Mud volcanism as a dangerous phenomenon for oil and gas facilities

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Abstract. The research dwells on the danger of mud volcanism for human economic activity, namely, oil and gas production. We performed quantitative assessment of mud volcanoes activities, using Azerbaijan and Kerch-Taman region as examples. Average annual number of mud volcanoes eruptions is 3–4 for Azerbaijan and 1–2 for Kerch-Taman region. We estimate the catalogues of mud volcanic eruptions for those areas to be 52 % and 39 % complete, respectively. Mud volcanoes eruptions are quite frequent. In both regions, over 50 % of all recorded eruptions occur within ten years of the latest eruption. Analysis of mud volcanic eruptions catalogues shows that the volume of breccia ejected during an eruption is practically not related to how long the mud volcano was quiescent. Analysis of potential impact of seismicity on mud volcanic activity shows that the probability of mud volcanoes responding to an earthquake is 6 % and 10 % for Azerbaijan and Kerch-Taman region, respectively.

1. Introduction
A mud volcano is a natural fluid dynamic system with intensive transport of substances (such as gas, water, and sedimentary rocks) and energy from the bowels of the Earth to the surface. Mud volcanoes are often found in areas of large oil and gas deposits. Mud volcanism is sometimes viewed as one of the signs indicating presence of hydrocarbons in the area [1]. A lot of engineering structures related to oil and gas production are designed and operated close to onshore and offshore mud volcanoes [2]. Mud volcanism is a dangerous geological phenomenon posing a serious threat to engineering infrastructure and natural ecosystems, and it may have serious socioeconomic and environmental consequences [3–6]. A relatively recent and vivid example is eruption of LUSI mud volcano back in 2006 near well BJP-1. The well was drilled with some violations of the process, which is considered to be one of the possible reasons for the eruption, which caused huge financial damage to Indonesian economy and dealt irreparable damage to the ecosystem of Java [4]. In addition to damage to expensive oil and gas facilities, there's a risk of a massive oil spill onshore and offshore. Response to such spills can be more expensive than all operating costs [2].

Oil companies put a lot of emphasis on security in areas of potential operations. Namely, they need to determine the most dangerous zones in areas of mineral resources production, as well as the scope of potential emergencies [2]. Therefore, at every stage of oil and gas fields development comprehensive measures must be taken to identify, monitor, and study mud volcanoes in the development area. This is necessary to predict potential emergencies and prevent consequences. These tasks get more difficult when developing offshore oil and gas fields, because underwater mud
volcanoes are harder to find than onshore ones. In these cases, we can use various methods to register and study fluid dynamic systems [5, 7]. Evidently, analysis of geological risks from mud volcanic activity requires knowledge of quantitative patterns in mud volcanoes eruptions.

2. Materials and methods
Statistical analysis of mud volcanoes eruptive activity was performed using Azerbaijan and Kerch-Taman region as examples. Azerbaijan is the largest mud volcanic province on Earth (over 350 volcanoes). Kerch-Taman region is among the top ten regions on Earth in terms of the number of mud volcanoes (over 80) [1]. There is a rather detailed catalogue of mud volcanoes eruptions for Azerbaijan, with data from 1810 to 2014 [1], updated with data up to 2018 [8]. The resulting database contains information on over 400 eruptions of 93 volcanoes. There is a similar catalogue for Kerch-Taman region with data from 1794 to 2016 [9], also updated with data up to 2018 [10–14]. The resulting catalogue contains data on over 100 eruptions of 30 volcanoes. We made a joint analysis of eruptions and earthquakes catalogues to study how seismicity influences mud volcanic activity [15].

Accurate and reliable quantitative assessment is only possible with a representative dataset. It is evident that the used mud volcanoes eruptions catalogues are incomplete due to lack of regular observations (especially before the middle of the 20th century). The chances of missing an eruption depend on its strength. The probability of a strong eruption not being recorded is lower [2]. It is also not very likely that an eruption will go unnoticed if the mud volcano is close to a settlement [16]. Therefore, completeness of mud volcanoes catalogues has its own importance and will be discussed separately further on.

3. Results and discussion
Currently over 2500 mud volcanoes were found on Earth, over 1400 of them offshore. The largest volcanoes and the most powerful eruptions are typical for mud volcanoes located in oil and gas areas [1]. In recent years people actively research and develop the Arctic region which is very promising in terms of oil and gas production. Currently there is one known underwater mud volcano in the Arctic, called Haakon Mosby, between the shores of Norway and Spitzbergen [7]. Certain geologic conditions lead us to think that, in fact, there are way more mud volcanoes in the Arctic waters than is currently known. Offshore oil and gas fields in the north-east of Sakhalin Island are being actively developed. Piltun-Astokhskoye, Dagi and Chayvo fields located in close vicinity of Dagi mud volcano are of special interest here [17]. Many mud volcanoes were found in the Black Sea and in the Sea of Azov. An increased number of mud volcanoes can be found in the Kerch Strait. This needs to be considered when ensuring navigation safety, because up to 10000 marine vessels go through the Kerch Strait every year [6]. Azerbaijan also actively develops its oil and gas fields close to numerous onshore and offshore mud volcanoes [1].

Major hazards are mud slides, gas emissions, spontaneous combustion of methane, deformation of the land surface and sea bottom, rockfalls and landslides, cracks in the eruptive center and around the volcano, appearance of zones with anomalous formation pressures, and volcanic earthquakes [5, 18]. Quite often wells drilling is accompanied by accidental gas discharge with burning methane. Islands and sand banks generated by underwater mud volcanoes eruptions are the main threats to marine traffic. Strong single gas outbursts from underwater mud volcanoes are dangerous too because they can cause the vessel to careen sharply and capsize due to changed water density. In 1953, a gas outburst from an underwater mud volcano caused the Kayo Maru 5, Japanese science vessel, to go down, killing 31 persons [3]. One of the types of mud volcanoes are mud diapirs, domed piercing structures with a core made up of pliant clays in the central part. Those clays are pushed upwards, raising, breaking, and bursting through the overlying rock. The core of the diapir does not always reach the land surface. Physical modelling indicates that the thicker the overlying rock (the deeper the heart of the mud volcano), the more pressure is required for the subsoil fluids to migrate to the surface. If the pressure was not sufficient, instead of a mud volcano we may end up with a mud diapir which did not reach the surface [19]. Mud diapirs which did not reach the sea bottom are also called blind
mud volcanoes, which goes to show how hard to find such natural objects are [20]. However, the mud diapirs are a potential threat for human economic activity. Drilling operations in area of mud diapir may cause development of a new mud volcano, in the form of a strong eruption. Mud volcanoes may also activate as a result of strong earthquakes. Earthquakes are considered to be a potential trigger for mud volcanic eruptions [16, 21].

Analysis of mud volcanic eruptions catalogues for Azerbaijan and Kerch-Taman region revealed some patterns. Since 1946 until now, Azerbaijan has 3–4 mud volcanoes eruptions a year (the average value is 3.62). Before 1946 the annual average number of mud volcanoes eruptions was significantly lower, from 0.35 (1810–1846) to 1.89 (1900–1946). We suppose the main reason was that some eruptions were not recorded, because there was no regular monitoring of mud volcanoes at that time. Otherwise, we’d have to believe that intensity of mud volcanic eruptions increased by several times over two centuries. This period is too short through the geological time for a significant increase of long geological processes to occur. Most likely before 1946 Azerbaijan had the same 3–4 eruptions a year. We estimate completeness of Azerbaijan mud volcanic eruptions catalogue as 52 %. Kerch-Taman region has 1–2 mud volcanoes eruptions a year since 1977 until now (the average value is 1.45). Before 1977, the average number of mud volcanic eruptions was significantly lower (0.32 times a year), which is probably not accurate because not all of them were recorded. Following the same logic, we estimate the completeness of mud volcanoes eruptions catalogue here to be about 39 %.

We analyzed the relation between the volume of sedimentary rock thrown out during mud volcanoes eruptions in Azerbaijan and Kerch-Taman region and the number of recorded eruptions with a certain volume of discharge (figure 1). In areas of strong and medium eruptions, we see a clear linear trend towards increased number of eruptions while the eruptions volume log decreases. However, when we get to weak eruptions, we see a drastic decrease in the number of eruptions. Yet most likely weak eruptions are more numerous than strong ones. The probable reason for this is that many eruptions were not recorded. If we extrapolate the resulting linear trend onto the weak eruptions, we can estimate the number of eruptions that were not recorded, as well as the total volume of mud volcanoes emissions over a selected period.

![Figure 1](image_url)

**Figure 1.** Relation between the number of recorded eruptions of mud volcanoes and the volume of ejected sedimentary rocks: a – Azerbaijan, b – Kerch-Taman region. The right scale shows the number of eruptions of a given volume of ejected sedimentary rocks. The left scale shows the percentage of eruptions of a given volume from the total number of recorded eruptions.

Active mud volcanoes are not as destructive as magma volcanoes, but they erupt far more frequently [18]. The time intervals between eruptions of each mud volcano vary greatly. However, both in Azerbaijan and in Kerch-Taman region we saw a common trend: when the quiescent time of mud volcanoes increases, there’s a rapid decline in the number of eruptions. In both regions, 51-54 % of all recorded eruptions occur within the first decade after the mud volcanoes becomes quiescent. We
should note that unrecorded eruptions we spoke of extend the time periods between eruptions, thereby increasing the share of eruptions with a long quiescent period.

Area of impact from mud volcanoes may go as far as 4–5 kilometers from the eruption center [18]. For instance, a lot of sedimentary rock is thrown out during an eruption. We can expect that the longer an active volcano remains quiescent, the more emissions we can expect on its next eruption. However, the available data does not support this theory. In over two centuries of observations, all scopes and sizes of emissions, from thousands to millions cubic meters, were recorded in Azerbaijan and Kerch-Taman region, after all kinds of quiescent periods (from one year to decades) (figure 2). There are many instances where a mud volcano just a year after its previous eruption threw out way more breccia than after many years of being quiescent, and many cases where things were just the other way around.

**Figure 2.** Volumes of breccia ejected during eruptions by mud volcanoes in Azerbaijan (1) and the Kerch-Taman region (2), in relation to the time interval since the last eruption.

Mud volcanoes activity can change due to earthquakes. The fastest responses of mud volcanoes were on the same day as the earthquake that triggered it. At the same time, there are cases where eruptions occur only two or three years after a seismic event [22]. There are quantitative assessments of threshold values of seismic impact on various fluid dynamic systems, including mud volcanoes. The following formula is quite common:

\[
\log R_{\text{max}} = 2.05(\pm0.10) + 0.45M
\]

where \(M\) is the earthquake magnitude, \(R_{\text{max}}\) is the maximum distance of epicenter from the fluid dynamic system where trigger effect can be observed [21, 23]. The \(R\) value in the formula is presented in meters. With this formula we determined cases of Azerbaijan and Kerch-Taman region mud volcanoes potentially responding to earthquakes. Our calculations indicate that in Azerbaijan in 1810–2018 earthquakes should have provoked 572 mud volcanic eruptions. In fact, 35 eruptions were recorded, so only 6 % of cases were a response. The mud volcano was considered to have responded to an earthquake if it erupted within two years of the earthquake. Using longer time intervals is not reasonable, because mud volcanoes typically erupt frequently [15]. Therefore, in a longer time interval, mud volcanoes will erupt for natural reasons, irrespectively of earthquakes. We should point out there were instances of anomalous reaction of mud volcanoes to earthquakes. For instance, after an earthquake of November 25, 2000 (\(M = 6.4\)) 19 mud volcanic eruptions was recorded in Azerbaijan, out of the potential 84, therefore,
probability of mud volcanoes responding to an earthquake was about 23%. If we remove this anomaly from our dataset, the probability of Azerbaijan mud volcanoes responding to an earthquake will be only about 3%. In Kerch-Taman region in 1794–2018, earthquakes should have provoked 31 mud volcanoes eruptions. In fact, three eruptions were recorded, so the response ratio was 10%.

4. Conclusion
Mud volcanoes are often found in areas of large oil and gas deposits, which poses a threat to oil and gas production facilities. Mud volcanic eruptions are frequent, and the impact area can be as large as several kilometers.

Quantitative analysis of mud volcanoes activity using Azerbaijan and Kerch-Taman region as examples shows that annual average number of eruptions in these regions is 3.62 and 1.45, respectively. The time intervals between eruptions of each volcano vary greatly. However, more than 50% of all mud volcanoes eruptions in both regions occur within the first decade after the previous eruption.

Analysis of eruptions catalogues for Azerbaijan and Kerch-Taman region shows that the volume of sedimentary rock thrown out by eruptions is not really related to the time the mud volcanoes were quiescent. In over two centuries of observations, all scopes and sizes of emissions, from thousands to millions cubic meters, were recorded in Azerbaijan and Kerch-Taman region, after all kinds of quiescent periods (from a year to decades).

Seismic events may impact mud volcanic activity serving as a trigger. At the same time, this impact is not the main factor of mud volcanoes eruptions; eruptions without any preceding earthquake are far more prevalent. Our calculations indicate that in Azerbaijan and Kerch-Taman region mud volcanoes respond to earthquakes in 6% and 10% of all potential cases, respectively. And since the mud volcanic eruptions catalogues are far from complete, we can suppose that the actual probability of response can be twice that much.

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