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About the Impact of Mud Volcano Eruptions and Earthquake on Petroleum Production Rates (South Caspian Basin)

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***Abstract*:- The paper considers the effect of Lokbatan mud volcano (MV) eruptions on the productivity rate of oil-bearing structure on the Absheron Peninsula in the South Caspian Basin (SCB). The Lower Pliocene sediments (Productive Series – PS) are the main reservoir of SCB. Observations covered 6 wells located at different distances from the MV and draining different PS horizons. During the analyzed period (from 1970 to 2013) 7 MV eruptions and one strong earthquake (with magnitude 6.7) occurred in the Caspian Sea to the south of the Absheron Peninsula. The effect of the MV eruptions on the dynamics of well flow rates is ambiguous (both in time and in space) due to a combination of such main factors as: (a) the local nature of this natural phenomenon; (b) different depths of gas and oil generation foci; (c) the screening role of the MV body for adjoining productive horizons and (d) the heterogeneity of the geological environment. The effect of an earthquake, which has significantly greater energy and an area of influence on the geological environment, has the characteristic feature: changes in well productivity rate occur mainly prior to a seismic event, long before the main seismic shock.**

Key words: Oil field; well productivity rate; dynamics; mud volcano eruption; earthquake; South Caspian Basin.

INTRODUCTION

The influence of tectonic processes on the dynamics of underground fluids is well-known. In particular, the effect of seismicity on the activity of mud volcanoes (MV) has been established [1-6]. However, this relationship is ambiguous, since earthquakes provoke a volcanic eruption only if the volcanic system is in a critical, metastable state. In that case, an earthquake can act as a trigger in a volcanic eruption.

Volcanic eruptions also form local and relatively weak tectonic tremors (volcanic earthquakes).

There is much evidence of the impact of earthquakes on the oil and gas fields, manifested by an increase in well productivity, both prior to

and immediately after the seismic shock, with a simultaneous increase of reservoir pressure [7-14].

As an example, we cite the results of a retrospective analysis of the productivity dynamics of 2 wells in the Buzovna petroleum field of the Absheron Peninsula in the South Caspian Basin (SCB) during the earthquake in 1961 with a magnitude of 6.7 in the Caspian Sea to the north of the peninsula (Fig. 1). In these wells that operated the same horizon, increase in oil production rates (by 10–12 tons) was observed approximately 20–25 days before the seismic event [15].

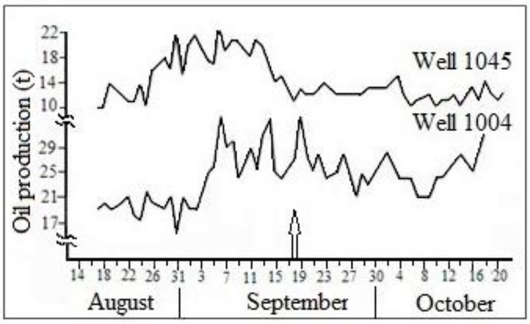

Fig. 1. Changes in oil production in wells at the Buzovna field of the Absheron Peninsula during the earthquake of 1961 (the arrow indicates the moment of the seismic event). In both cases, there is an increase in oil production rates before the seismic event

Thus, seismic activation of the subsoil leads to disruption of the dynamic equilibrium (natural or man-made) in the rock-fluid system, contributing to migration processes.

The genetic relationship between the oil and gas potential of structures and the mud volcanoes that pierce them is well known, and are the derivatives of a single vertical zoning of oil and gas generation. It is of interest to study the effect of eruptions of a MV on the development regime of the oil and gas bearing structure to which it is confined.

Despite many years of studies of MVs this problem still remains almost unstudied; most likely, due to the fact that part of the MVs identified in various basins are associated with structures that are not commercially oil and gas bearing and, on the other hand, volcanoes although confined to fields under development, are either at the initial stage of development (in the form of clayey diapirs), either extinct or buried.

In this regard, this paper is devoted to the study of the effect of MV eruptions on the dynamics of oil and associated gas production rate of the long-developed Lokbatan field. During the development of this field a strong earthquake occurred, so that its effect on well productivity was also considered.

GEOLOGİCAL BACKGROUND AND DATA BASE

The main object of research is the large multilayer oil field Lokbatan, affected by the most active mud volcano in Azerbaijan, also called Lokbatan.

The Lokbatan oil field located on the Absheron peninsula 15-20 km south-west of Baku (Fig. 2) was discovered in 1932.

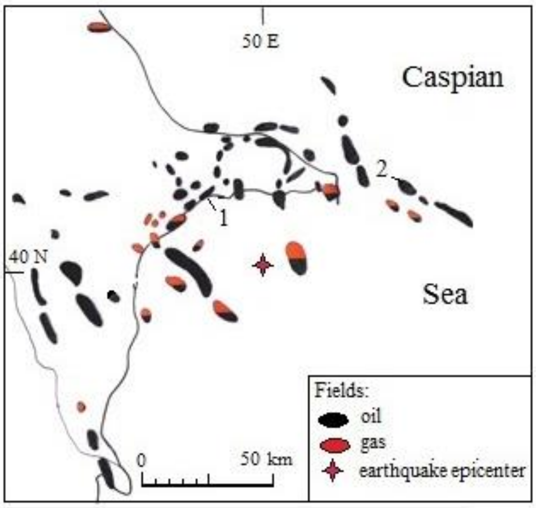

Fig. 2. The oil and gas fields (mud volcano) Lokbatan (1) and Chilov (2), as well as the epicenter of the earthquake on November 25, 2000. Towards to the deep-water part of the basin, gas-oil fields are replaced by gas-condensate fields.

The Lokbatan structure is a brachyanticline fold of almost latitudinal strike with a relatively gentle (45-50 °) south and steeper (55-65 °) north wing. The fold is complicated by a large axial fault with amplitude of 300-350 m, along which the south wing and the arch part are significantly raised and overlap the north wing. The arch part of the fold is also broken by a series of small longitudinal and transverse faults (Fig. 3).

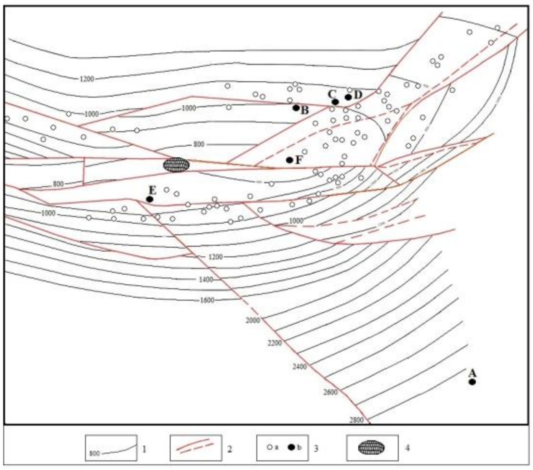

Fig. 3. Structural map of the Lokbatan field along the 7th horizon of the PT with the location of the mud volcano of the same name and the wells under study: 1- isolines; 2 - tectonic disturbances; 3a - productive wells; 3b - investigated production wells; 4 - mud volcano. Deposits on the deep SE wing of the structure (well A) and in a tectonically isolated block (well F) are characterized by relatively higher gas content.

Drilling revealed the entire stratigraphic section of the Productive Series (PS, Lower Pliocene), the main oil and gas reservoir in SCB and lithologically is represented by unevenly alternating layers of sand, siltstone and clay. The thickness of the sand horizons varies from 10-15 m on the arch and up to 60-70 m on the wings of the fold. The total thickness of the PS on the south wing of the fold reaches 2250 m, and on the arch and on the north wing does not exceed 1750 m.

Well No. 45, drilled in 1933 at the Lokbatan field to the east of the mud volcano crater, produced a powerful oil gusher from horizon VI with an initial daily rate of 15–20 thousand tons.

12 oil and gas bearing horizons, occurring at depths of 410-3600 m, were identified in the PS section (Fig. 4). The highest productivity is characterized by horizons VI, VII and VIIa, which in 2007 accounted for 61.2% of the total oil production in the field. The oil recovery factor for the field is about 0.42.

Water was injected into the reservoir in order to maintain reservoir pressure and increase oil recovery from 1956 to 1995.

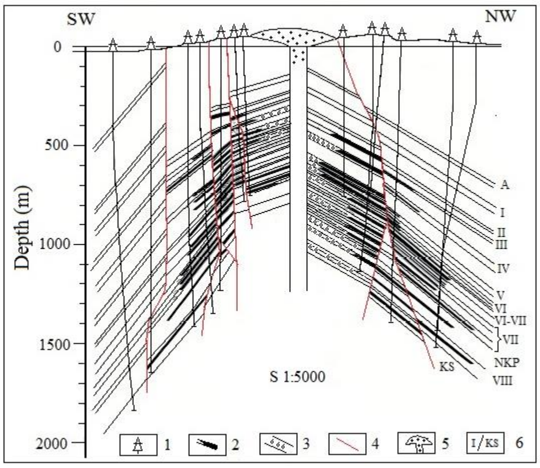

Fig. 4. Geological profile through the Lokbatan structure (position, see Fig. 2). The field is multi-layer and has a block structure.

The density of oils of the upper part of PS (up to horizon VII inclusive) varies in the range of 0.855-0.920 g/cm3. Oils of the lower division of PS (VIII horizon and Kirmaky Suite) are characterized by a lower density (0.854-0.890 g/cm3). The initial values of the gas factor vary between 85-106 m3/ t.

Initial reservoir pressures are equal to hydrostatic pressure. As a result of field development, reservoir pressures decreased by 40 -75%.The temperature gradient averages 25-27 °C/km.

Because the field is at a late stage of development today, the average daily oil production per well is less than 0.6 tons, and water injection reaches 94%. Due to the low content of associated gas in oil, in some wells (or in some periods) it was not measured.

The Lokbatan MV is the most active in Azerbaijan. The first information about the eruption of this volcano dates back to 1888, and 25 of its eruptions are currently recorded.

An analysis of the effect of the eruptions of the Lokbatan mud volcano on the dynamics of the average daily oil and associated gas production (calculated for monthly interval) covers the period from 1970 to 2013. The wells studied are located in different parts of the structure and at different distances from the MV (see Fig. 3) and drain various stratigraphic units of the reservoir.

Several eruptions of this volcano were observed (Table 1).

Table 1 Brief description of eruptions of the Lokbatan mud volcano over the observation period [according to 16, 17].

Eruption date	Duration of eruption	Brief description of the eruption
October 1, 1972	1 hour	A strong underground rumble and gas explosion. The column of fire to a height of 200m, after 3-4 minutes it fell to 20m. Discarded breccia covered an area of 1.74 hectares. Numerous cracks formed
October 6-7, 1977	2.5 hours	Underground rumble, a strong hiss and then gas explosion. The height of the burning gas reached 200-300m. The volume of gas released is estimated at approximately 30 million m^3. Breccia with a thickness of 0.5 to 4 m covered an area of 6.2 hectares.
March 31, 1980	19 minutes	Powerful explosion, release of gas and breccia. Pillar of flame reached 100m. Breccia with a volume of 50 thousand m^3, covered 1/3 of the old cover.
March 25, 1990		The eruption occurred 40 m from the main crater. The breccia protrude 60x40m in size was noted. Two concentric cracks formed, with a depth of 1.5-2 m and a width of 1.0-1.5 m. The crater is lowered to 6 m.
October 24, 2001	25-30 minutes	Strong underground rumble. The height of the flammable gas is up to 50-60 m; it was 4-5 m at the end of the eruption. In the center of the eastern crater the burning gases (up to 2 m high coming from the cracks in three places) lasted more than a month. Breccia, in the volume of 304 thousand m^3 with its average thickness of 2.0 m, covered an area of 15.2 hectares.
February 4, 2010	5-6 minutes	Underground rumble, explosion without ignition of gas, breccia ejection, covering an area of more than 1 ha. At 40 m from the main crater, a breccia protrude 60x40m in size was noted, concentric cracks formed.
September 20, 2012		The height of the flame column is up to 100 m. The amount of ejected breccia is more than 3,000 thousand m^3. Radial cracks formed 2 m deep and 0.5 m wide.

Almost all major eruptions of the Lokbatan volcano were accompanied by the removal of large volumes of volcanic breccia (up to 100-300 thousand m3) to the earth's surface, ignition and combustion of gases (Fig. 5).

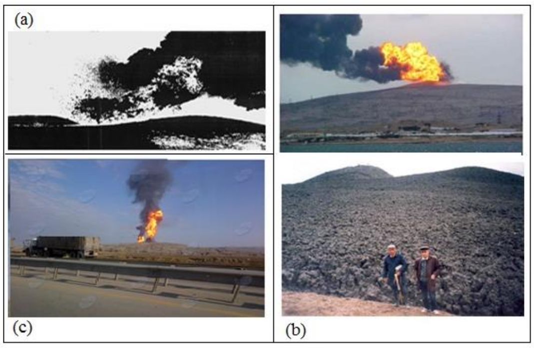

Fig. 5. Eruptions of the Lokbatan volcano on October 6-7, 1977 (a), October 24, 2001 (b) and September 20, 2012 (c). The black color of the puff of smoke confirms the presence of liquid hydrocarbons in the gas.

It is important to note that during the period under review approximately 35 km from the Lokbatan field on November 25, 2000 a strong earthquake occurred (with magnitude 6.7) with an epicenter in the Caspian Sea (see Fig. 2). Earthquakes were felt over a vast area along the coast of the Caspian Sea. In the zone of influence of this earthquake there were a number of oil and gas fields, which could affect the mode of their development.

RESULTS

Figure 6 shows graphs of changes in well productivity during each eruption observed.

During this period, certain trends (above and below the average level) and local variations in the dynamics of productivity (both oil and gas) of the wells are noted. However, it is not possible to unequivocally state the conditionality of these changes by the 3 MV eruptions that occurred during this period.

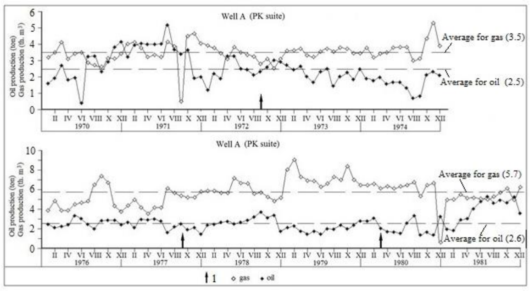

Fig. 6. Dynamics of productivity of well A at the Lokbatan field (for the position, see Fig. 3) during the period 1970-1981: 1- time of mud volcano eruption. There is no obvious impact of volcanic eruptions on the dynamics of oil and gas production.

During the eruption of the MV on March 25, 1990 in all the examined wells that exploit different horizons (VII horizon in wells A and B, VI horizon in well C), a decrease in oil and gas production (with some time shift) is observed (Fig. 7). In well A, after the eruption, the production of both oil and gas is stabilized. After the eruption in well C, oil production stabilizes at an average level, but gas production is less stable and is characterized by multidirectional fluctuations. The dynamics of the productivity of well B after the volcanic eruption is different in comparison with wells A and C: there is an increase in gas production and a particularly contrasting increase in oil production, which lasts for several months.

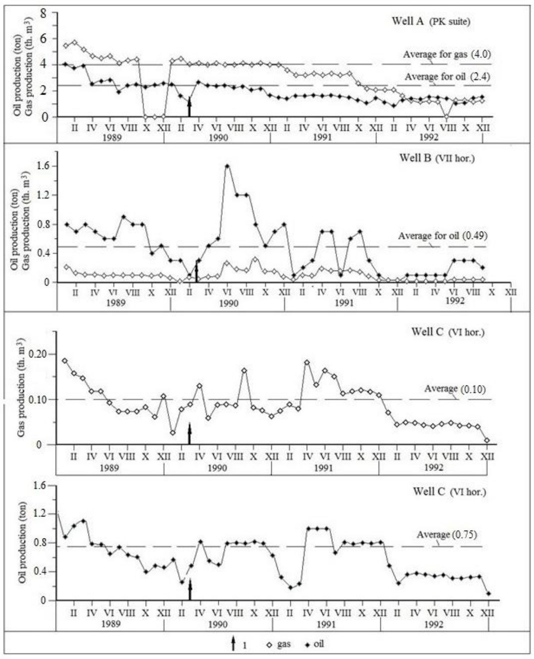

Fig. 7. Dynamics of productivity of wells (A), (B), and (C) at the Lokbatan field (for the situation, see Fig. 3) in the period 1988-1992: 1- time of the volcano eruption. Some noticeable changes in the dynamics of oil and gas production during the volcanic eruption are observed only from horizon VII (well B).

There were no significant changes in well productivity during the volcanic eruption on October 24, 2001. A short-term increase in oil production was noted in well E immediately after the eruption (Fig. 8).

The perceptible earthquake that occurred on November 25, 2000, before the MV eruption, was contrasted in the dynamics of well productivity (with the exception of only well A) with the characteristic feature being a change in the flow rate long before the seismic event. This change is manifested first by a fall, and then by a protracted increase in well productivity. As a rule, a seismic event occurs during a period of an increased level of flow rates, which decreases after an earthquake.

Two wells (A and F) showed an unusual character in the dynamics of their productivity. Approximately two months after the MV eruption, a significant increase in oil production was noted and, in well F, an even more contrasting increase in gas production was also observed. The reason for this phenomenon is difficult to explain, since during this period (2002-2003) no significant geodynamic event was recorded in the SCB.

During the period considered, two eruptions of the Lokbatan MV occurred (on February 4, 2010 and September 20, 2012), which differ in their nature as recorded in Table 1. Thisfact is also reflected in the productivity dynamics of all 5 wells examined (Fig. 9).

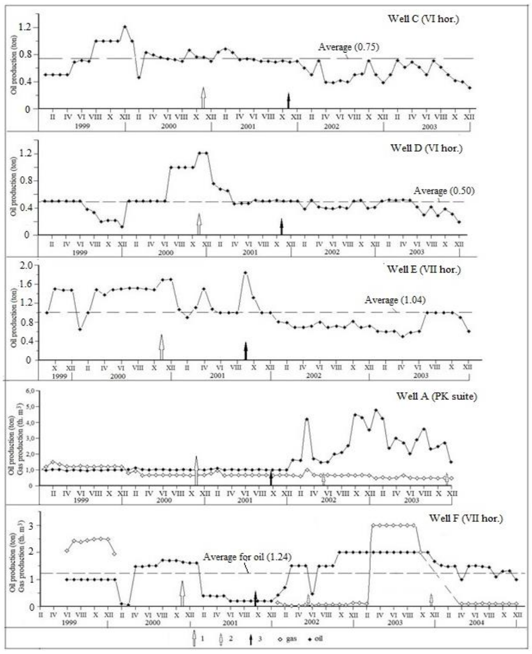

Fig. 8. Dynamics of well productivity (A, C, D, E and F wells) in the Lokbatan field (see position in Fig. 3) in the period 1999-2004: 1- time of the near earthquake and 2- remote Iranian earthquakes; 3- time of the volcanic eruption. In comparison with MV eruptions, seismotectonic processes have a relatively greater impact on the dynamics of oil production.

In all wells, the greatest effect in fluid dynamics was observed during the MV eruption in February 2010. Moreover, the increase in well flow rates occurs long before and immediately after the eruption (with the exception of wells C and D, which drain the overlying VI horizon).

There were no significant changes in the oil production rate of wells during the next MV eruption on September 2012; one can only note contrasting multidirectional fluctuations in the gas production rate in well F.

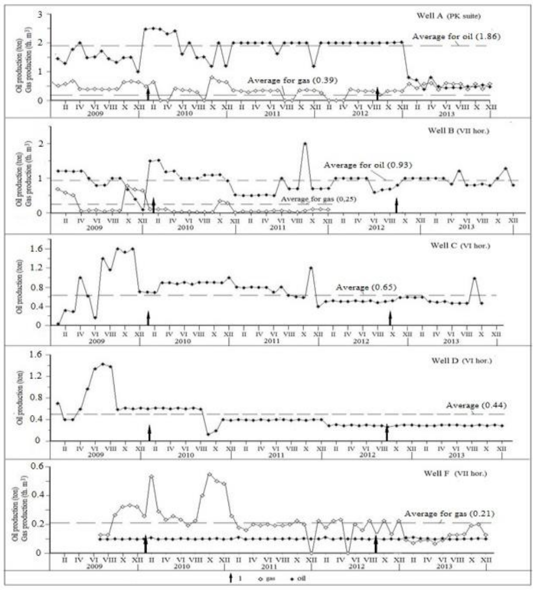

Fig. 9. Dynamics of well productivity (A, B, C, D and F wells) in the Lokbatan field (see position in Fig. 3) for the period 2008-2013: 1- time of the volcanic eruption. Noticeable changes in the dynamics of the productivity of a well, an isolated tectonic block (see Fig. 3), may be due to the impact of the volcanic eruption.

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DISCUSSION

Before discussing the results of the analysis of the well productivity dynamics at the Lokbatan field in connection with the eruptions of the MV and an earthquake, a number of fundamental features of these processes and their controlling factors should be noted.

Long-term studies of the MV of Azerbaijan allow one to conclude that their formation is a consequence of hydrocarbon generation in basins with a high sedimentation rate, a thick sedimentary complex (more than 10 km) and clay rocks prevailing in the section. According to the vertical zoning of oil and gas formation, the main energy factor in the formation and periodic activation of MV is the intense processes of gas generation at the late stage of catagenesis and metagenesis (gas window). According to calculations the depth of the source of SCB gases (including gas of MV) is in the range of 7-15 km (peak at a depth of 11-12 km), the depth of the source of oil formation is higher in the section, in the range of 5-9 km (Fig. 10) [18].

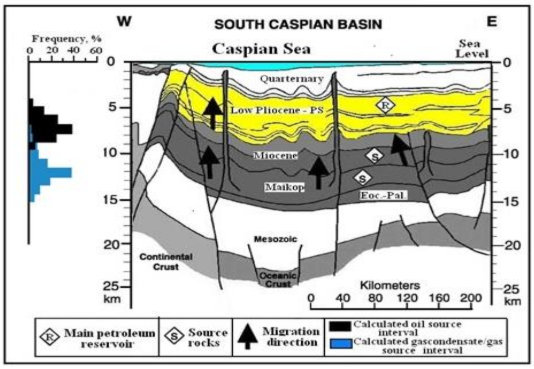

Fig. 10. The vertical zoning of oil and gas formation in the SCB (according to calculated values of the maturity of oils and gases). Gas source interval is located deeper than oil source interval.

The processes of gas generation lead to their accumulation in the focus of the volcano. When the volume of gas and, accordingly, the pressure at the focus of the volcano reaches a critical threshold, it erupts. This process occurs periodically. The frequency of the eruption depends not only on the intensity of gas formation and accumulation, but also to a great extent on the conditions of preservation. An indicator of the conditions of gas conservation in the MV system is the observed scale of manifestation on the surface in quiet periods. Volcanoes characterized by intense continuous gas shows at the surface do not contribute to the accumulation of energy and, therefore, rarely erupt or do not erupt. One of the main factors controlling the intensity of energy losses is the clay mass density in the MV channel (Table 2).

Table 2 Specific gravity of mud breccia on some Azerbaijan MVs

Mud volcano	**Specific gravity of mud, g/sm^3**		**Number of eruptions**
	by volume	**by weight**	
Lokbatan	1.8	1.9	25
Shikhzagirli (plateau) -1	1.60	1.66	18
Shikhzagirli (plateau) -2	1.53	1.59	18
Dashgil - gryphon	1.27	1.4	5
Shikhzagirli - detached mud cone	1.19	1.22	Not erupted
Perekishkyul	1.26	1.36	Not erupted
Perekishkyul-2	1.04	1.11	Not erupted

According to estimates [19], an average of 250 million m3 of gas is released into the atmosphere during a MV eruption. However, such intense gas flows through the volcano during the eruption are not watched in the productivity of the wells, due to the fact that the walls of the mud volcanic channel are highly clayey and serve as vertical blocks for productive horizons. A clear confirmation is the formation of hydrocarbon deposits restricted by the body of the MV (see Fig. 4).

One of the factors controlling the nature of mud volcanic activity is the occurrence in the subsurface of tectonic compression and extension. So, with the predominance of tensile processes, the eruption of HS is manifested by the emission and ignition of large volumes of gas (see Fig. 5). In the case of a predominance of compression forces during the activation period of the MV, large volumes of gas are not ejected, but a diapir-like squeezing of the clay mass occurs, as, for example, in the West Cheildag and Goturdag MV. On the West Cheildag MV the process of extrusion of plastic rocks, lifted to a height of 4-5 m, is observed (fig. 11a). On the Goturdag volcano breccia is extruded from the crater like paste from a tube (fig. 11b).

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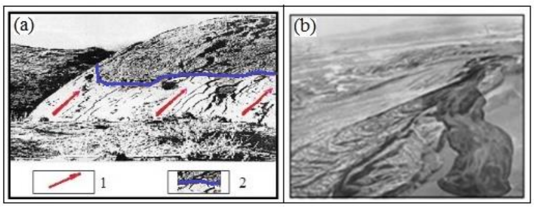

Fig. 11. The West Cheildag (a) and Goturdag (b) mud volcanos that, during activation, press out mud on the surface: 1 - the direction of motion of the clay mass; 2- border between freshly squeezed and old breccia. These are examples of volcano activation without a noticeable manifestation of fluids.

A similar pattern of Lokbatan MV activity was observed on February 4, 2010, when breccia bulging without ignition of gas was noted. The nature of fluctuations in the productivity of wells during such kind of eruptions differs from variations during the classical nature of eruptions. The fluid dynamic effect during the activation of the mud volcano on February 4, 2010 has a character similar to the effect of an earthquake.

An analysis of the graphs shown in Figures 6-9 allow one to draw a general conclusion about the ambiguity of variations in well productivity during various eruptions of the Lokbatan MV, caused by a complex of factors such as:

- spatial heterogeneity of the geological environment (tectonic, geophysical, lithofacial, geochemical) of different scale levels (regional and local). In particular, the geological heterogeneity of the Lokbatan fold is controlled by its block structure, the spatial change in porosity and permeability of the reservoir rocks, the density of oils, and their gas saturation. The heterogeneity of the geological environment determines the different intensities of oil and gas inflows to the wells;
- the degree of remoteness of the wells from the mud volcano. Due to the local nature of the processes in the mud volcanic system, the reaction of remote wells (for example, well A) is less noticeable;
- well drainage of various productive horizons. The role of this factor is visible, for example, when comparing the productivity dynamics of wells A (PK suite), B (VII hor.) and C (VI hor.) during the volcanic eruption on March 25, 1990 (see Fig. 7).

A common similar sign for these two different natural phenomena is that both of them ultimately lead to unloading. However, these natural phenomena are significantly different in their energy capacity: the energy released by earthquakes is several orders of magnitude higher than the energy of mud volcano eruption.

The mechanism of energy storage in the centers of earthquakes and MV is also different. As noted above, the MV eruption provokes gas energy, which periodically accumulates to a critical level. Earthquakes precede long processes of accumulation of tectonic stresses in its focus. Seismic oscillations that occur during an earthquake, depending on the power capacity and depth of focus, can spread from several hundred to several thousand kilometers.

Thus, the area influenced by an earthquake is many times greater than the area of formation and influence on the geological environment of the eruption of a mud volcano. In this regard, fluid dynamic effects can be observed not only from local, but also from remote earthquakes. From this point of view, contrasting fluctuations in oil and gas flow rates identified in 2002-2003 in wells A and F can be associated with two destructive earthquakes in Iran [20-21], the epicenter of one of which (Qazvin) was only 30 km to the southwest from the SCB (Fig. 12, Table 3) the epicenter of one of which (Qazvin) was only 30 km to the southwest from the SCB (Fig. 12, Table 3) [20-21].

The earthquake in the Qazvin region, south of the Elburz mountain range, destroyed 5,000 homes, leaving 25,000 people homeless. The Bam earthquake was particularly destructive and more than 45,000 people were killed, and 30,000 were injured.

Fig. 12. Location of 2002-2003 Iranian earthquakes epicenters: 1- earthquake epicenters.

Table 3. Parameters of Iranian earthquakes in 2002-2003

Area	Date of events	Coordinates	Magnitude	Depth (km)
Qazvin	22.06.2002	35°37'48.0"N 49°03'00.0"E	6.3	10
Bam	22.12.2003	28°51'00.0"N 58°15'00.0"E	6.6	15

Accordingly the nature of the dynamics of well productivity during earthquakes, in comparison with the MV eruptions, has its own distinctive features. One of the main features is that contrasting changes in the dynamics of oil production occur mainly long before the main seismic shock. The nature of these changes is a sharp drop in production, with a subsequent increase. A relatively stable increased oil production is seen during the main seismic shock. Fluctuations in the period of the immediate shock are not so significant. In all cases, after a seismic shock, oil production decreases to the average or below average value. The beginning and duration of the observed changes both during of the pre-shock and after the earthquake are different in different wells, most likely due to the heterogeneity of the geological environment.

CONCLUSION

The results of a retrospective analysis of the productivity of some wells in the long-term operating oil field Lokbatan show that there is no clear influence of the eruptions of the Lokbatan mud volcano on their dynamics due to a complex of such main factors as:

(a) displacement along the sedimentary section of the foci feeding the structure with oil and gas;

(b) isolation of oil reservoirs and the channel of a mud volcano from each other. Intense gas flows through the channel during the eruption of MV do not significantly affect the productivity of the wells. The observed fluid dynamic effects from mud volcanic eruptions are most likely controlled by changes in pressure in the supply channel;

(c) multiscale (regional and local) spatial heterogeneity of the geological environment (tectonic, lithofacial, geochemical, etc.).

In contrast to the MV eruption, the fluid dynamic effect of the earthquake is more contrasting and has its own characteristic features due to the fact that an earthquake is an energetically more powerful natural phenomenon, which has a significantly larger area of influence on the geological environment. Such confirms the fluid dynamic effect of not only local, but also remote earthquakes in Iran.

Contrast changes in the dynamics of oil production occur, as a rule, during the pre-shock phase of a seismic event, long before the main seismic shock. The beginning and duration of these changes are different most likely due to the spatial heterogeneity of the geological environment.

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