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A Review on Mud Volcanoes and Petroleum Potential of the South Caspian Basin

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INFORMATION

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ABSTRACT

There is a close relationship between mud volcanoes (MVs) and oil and gas fields. The close relationship between MVs and petroleum systems has been proven in many studies. Most of the extensive information published on the South Caspian Depression and its hydrocarbon resources is only available in the Russian language, and commonly in books and journals that are not readily available in the open-access. Therefore, this study reviews the structural control of MVs in the petroleum system of the South Caspian basin. It presents the results of surveys to study hydrocarbon systems of the territory using solving oil and gas geology issues. MVs have become evident that a sedimentary complex of depositions allows us to assess the role of fluid dynamic processes in forming and placing hydrocarbon deposits in the South Caspian Basin.

1. Introduction

The Caspian Sea region is well known for its abundant oil reserves. Naturally burning gas seeps led to the ancient name "Land of Fire," which provided a center for Zoroastrian religious activity and warmth for travelers following the Silk Road (Smith-Rouch, 2006). The Caspian Sea is one of the oldest oil production areas. The Caspian Sea is the largest enclosed body of water on Earth. Due to its size and the fact that its bed is composed of oceanic earth crust, it can be classified as the largest drainless lake or sea. It is located at the junction of Europe and Asia. The Caspian Sea is a unique object, and the hydrocarbon resources and biological wealth have no analogies. Scientists are still arguing about the nature of water reservoirs. Some classify it as the largest lake on the Earth, and others refer to the drainless seas. The South Caspian Basin encompasses the southern extension of the Caspian Sea, including land areas in eastern Azerbaijan, western Turkmenistan, and northern Iran (Fig. 1).

The modern stage of geological development is characterized by intensive study of the structure of the bottom of the sea and oceanic water reservoirs. Moreover, this study covers areas of the oceans and relatively small inland - epicontinental seas. This is quite understandable since the development of issues of the geological structure of these water reservoirs is necessary to:

- clarify the patterns of the structure and theory of the inland seas' development,
- a more profound understanding of the geology of regions surrounding such seas,
- search for minerals, primarily oil and gas, at the bottom of these water reservoirs, which are large sedimentary depressions.

Among the continental water reservoirs, the Caspian Sea holds a special place, which is a sizeable heterogeneous depression crossing various geo-structural elements. Even though a great deal of work has been devoted to the geology of the Caspian Sea and extensive research is in progress here, many issues related to the structure and history of the development of this water reservoir remain open.

This applies primarily to the ratio of structural elements of the eastern and western parts of the Caspian Sea, the position of individual structures, the ratio of structural plans of the basement and individual stages of the sedimentary cover, etc.

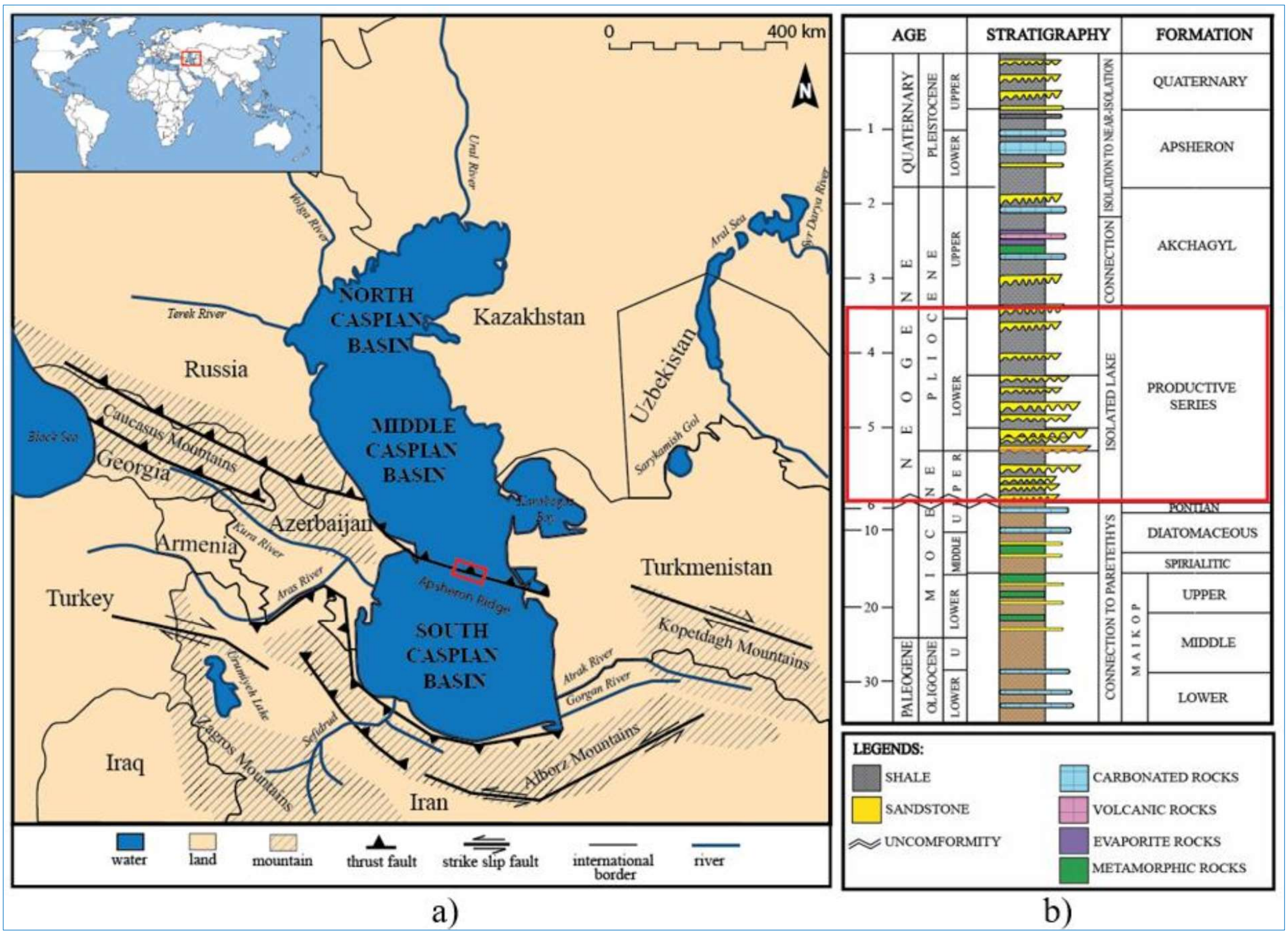

Fig. 1. a) Geological map of the South Caspian Basin. The red rectangular indicates the approximate location of the study area and b) Generalized stratigraphic column of the South Caspian Basin. The red rectangular emphasizes the reservoir target (Yazmyradova et al., 2022)

Most of the extensive information published on the South Caspian Depression and its hydrocarbon resources is only available in the Russian language, and commonly in books and journals that are not readily available in the open-access. Therefore, this study reviews the control of MVs in the petroleum system of the South Caspian basin.

2. Geological Structure and Petroleum Resources

Studies by previous researchers have established that the region of the Caspian Sea is a structurally heterogeneous formation (Fig. 2) (Guliev et al., 2003; Smith-Rouch, 2006; Green et al., 2009; Simmons, 2011; Romanko et al., 2022). The region in question is mainly a platform formation, although heterogeneous. The Caspian Sea is where industrial oil and gas production is carried out. Until now, hydrocarbon production has been concentrated in the Southern Caspian Sea in the Absheron-Balkhan uplift zone, on the Absheron and Baku archipelagos.

Principal hydrocarbon reserves in the South Caspian Basin are concentrated in sandy strata of the Balakhani age (productive strata) of the Pliocene epoch. These geophysical studies of wells (well logging) show that the coarser-grained rocks of the Balakhani age were deposited in constantly meandering paleodelta systems, and the light fraction was carried by sea currents and at subsequent stages of sedimentation (Kerimov et al., 1992). These conditions changed places in the area vertically. As the basin filled, depending on the features of tectonic processes causing transgression and regression of the sea coastline, river systems occupied the same broad zones. This process was hereditary, i.e., the river systems remained in the former zones of total area. This is evidenced by well-logging data, from which it can be seen that the sediment characteristic has some vertical stability. It is evident that such a situation in the evolution of the basin filling led to the formation of multilevel layered deposits created by river systems on the geological section.

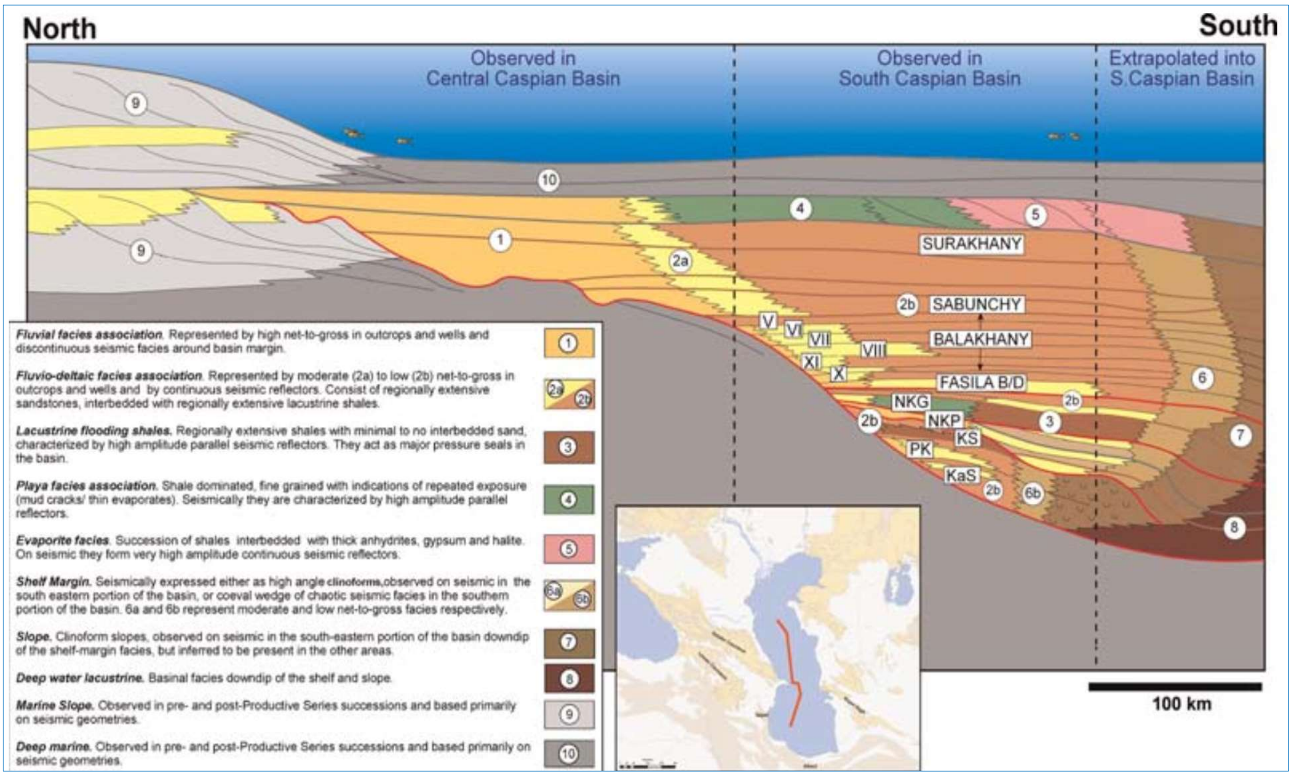

Fig. 2. Depositional model for the Productive Series. The location of this north-south schematic diagram is shown in the inset map runs from the north of the Central Caspian Basin to the South Caspian Basin. The Productive Series is a sizeable lowstand wedge thickening southwards into the South Caspian Basin (Green et al., 2009)

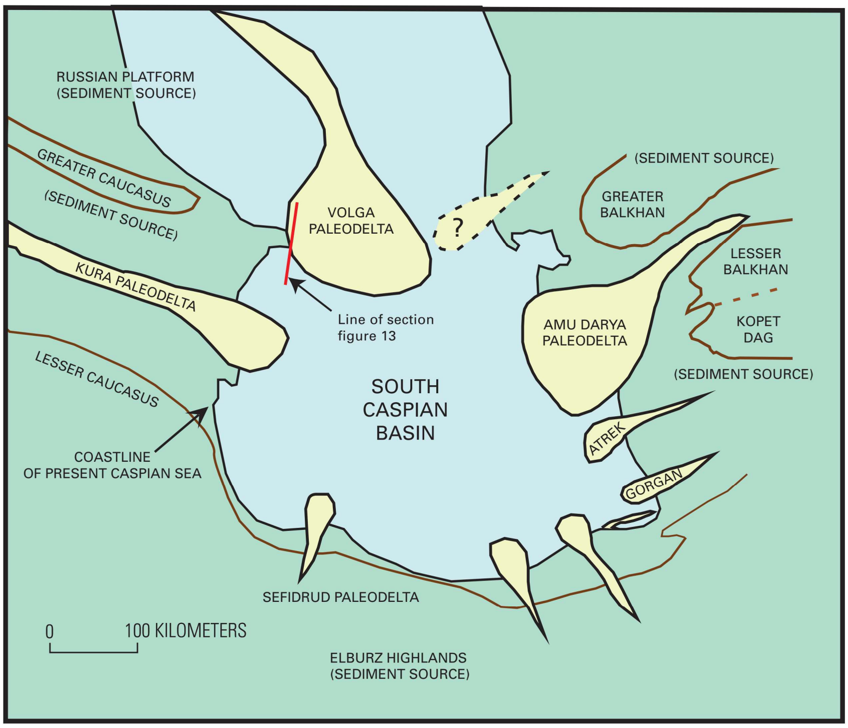

Fig. 3. Schematic map of possible sources of sediment deposited in paleodeltas prograding into the South Caspian Basin during middle Pliocene time (Smith-Rouch, 2006) (see Figs. 4 and 6)

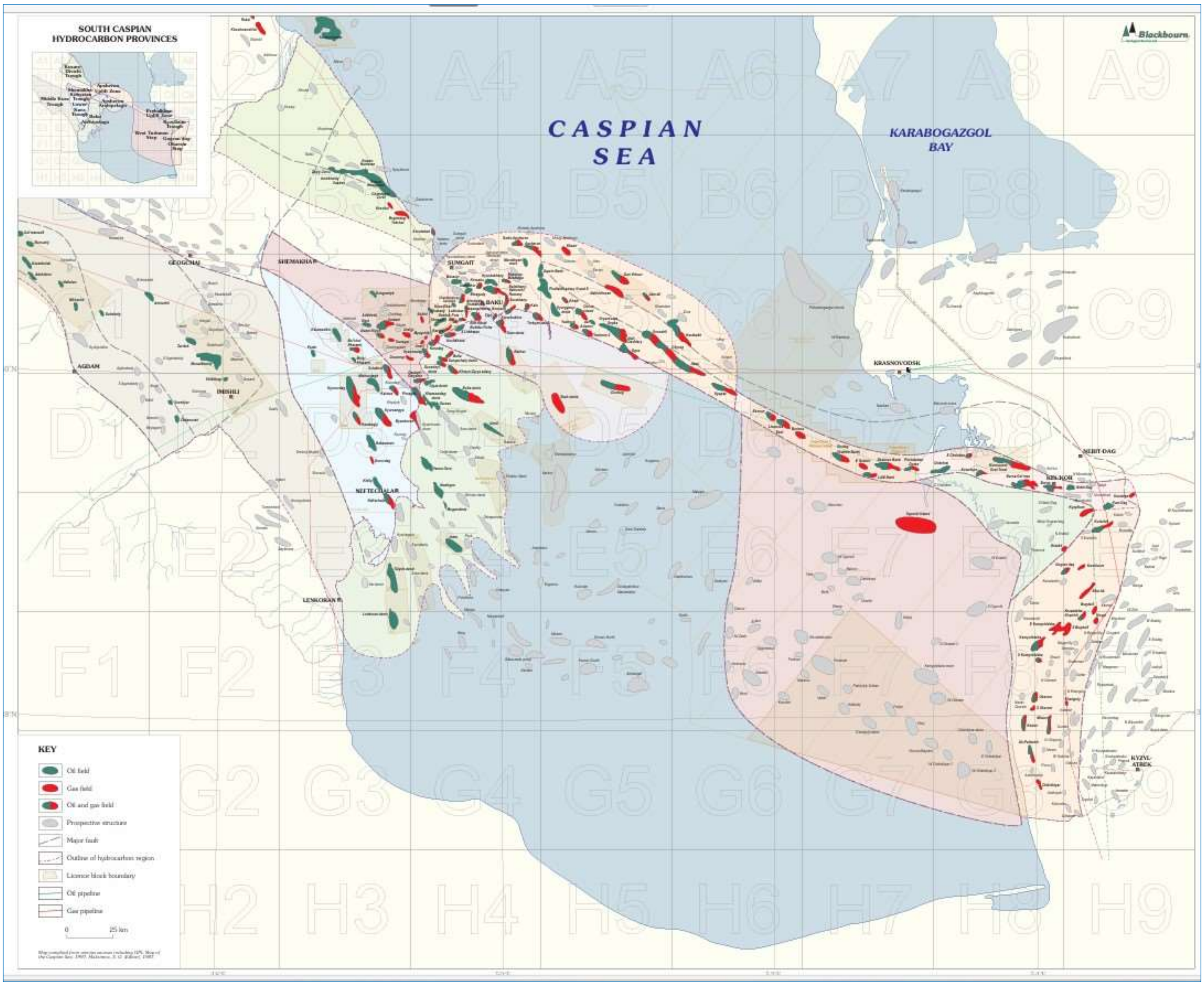

Fig. 4. South Caspian hydrocarbon provinces (https://www.blackbourn.co.uk/reports/south-caspian/)

Fig. 3 shows the results of work on restoring the paleogeography of river systems. As can be seen, the reservoir structure is influenced by the paleogeography of the river operating in the same region. Here, the reservoir is represented by a variety of paleochannels. This structure is typical for areas of sedimentary sections formed as a result of activities of Kura Paleodelta, Amu Darya Paleodelta, and Volga Paleodelta.

The region has abundant petroleum resources, and oil and gas production has played a significant commercial role for more than 150 years, especially in Azerbaijan and, to a lesser extent, in Turkmenistan (Fig. 4). Significant oil reserves are concentrated in 2,500-3,500 meters of shallow-marine, deltaic to lacustrine deposits of the Middle Pliocene. The richest source rocks are in the middle part of the Oligocene-Miocene Maykop Series. The principal reserves and targets for future exploration are in the middle Pliocene Productive Series.

In this depositional environment, good reservoir porosities and permeabilities could be preserved to depths as great as 12 kilometers. The Oligocene-Miocene Maykop/Diatom Total Petroleum System within the South Caspian Basin is separated into five hydrocarbon assessment units: Apsheron-Pribalkhan Zone, Lower Kura Depression, and Adjacent Shelf, Gograndag-Okarem Zone, Central Offshore, and Iran Onshore-Nearshore (Buryakovsky et al., 2001; Guliev et al., 2003; Smith-Rouch, 2006).

3. Mud Volcanoes and Petroleum Potential

MVs, characterized by the release of mud, water, and gases, are found worldwide, particularly in compressional tectonic settings such as in accretionary complexes along subduction zones. Similar to magmatic volcanoes, the release of fluids from MVs may occur during the quiescent or eruptive periods. Mud, water, and gases typically ascend through conduits from pressurized reservoirs. It has been summarized as following the factors controlling the occurrence of MVs: (i) recent tectonic activity, particularly a compressional regime; (ii) rapid loading of rocks due to fast sedimentation, accretion, or overthrust; (iii) active hydrocarbon generation; and (iv) existence of thick, fine-grained, soft sediments deep in the sedimentary succession.

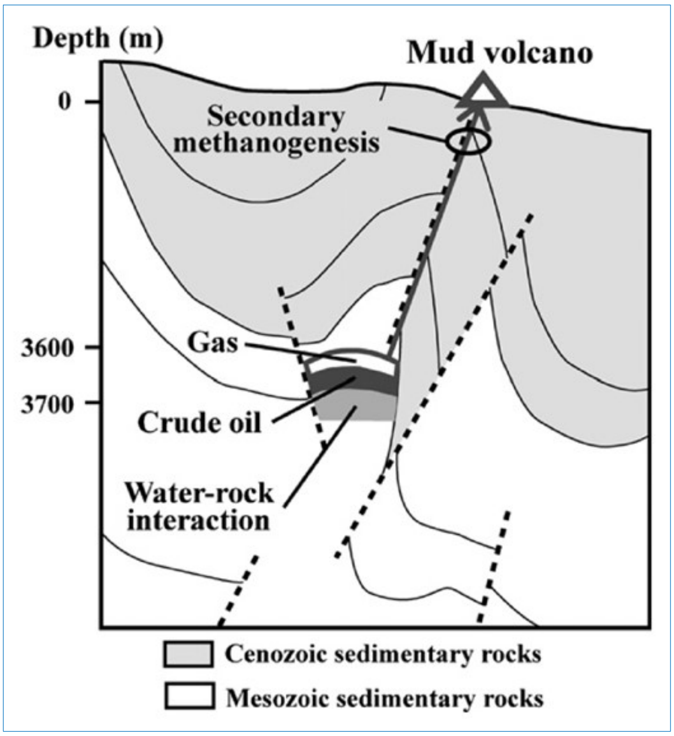

Fig. 5. Schematic illustration of the origin of a mud volcano (Nakada et al., 2011)

The main factor of mud volcano formation is gravity instability in low-density sediments below the high-density rocks induced by fast sedimentation. Gravity instability provides mud diapirism, i.e., the intrusion of shale or clay into overburdened sediments (Nakada et al., 2011). MVs are mainly formed due to an extensive discharge of hydrocarbon-rich fluids from deeper sedimentary units. This phenomenon, commonly occurring in petroliferous regions, results from the upward transport of deep-generated water and hydrocarbons to the subsurface. The emitted fluids consist of a mixture of mud, water, and gases, mainly methane, and an admixture of carbon dioxide, hydrogen sulfide, heavier methane homologs, and other petroleum components. The origin of hydrocarbon gases at MVs can be either thermogenic (formed by the maturation of buried organic matter in the subsurface as a consequence of increasing temperature and pressure) or biogenic (produced by anaerobic microorganisms from the organic matter at low temperatures) or a mixture of both (López-Rodríguez et al., 2014).

There is a close relationship between MVs and oil and gas fields. Mud Volcanoes are a common occurrence in oilfields. These MVs, closely related to gas and water outlets, are generally formed near anticline peaks or fractures that arise from folding. More MVs on anticlines contain petroliferous levels and are close to the surface (Fig. 5).

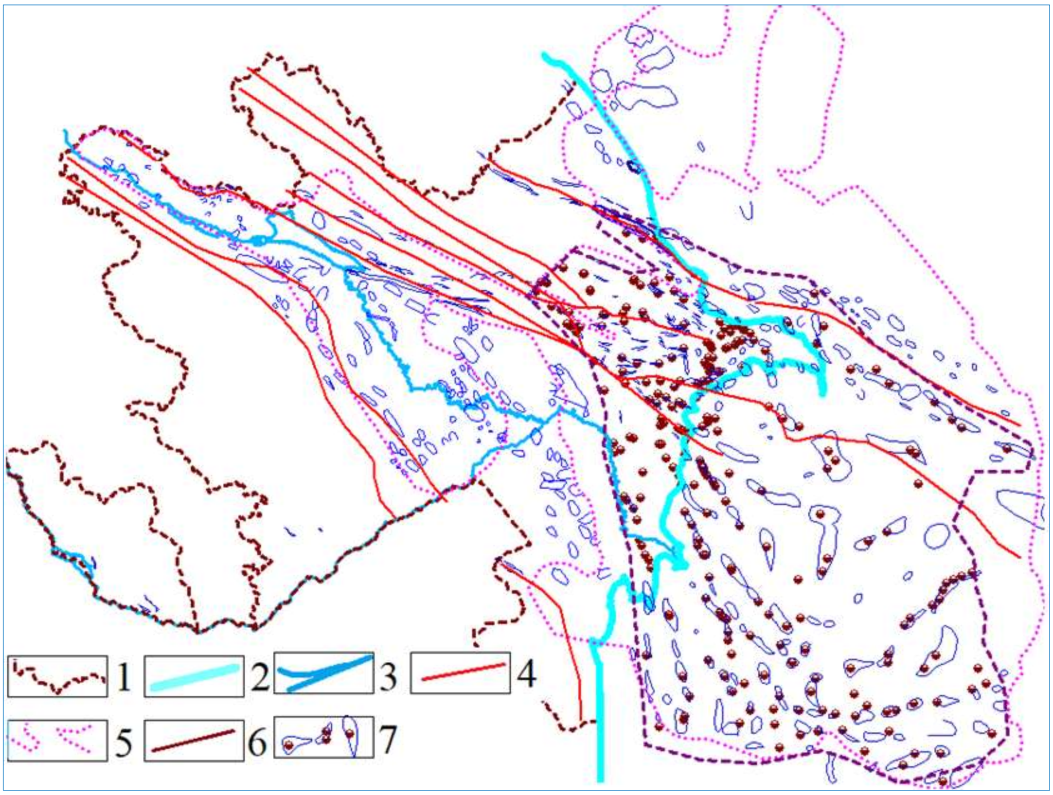

Fig. 6. Area for accumulation of the Maikop sediments and development of mud volcanism. Conventional designations: 1 – state border, 2 – the coastline of the Caspian Sea, 3 – beds of the Kura and Araks rivers; 4 – tectonic fault lines; 5 – the boundary of the distribution of the Maikop sediments, established by seismic survey; 6 – area of distributing MVs and anticline uplifts in the Pliocene, 7 – mud volcanic anticline uplifts (see Fig. 4)

Significantly, few MVs are observed in areas with petroleum levels that are too deep. MVs are characteristic features of tertiary (mostly Neogene, part of Quaternary) oil and gas fields. However, fossil MVs have also been encountered. Nearly 220 MVs are known in Azerbaijan. MVs are located in the west and southwest of Baku. They are regions where oil and gas fields can be intensely located. MVs are the most prominent indicators of active methane/hydrocarbon venting on the seafloor on both passive and active continental margins. The close relationship between MVs and petroleum systems has been proven in many studies (Guliev and Feizullayev, 1996; Planke et al., 2003; Guliev et al., 2003; Stadnitskaia et al., 2007; Mazzini et al., 2009; Nakada et al., 2011; Tassi et al., 2012; Bonini et al., 2013; López-Rodríguez et al., 2014; Oppo et al., 2014; Oppo and Capuzzi, 2015; Mazzini and Etiope, 2017; Alizadeh et al., 2017; Babadi et al., 2020; Palabiyik et al., 2020a, 2020b, 2020c).

Oppo and Capozzi (2015) have reported that the formation and consumption of sediment (mud and sand) volcanoes has four stages in Western Turkmenistan: (a) The deep conduit of mud volcano is responsible for partial degassing of the reservoir, thus preventing significant hydrocarbons accumulation. (b) During a quiescence phase of the mud volcano, hydrocarbon migration increases overpressure in the reservoir. (c) Continuous hydrocarbon migration led to overpressure to the above hydrofracturing gradient and contributed to sand remobilization. (d) Progressive erosion exposed sandstone intrusions, which are now responsible for partial reservoir degassing.

Regional seismic surveys were carried out in the South Caspian basin in 1995-2023; the results confirmed the presence of many (sometimes gigantic, covering an area of 100x7 km) mud volcano structures at the bottom of the Caspian Sea (Smale et al.,1997; Smith-Rouch, 2006; Guliyev et al., 2011). Fundamentally, new data have been obtained on the formation mechanism of MVs and their role in the formation of oil and gas deposits in the South Caspian Basin and in the degassing of the sedimentary layer of the Earth's crust. More than 500 zones with powerful gas emissions have been identified, located on 276 MVs (Fig. 6). Data on the partial replenishment of the resources of exploited deposits were obtained (Guliev et al., 2003; Guliyev et al., 2011; Yusubov and Guliyev, 2011; Aliyev et al., 2013; Yusubov and Guliyev, 2022).

Degassing of sedimentary cover of the Earth's crust in the South Caspian depression occurs in two ways. Firstly, it is pretty apparent that hundreds of terrestrials (176) and underwater (100) MVs are erupting gases, which regularly resume their activities. Secondly, there is a less noticeable, but perhaps no less large-scale form of degassing of the sedimentary layer of the Earth's crust with the participation of faults formed with the assistance of tectonic compression forces and as a result of the activity of MV. It can be that with an incomplete implementation of the degassing of a sedimentary layer of the Earth's crust with the participation of MV and fracturing of the continuity of the layers playing the role of a tire, gas deposits are formed under favorable conditions.

4. Conclusion

MVs are mainly formed due to an extensive discharge of hydrocarbon-rich fluids from deeper sedimentary units. This phenomenon, commonly occurring in petroliferous regions, results from the upward transport of deep-generated water and hydrocarbons to the subsurface. There is a close relationship between MVs and oil and gas fields. The close relationship between MVs and petroleum systems has been proven in many studies. Therefore, MVs locations and 3D seismic data combined with well-logging results can make to predict and map the areas of hidden discharge of deep fluids in the upper part of the Earth's crust. Also, it can lead us to solve the source and form of hydrocarbon migration and to a direct forecast of oil and gas potential of South Caspian Depression. Examining the possible relationships between the geological formation process of paleodelta structures with MVs can also help determine the true petroleum potential of the basin and may lead to the discovery of new oil and gas fields.

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