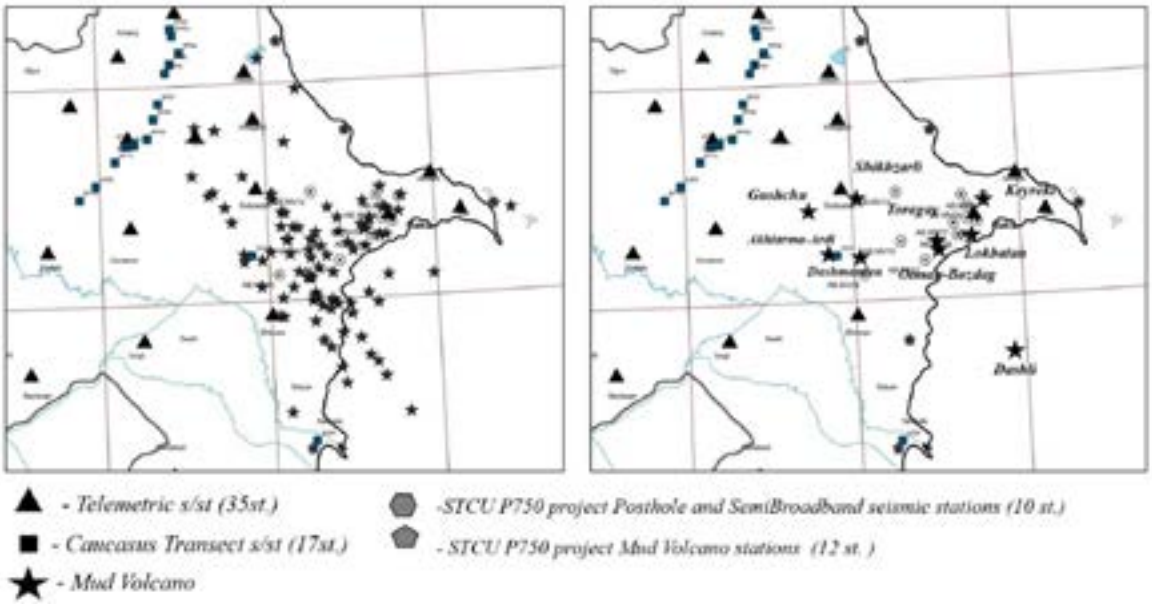

Fig. 6. Location map of digital seismic stations and active mud volcanoes in Azerbaijan

Thus, according to the data of seismo-telemetric stations, the process of eruption of the mud volcano Lokbatan was registered.

Results

Note that the first digital data of the Lokbatan volcano eruption were recorded in 2010. Compared to the previous ones, the February 4, 2010 eruption was much weaker. It began in the morning with an underground rumble, as always with an explosion, but without gas ignition, and a short-term release of volcanic breccia onto the earth's surface, which, flowing down the slope, covered an area a little over one hectare. The eruption of the volcano during the day was characterized by 4 phases of activation recorded only by one nearby seismic station "Gobu". The first one took place in the morning, at 9:30 am (which lasted 4.5 minutes), followed by 1:10 pm, 4:30 pm and 8:05 pm (about 5 minutes long). 09:47:05 – 09:50:15 and 12:48.10 – 12:52:00 respectively. In addition, on the night of February 5, another, as it were, instantaneous activation of volcanic activity was established at the time of 00:08:49 – 00:08:50.8. Due to the lack of sufficient material, the depth of the eruption and the released energy could not be determined.

On September 20, 2012, the next 24th eruption of this volcano occurred. It was recorded by seismic stations "Gobu", "Nardaran", "Gala", "Gobustan", "Ali-Bayramly", "Altyagach", "Pirgulu" and "Siyazan". The eruption began with the release of steam and breccia, at first to a small height, and then the process became more intense, fluids and breccia were ejected to a height of about 100 m. The phase ended with the ignition of the main plume (Fig. 7).

Fig. 7. Fire torch during the eruption of the mud volcano "Lokbatan"

The volcanic eruption of 2012 during the day was characterized by 3 periods of activation. The first one occurred in the morning at 04:59:17.7 (eruption duration 7 minutes, focus depth 5 km, $E=0.64\times10^7$ J), the next ones at 09:14:40 (eruption duration 4 minutes, focus depth 5.5 km, $E= 0.70\times10^7$ J) and at 09:23:00 (duration of eruption 12 minutes, focus depth 1.2 km, $E=3.15\times10^7$ J).

On May 2, 2017 at 08:55:51 another strong eruption of the Lokbatan volcano occurred. The duration of the eruption was 4 minutes, the depth of the focus was 4 km. The released energy was E=1.12×107 J.

The last eruption of this volcano occurred on August 11, 2022. In fig. Figure 8 shows the wave record of the eruption obtained at the new digital stations of the SeisComp4 system. The thickness of the outflowing cover of mud was 80-90 cm with an area of up to 4 hectares. The eruption began in the morning at 09:36:35. The depth of the eruption was

3 km, and the released energy was 0.6×10^7 J. As can be seen in fig. The duration of the eruption was 5 min. 12 sec.

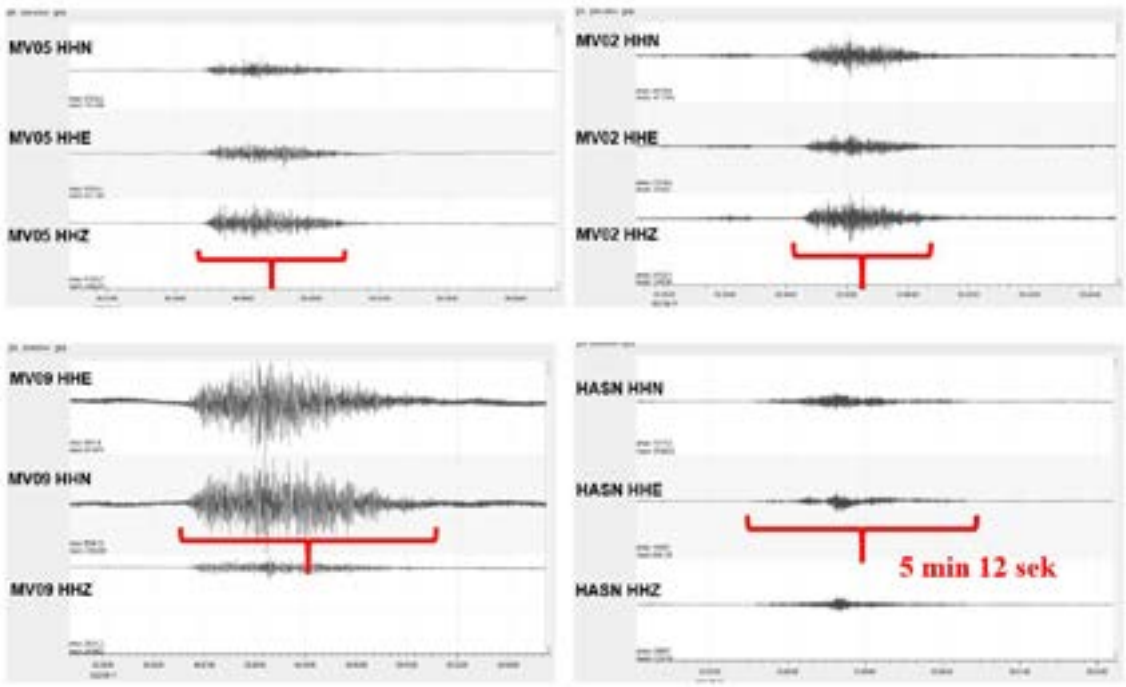

Fig. 8. Lokbatan mud volcano eruption on 11 August 2022

Analysis of the spectrograms of wave images of the Lokbatan mud volcano eruption for 2010, 2012, 2017 and 2022 obtained at the Gobu digital station showed that the eruption fluctuates in the frequency range f=0.3-3.0 Hz.

The results of the work and their discussion

In recent decades, many scientists, conducting research, began to realize the connection between mud volcanism and seismicity. Significant results in this matter are presented in the works. Considering the relationship between mud volcano eruptions and earthquakes, F.S. Ahmedbeyli (1975) [Ahmedbeyli, 2004] argued that seismic shocks create favorable conditions and can contribute to the eruption of mud volcanoes. It is also noted that in some cases, mud volcano eruptions and earthquakes coincide in time, and sometimes the interval between events is several days.

Despite the fact that before the eruption of the mud volcano Lokbatan on August 11, 2022, no earthquakes were observed within a radius of 50 km, however, a day later, on August 12, an earthquake with a magnitude of 3.5 occurred in the Caspian Sea, 60 km NE from the volcano. After analyzing the source mechanism data for 2022, the Lode-Nadai stress state coefficient was calculated. It was found that both the Lokbatan volcano and the earthquake source are in a zone of stressed state of compression. Based on Kulikov's theory that the change in the hydrodeformation field manifests itself where the earth's crust is under compression and its volume is reduced, resulting in an increase in the water level in the wells, it can be assumed that the geodynamic situation of the study region, characterized by compression in 2022, has become caused both the eruption on August 11, 2022, and the earthquake on August 12, 2022.

Conclusions

Thus, summing up the research, it was found that the eruption of the mud volcano Lokbatan in 2012 was characterized by 3 periods of activation at a depth of 4 km. The released energy was E=1.12-10^7 J. The depth of the eruption on May 2, 2017 is 4 km. The last eruption of this volcano, which occurred on August 11, 2022, was characterized by a depth of 3 km, and the released energy was 0.6-10^7 J. Analysis of the spectrograms of wave images of the Lokbatan mud volcano eruption for 2010, 2012, 2017 and 2022 obtained at the Gobu digital station showed that the eruption fluctuates in the frequency range f=0.3-3.0 Hz. Based on the above data from the analysis of igneous rocks, registration by telemetry stations of seismic events that occurred during the eruption, as well as geophysical studies. In [Kazimova et al., 2012], a conceptually new model of the internal structure was proposed – a multi-chamber structure of the Lokbatan mud volcano. In addition, the idea about the stage-by-stage process of the formation of mud volcanic breccia and its final formation in the near-surface zone, which was expressed earlier, was confirmed. It has been suggested that at least two mud volcanic chambers are located at depths of 1.2-3 km and 4-6 km and practically coincide with the above seismic sources. The upper one corresponds (depth 1.2 km) to the Pleistocene deposits of the Quaternary system (Absheron stage), and the second corresponds to the Pliocene deposits (productive stratum) of the Neogene system (5 km), saturated with hydrocarbons. This may well explain the presence of such a large amount of gas that ignites during all recorded eruptions of the Lokbatan mud volcano, including the eruption of September 20, 2012 and May 2, 2017. The centers of development of mud volcanoes are located mainly at depths of 1-6 km, i.e. the development of mud volcanoes is associated with active internal processes occurring mainly in the sedimentary strata of the earth's crust.

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