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FORECAST OF BRINE BLOWOUT ZONES IN THE AMU DARYA BASIN AND ANALYSIS OF BRINE BLOWOUT IN OIL AND GAS FIELDS

Abstract: The purpose of this study is to forecast possible brine blowout zones in the Amu Darya basin and further analyse these manifestations in oil and gas fields to assess their potential for hydrocarbon extraction. The study examined the geological structure through the assessment of lithological and facies maps and sections, the geochemical content of salts and isotopic composition of waters, and hydrogeological methods, including analysis of groundwater regime and well drilling. The obtained data deepened the understanding of the region's geological structure and identified potential hydrocarbon concentration zones, which are crucial for further extraction and utilisation of these resources. Specifically, potential brine blowout zones were determined through analysis of structural features and rock composition. This is critical for subsequent exploration and identification of deposits with high hydrocarbon extraction potential. In addition, the study provided a detailed characterisation of depressions and their physical properties, including viscosity, density, and thermal conductivity. This analysis led to a deeper understanding of the nature of depression formations and the development of more effective methods for their extraction and processing. The data analysis methods ensure more accurate and reliable results, helping not only to determine optimal development points for deposits but also to reduce risks associated with costly drilling and extraction operations. The obtained findings have practical value for the oil and gas industry, contributing to improving the efficiency of hydrocarbon extraction and processing processes, which are essential for the sustainable development of the industry and ensuring regional energy security.

Key words: hydrological methods, geological structure, geochemical analysis, hydrocarbon extraction, drilling

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Introduction

The Amu Darya basin, one of the key geological formations in the central part of Central Asia, attracts the attention of researchers and industrialists due to its unique geological nature and considerable potential for the discovery and development of hydrocarbon resources. One of the main factors that make the Amu Darya basin attractive for research is its geological diversity. This region is characterised by the presence of diverse geological structures, including faults, fold belts, depressions, and other formations. Such diversity creates conditions for the formation and accumulation of hydrocarbon deposits of various types and scales. Researchers are particularly interested in these geological features, seeking to understand the mechanisms of deposit development in this depression. Much attention is also paid to the potential of the Amu Darya basin for the discovery of hydrocarbon resources. For many years, research and exploration in this region have indicated the presence of prospective zones where not only oil but also natural gas are likely to be found. This makes the depression a target for oil companies and government agencies focused on the development of the energy sector.

The conduct of this study is justified by the need for a deeper understanding of the geological characteristics of the Amu Darya basin and the analysis of brine blowouts of hydrocarbon deposits to assess their potential for extraction of hydrocarbon resources. This is important for optimising exploration and development processes and for developing effective strategies to manage hydrocarbon reserves. Such an approach not only contributes to increasing the efficiency of extraction and exploitation of deposits but also ensures sustainable development of the oil and gas industry as a whole, which is a key aspect of ensuring energy security in the region and meeting the population's needs for energy and other oil products (Iskandarov et al., 2024). This study also contributes to scientific progress and expanding knowledge about geological processes and resources, which can be beneficial for future projects and innovations in the oil and gas industry.

Research in the field of forecasting brine blowouts and analysis in oil and gas fields has attracted the attention of scientists. For example, studies by Z. Ma and G. Mei (2021), M. Yousefi et al. (2021) on methods of analysing geological data can be applied to accurately identify prospective areas for further hydrocarbon extraction. The studies by B. Sanjuan et al. (2022) and L. Munk et al. (2021) on geochemical analysis allow for a better understanding of the composition and origin of tars, which is important for developing effective extraction strategies. Researches by A. Deryaev (2023a, b) and Y. Huang et al. (2021) on hydrogeological factors help to consider the influence of groundwater on field development. The computer modelling studies by L. Hu et al. (2021) and P.E. Ayawah et al. (2022) allow for the prediction of processes in underground formations, which is useful for optimising extraction. Analysis of the geological structure and its influence on the formation of deposits, as investigated by M. Parsa and E.J.M. Carranza (2021), K. Eldursi et al. (2021), is also a key aspect of the subject, as it helps to understand the conditions of hydrocarbon resource formation. These studies, aimed at providing a comprehensive overview of methods and approaches to examining this subject, make an important contribution to understanding the formation and exploitation of oil and gas resources in the Amu Darya basin regions. However, despite this contribution, there are gaps that require further investigation, such as a detailed analysis of the geological processes of tar formation, the environment, migration, and hydrocarbon accumulation to develop more accurate methods for predicting zonal extraction.

The purpose of the study is to identify areas with high potential for brine formation in the Amu Darya basin. Research objectives:

1. To analyse the hydrogeological parameters of groundwater zones and determine their influence on the formation and placement of oil and gas fields.
2. To assess the geological and hydrogeological conditions of groundwater zones to determine their potential for hydrocarbon extraction.

Materials and Methods

Systematic assessment of geological information on specialised maps and vertical sections of the crust of Earth allowed the identification of various geological formations. This has also helped to identify factors contributing to the formation of these formations and to forecast the possible presence of hydrocarbon deposits and other valuable minerals. Analysis of crustal deformation processes, such as assessing faults, fold structures, and other changes, provided an opportunity to understand the geological history of the region, identify structural features that may have influenced the formation and accumulation of hydrocarbon deposits, and assess geological stability for planning geological exploration work.

The examination of the chemical composition of minerals and dissolved substances in rock formations and water sources through assessment allowed for the evaluation of the chemical properties of rocks and water resources, identification of their geochemical characteristics, and determination of the possible presence of valuable minerals, including hydrocarbons. This process contributed to a more detailed understanding of the composition of geological formations and water sources, which is important for researching and assessing the natural resources of the region. The assessment of the isotopic composition of water molecules in various aquifers served as the basis for determining the origin of water resources, assessing the degree of pollution, and identifying geological processes that affect the formation and quality of water (Doroshkevich et al., 2017). This method allowed for a deeper understanding of the sources of water resources, identifying chemical and geological factors that affect the composition and properties of water, which is important for effective water resource management and ensuring their safety and sustainability (Pidubnyi & Deineha, 2023). Gas geochemical studies, including assessments of the content of various gases in the atmosphere or emissions from rock formations, contributed to the identification of geochemical processes in the crust of Earth and the discovery of potential hydrocarbon or other valuable gas deposits. This helped to better understand the chemical processes occurring in rock formations and identify promising resources for further analysis and development.

The study on parameters determining the quantity and movement of groundwater in rock formations provided an understanding of groundwater dynamics, recharge and discharge regimes, and interaction with other aquifer systems. This was of high importance for assessing water supply possibilities and effective water resource management. The results obtained allowed for a more accurate assessment of the availability and quality of groundwater, its potential impact on the environment, and possible ways to optimise the use of water resources considering societal needs and environmental preservation. The mapping of hydrogeological zones, including determining the geological structures influencing the storage and movement of groundwater, contributed to identifying various hydrogeological conditions. This has not only helped to determine potential water deposits but also identified

hazardous zones for groundwater. It has provided a more comprehensive understanding of aquifers, their capabilities and limitations, which is crucial for effective water resource management and making informed decisions on the use of groundwater reserves.

Results

The Amu Darya Basin, also known as the Amu Darya basin, is a large depression located in the western part of Central Asia (Figure 1). It encompasses parts of Turkmenistan, Uzbekistan, Afghanistan, and Tajikistan. The basin is formed by a cratonic depression filled with thick sedimentary rock layers. The Amu Darya River, one of the longest rivers in Central Asia, flows through the basin. Its source is in the Pamir Mountains, and it flows northwest into the Aral Sea. The Amu Darya Basin is an important agricultural region, with cotton being the main agricultural crop grown here. However, cotton field irrigation reduced the flow of the Amu Darya River, resulting in the rapid drying up of the Aral Sea.



Fig. 1. Amu Darya Basin, Turkmenistan Source: compiled by the author based on “Distance Learning Module 13 – Panj and Amu Darya River Hydropower and Irrigation” (2024).

There are also a number of natural gas fields in the Amu Darya basin. These deposits are the main source of energy for Turkmenistan and Uzbekistan. It is believed that the basin also has potential for oil exploration. Identifying zones in deposits with the highest probability of such complications may improve the technical and economic performance of drilling operations in areas with bitumen manifestations (De la Rosa et al., 2021; Krylova et al., 2023). Typically, geophysical methods, particularly the method of common depth point, are used for these purposes. However, as drilling shows, not all types of bitumen manifestations are predicted by existing geophysical methods. Another drawback of this type of prediction is the forced, morphology-unrelated placement of exploration and, subsequently, exploratory and production wells outside the bitumen manifestation zones, which sharply reduces the efficiency of geological exploration and field development.

The identified regularities of high-pressure bitumen formation in salt-bearing deposits allow not only for predicting the zone (location) of bitumen manifestations but also for

forecasting the geological situation in salt-bearing deposits, ensuring the correspondence of drilling technology to the geological conditions of the section. In the evaporite formation of the Amu Darya basin, three types of bitumen (bitumen water, bitumen gas, and bitumen gas water) are distinguished, for which various prediction methods are advisable at the pre-project stage.

Forecast in artesian horizons

For artesian horizons-reservoirs, identified based on lithological-facial analysis of the complex and testing of formations, the regional aquifer is assumed within their distribution. There are also no special difficulties in forecasting reservoir pressure. In conditions of a closed-type aquifer horizon, such as Sharapli, Yolotan, and Sakar, which have no recharge area and a very limited load of underground solutes, favourable conditions are created for the accumulation of reservoir energy (Li et al., 2021). The accumulation of reservoir energy in such systems, called Elysian hydrodynamic basins, occurs zonally. The zonality of reservoir energy accumulation in the Amu Darya hydrogeological basin is traced depending on the tightness of the fluid seal and the depth of immersion of the aquifer horizon. Maximum values of the abnormality coefficient of reservoir pressure (ACRP) are predicted in the troughs (Prekopedag, Beshkent, Sandikachin) with a gradual decrease towards the most uplifted areas.

Figure 2 shows the general diagram of the distribution of groundwater. The Sakar horizon, belonging to the evaporite aquifer complex, has no tight fluid seals from the underlying Jurassic aquifer complex. It represents a buffer, transitional zone from evaporite to carbonate aquifer complex. Along the section, there is a gradual distribution of pressure from higher to lower, and mineralisation and chemical composition of solutes.

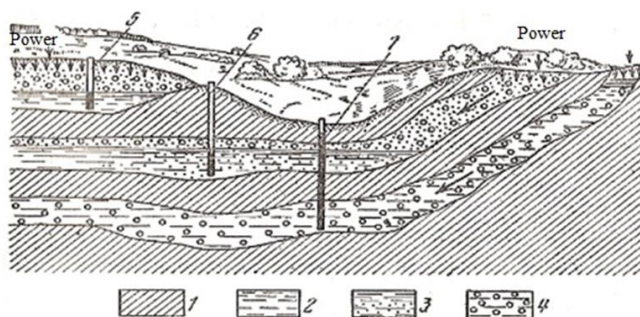


Figure 2. Diagram of artesian waters. Note: 1 – aquitard rocks; 2 – groundwater; 3 – interlayer non-pressure aquifer horizon; 4 – artesian pressure aquifer horizon; 5 – well fed by groundwater; 6 – well fed by interlayer water; 7 – artesian well. Source: compiled by the author based on J. Chen et al. (2018).

In general, for the entire aquifer complex and in the Sakar horizon, there is an increase in the level of reservoir energy from the upper Sharapli horizon to the roof carbonates of the Sakar horizon, followed by a gradual decrease in the absolute permeability coefficient in the Sakar horizon to the level typical of Oxfordian carbonate deposits.

Forecast of manifestations in saline-anhydrite deposits

Considering the peculiar occurrence of brine in saline-anhydrite deposits, the forecast for its distribution should be divided into regional and local. Regional forecasting refers to identifying the structure where the brine blowout is expected, while local forecasting involves

outlining the zone of the brine blowout and identifying specific geological conditions in the zone. According to the features typical of brine blowouts, the following signs can be distinguished in the Amu Darya basin, which can be the basis for a regional forecast. Brine-bearing areas occur only in the zones of development of saline deposits with a thickness of more than 500 m, providing accumulation and preservation of the level of reservoir energy in sub-salt deposits exceeding hydrostatic by more than 1.1 times and in the presence of collectors in sub-salt deposits. Within the boundaries of the development of these signs (thickness and collector), anticlinal structures and flexural bends, having a steepness of wings towards sub-salt deposits of more than $2-3^\circ$ at depths of more than 2000-3000 m, become brine-bearing. For shallower depths, the steepness of the wings should be greater.

The forecast for local areas of brine saturation within the salt-anhydrite formation in the brine-bearing area is based on predicting a specific geological situation in the section of the salt-anhydrite formation within the trap. Such a forecast is possible based on the distribution patterns of brine parameters (Kim et al., 2023). For the brine blowout zone, parameter values (frequency of occurrence, flow rate, mineralisation, pressure) have been differentiated from their maximum values at the hub to their minimum on the structure's periphery. As a result, when designing well construction, it is necessary to forecast the geological features of the saline-anhydrite layer depending on its position on the structural plan of sub-salt productive deposits. Deviations in the flow rate distribution and pressure caused by faults, isolating blocks, or energy discharge in the brine blowout zone into the aquifer horizon may occur in the established regularity. Such deviations are noted in the areas of South Yolotan, Khodgamabas, and Zevardy.

The analysis of the main characteristics defining the hydrogeological properties of the Kimmeridgian salt deposits in the Amu Darya oil and gas basin has led to the conclusion about the necessity of changing the conventional approach to considering these deposits as a regional fluid seal. The results of the analysis indicate the need to consider them as a closed-type aquifer complex. The nature of the aquifer object disclosure indicates the presence of various types of brines in the section of the evaporite formation, which are contained in different deposits comprising this formation (Ouhamdouch et al., 2021). In the evaporite aquifer complex, brines located in collector beds and brines of stratal occurrence can be distinguished. In the Amu Darya hydrogeological basin, these include brines in the Sharapli, Yolotan, and Sakar aquifer horizons, which are associated with sulfate-carbonate layers alternately interbedded with chloride layers acting as fluid seals. In addition to manifestations associated with aquifer horizons, there may also be manifestations gravitating towards regional linear fault zones. These manifestations in closed-type basins can be assessed based on the proximity of leaking wells to the influence sphere of fault zones. Fault zones, arising during and after the accumulation of the evaporite formation, not only disrupt the tightness of salts but also contribute to the formation of favourable capacitive-filtration properties in the solid rocks comprising the evaporite formation, such as anhydrites, carbonates. This leads to the accumulation of significant reserves of reservoir fluid in these rocks.

Along with the processes of forming underground brines typical for any aquifer complex, in saline-anhydrite deposits, the formation of fracture-type underground brines within anticlinal structures is possible thanks to the individual properties of salts and anhydrites. It is assumed that the process of forming an anticlinal fold is accompanied by the formation of vertical local tectonic disturbances in the saline-anhydrite deposits, into which fluid from aquifer horizons is directed. The scale and dynamics of manifestations are directly related to

the nature of structural changes. The most intense brine blowouts and the highest frequency of brine exposure are recorded at the hub and less so at the periphery. Tectonic processes are likely the main causes of changes in the parameters of the aquifer horizon within this structure. They not only determine the nature and intensity of secondary crack formation but also, together with the characteristic properties of salts such as plasticity, fluidity, impermeability, and solubility, contribute to the redistribution of geostatic stresses within the structure. This type of brine blowout is widespread in the internal areas of the Amu Darya saline basin. Brine blowouts are not exclusive to the Amu Darya basin. High-pressure brines in saline deposits are encountered in almost all oil and gas basins.

Dnieper-Donets Depression

The Dnieper-Donets Depression is located in the southern part of the East European Platform. Saline deposits here are developed in two complexes – Lower Permian and Devonian. The Lower Permian saline deposits lie at a depth of about 2000 m and have a thickness of 500-1500 m. Devonian saline deposits lie at depths of up to 4000 m in the north-western part of the depression, and in its central and south-eastern parts, they are at depths inaccessible to drilling. Both complexes control oil and gas accumulations. The Lower Permian saline complex (Bakmut series) is the most studied. The complex serves as a regionally sustained fluid seal for gas fields, protecting them from destruction. It is precisely to this complex that gas deposits with abnormally high reservoir pressures (AHPR) are associated (Rokytianskyi & Gamulya, 2021).

In general, saline deposits in the Dnieper-Donets Depression, unlike the Amu Darya basin, are heterogeneous in composition and not consistent in thickness. The volume of pure salts and anhydrites here does not exceed 50%. The section is mainly represented by frequent alternations of rock salt beds, gypsum, and anhydrite with layers of aleurolites, clays, sandstones, and dolomitised limestones. The gas accumulations with AHPR in the Bakmut series are noted in Shebelinskyi, Yefremivskyi, Mashevskyi, Melikhovskyi, Zakhidno-Krestyshenskyi, Krestyshenskyi, and other fields. The gas accumulations are discovered at depths of 1234-2800 m. Reservoir pressure varies within the range of 19.3-49.2 MPa, with ACRP ranging from 1.21 to 203. For instance, at the Krestishenskyi field, where the homogenous section is represented by interlayers of anhydrites, rock salt, limestones, and dolomites with sandy-clay deposits, signs of gas-bearing were observed in several wells. They were manifested as degassing of the flushing fluid. To prevent gas emissions, these manifestations were eliminated by densifying the flushing fluid to 1480-1500 kg/m³.

Gas formation in saline deposits occurred due to disjunctive disruptions. For example, at the Shebelinskyi field, it is believed that gas from a massive reservoir penetrated through disruptions to the first salt beds, and then gradually filled all somewhat permeable rocks of the lower anhydrite section, migrating from the crest to the wings and periclinal of the uplift, displacing water accordingly. This genetic principle forms the basis of the methodology for the quantitative forecast of AHPR, which assumes that gas flows from reservoirs into evaporite strata occur with minimal pressure losses through ruptured disruptions, fragmentation epochs, fissuring, widely developed in areas of accumulation spreading, with AHPR. AHPR at the forecast point of the section is estimated based on the initial pressure in the main reservoir, considering gas accumulations in the sealing stratum and the main reservoir as a single hydrodynamic system, in which pressure changes with depth according to the mass of the gas column. At the same time, maximum AHPR values are recorded in the crest part of the main reservoir due to its large thickness. For example, at the Shebelinskyi field,

the thickness of the reservoir is 1160 m; the initial reservoir pressure varies from 23.5 at the crest to 24.7 MPa at the gas-water contact; ACRP ranges from 1.04 to 1.72, i.e., the productive horizon beyond the field has a reservoir energy level of less than 1.1.

In the Bakhmut series deposits, AHPR is characteristic only of gas and condensate accumulations, and in the absence of such, the section is characterised by hydrostatic pressure, including in lenses saturated with formation waters. Manifestations of considerable scale are typical for the young salt formations of the Cenozoic and Mesozoic eras. For more ancient (Paleozoic) deposits, due to the greater compactness of the rocks, predominantly gas and oil manifestations are characteristic (Zhemchuzhnikov et al., 2024). Presumably, the basis for a differentiated forecast should include not only the indicator of “reservoir properties,” which may change under the influence of neotectonic movements but also the level of potential energy in subsalt deposits during the formation period of the anticlinal structure and reservoir (Khardazi et al., 2023). For example, manifestations will occur if AHPR in subsalt deposits is formed before the formation of a gas reservoir. At the same time, at the Shebelinskyi, Kechigevskiy, Yefremovskiy, and Krestishenskiy fields, the level of reservoir energy at the gas-water contact is close to hydrostatic. Under such conditions, in the presence of AHPR in the gas reservoir, gas will penetrate into the salt deposits due to its height (Sambo et al., 2022). As the territory characterised by thicker salt deposits and the presence of AHPR in subsalt deposits develops, the number of wells registering brine manifestations will probably increase.

Western Pre-Caucasus

The structural features of the Western Pre-Caucasus have much in common with the Amu Darya syncline. Like in the Amu Darya syncline, salt tectonics are atypical for the Pre-Caucasus, but neotectonic processes are actively manifested. Within the framework of the Western Kuban Depression and the Eastern Kuban Depression, brine manifestations with particularly high ACRP reaching 2.3 have been established in the sulfate-halogen deposits of the Upper Jurassic age.

The sulfate-halogen thickness has a very similar lithological structure. It consists of four units: the first, lower unit, with a thickness of up to 150 m, has limited distribution and is represented by thinly interbedded anhydrites and limestones with subordinate layers of argillites and rock salt. The second unit is developed in the central, most submerged part of the basin and is composed of relatively homogeneous rock salt and anhydrites. The thickness of the unit is up to 460 m. The third unit has a regional distribution and is represented by anhydrites and halite with layers of argillite-like clays, marls, and limestones. The thickness is up to 530 m. The fourth, upper unit, has wide regional development and is represented by alternating colourful clays, argillites, anhydrites, and gypsums with layers of rock salt. The thickness is up to 160 m.

Inside the third and fourth units, two horizons stand out, having regional distribution and serving as the main reservoirs of high-pressure brines (brines). Their thickness over a larger area of development is 5-10 m. Lithologically, these horizons are represented by halite in the lower part, directly above which are argillite-like clays, sometimes carbonates. Each horizon is enclosed between layers of dense anhydrites and rock salt. An increase in AHPR is characteristic of these reservoirs in the most submerged parts of the depression. It is logical that the degree of AHPR manifestation, as in the Amu Darya syncline, increases from the margins to the centre, where the thickness of the sulfate-halogen

deposits exceeds 1200 m. In the axial part of the Eastern Kuban Depression at depths of 3-4.8 km, reservoir pressures reach 70.6 MPa, with ACRP ranging from 1.42 to 1.6. In the zone of articulation with the Caucasus folded structure in the sulfate-halogen deposits, reservoir pressures range from 10.6 to 54.7 MPa, with ACRP ranging from 1.2 to 1.37.

During drilling in salt-anhydrite deposits, intensive brine manifestations are noted, leading, as in the Amu Darya syncline, to the discharge of flushing fluid, gas blowouts, significantly complicating deep well drilling in many gas-bearing areas, such as Jubilee, Kusherskaya, Labinskaya.

Caspian Depression

The Caspian Depression, located in the south-eastern part of the East European Platform, is one of the largest evaporite basins. The lower Perlite salt deposits lie on a thick (over 1000 m) layer of predominantly carbonate rocks. Drilling has established regional prospects. Almost all wells that have penetrated subsalt deposits have noted inflows or signs of oil and gas (Kholismatov et al., 2022).

The salt deposits are predominantly composed of halite. Within it, layers of anhydrites, dolomites, potassium salts, and terrigenous rocks are encountered. There is a regular change in the composition of the salt thickness from the periphery to the centre of the Caspian Depression, from terrigenous-sulfate-halogen and carbonate-sulfate-halogen to predominantly halogen with thin layers of anhydrites and terrigenous rocks. Accordingly, the thickness of the halogen formation increases from the peripheral parts of the depression to its central part and reaches 3500-4000 m.

The presence of a thick, predominantly halite cap has predetermined its good impermeability and conditioned the accumulation of reservoir energy in subsalt deposits (Kudrewicz et al., 2022.). As one moves away from the syncline margins towards the centre, there is a gradual increase in the anomaly of reservoir pressures in subsalt deposits. For example, in the zone up to 15 km from the syncline edge, as well as beyond it, reservoir pressures were close to hydrostatic: the values of the reservoir pressure anomaly coefficient fluctuate from 1 to 1.1-1.2. However, on the structures of Astrakhan and Tengiz, which are located at a distance of 25-30 km from the region's regional Permian halogen-sulfate cap uplift, the anomaly coefficient is 1.38-1.57 already, and on structures like Bikzhal, Kenkiyak, North Kindysay, Karatyube, Karaton, located 50-55 km away, it reaches 1.89 and higher. Thus, the distribution of ACRP in the depression is determined not only by the depth of occurrence of the sulfate-halogen formation but also by the distance of the anomalous reservoir pressure zone from the syncline margin. The same tendency in the distribution of ACRP is observed in the Amu Darya syncline. Many common features with the Amu Darya syncline are observed in the lithological composition and thickness of salt deposits, in the productivity of subsalt deposits, and in the ratio of structural plans in the presence of structures where salt does not play an active role.

During drilling, zones of brine manifestations are encountered. As established by numerous wells, brine manifestations were recorded in areas located in the southern sector of the depression (Astrakhan arch, North Caspian bulge) and in the northern marginal zone – Orenburg region. In the Tally structure of the Orenburg region, one of the wells obtained a water inflow with a density of 1.25 g/cm³ and an excess pressure at the wellhead of 7-8 MPa from a depth of 800 m in the hydrochemical suite of the Kazan sub-stage. In the Irtek area, from well 100 at a depth of 1540 m, a water inflow with a flow rate of 800 m³/day was ob-

tained from the anhydrites of the Permian stage, and the pressure at the wellhead reached 15.6 MPa. In both cases, the ACRP was close to geostatic. A particularly large number of brine manifestations were recorded at the giant Orenburg gas field (OGF) – 50 out of 500 drilled wells. The halogen thickness of the Orenburg ridge has a complex structure. It forms a large anticlinal fold, which, in general, reflects the subsalt structure. The southern wing is the most complexly built, with up to 2-3 rows of salt ridges evident here.

The cut of saline deposits of the Iren horizon of the Kungurian stage of the Lower Permian, which serves as a cap rock for a gas condensate field, consists of two packs. The upper sulfate-halogen pack is composed of frequently alternating layers of rock salt and anhydrite with a total thickness of 200-300 m, and the lower layer is a rock salt layer with an average thickness of 370 m. The total thickness of the cap rock reaches 1200 m in the peripheral parts of the fold and 300-800 m in the vault area. Rock salt throughout the section smells of hydrogen sulfide and sometimes of oil. Luminescent-bituminological analysis showed the presence of light bitumens primarily along fractures and edges of crystals. These elements (hydrogen sulfide, oil) indicate limited vertical migration of hydrocarbons from the underlying productive limestone, which contains the sulfur-containing gas condensate deposit (Wang et al., 2021). In the vault area of the main gas condensate deposit, increased formation pressures were encountered. Here, the ACRP reaches 1.5-1.6. As depth increases, ACRP decreases; at a depth of 1700 m, it equals 1.2, and near the base of the deposit, the pressure approaches hydrostatic.

In the saline deposits, lens-shaped brines are widely distributed. They have been found at depths ranging from 425 to 1144 m from the surface of the earth and from 22 to 558 m below the roof of the Iren horizon. The brines are associated with different anhydrite layers, located close to their contact with salt layers. When wells are drilled, they flow to the surface with a flow rate ranging from 10 to 24000 m³ per day. Static pressures at the wellhead vary from 1.2 to 6 MPa, formation pressures range from 8.3 to 18.8 MPa, density varies from 1.22 to 1.28 g/cm³, and viscosity is 3.57*10⁻³ Pa/s. Instances of high-pressure brine influx have been observed; for example, in well 73 at a depth of 1300 m, a horizon was drilled where the formation pressure reached 21 MPa. Analysis of pressure recovery curves after pumping from well G-1 allowed the determination of a permeability coefficient of 1.574*10⁻¹² m², a hydraulic conductivity of 44.1*10⁻¹⁰ m²/Pa·s, and a piezoconductivity coefficient of 8031 cm²/s. Pumping was performed with various flow rates (78-284-488-692-722 m³/day), with depressions ranging from 0.28 to 2.66 MPa. The specific flow rate ranged from 78 to 260 m³/day per MPa of depression. Well G-1 was operated for some time, during which 3847 m³ of brine was extracted, resulting in a reduction of formation pressure by 0.2 MPa. The reserves of the brine lens, estimated by the method of formation pressure drop, are about 7 million m³.

The chemical composition of the brines remains homogeneous across all areas. Their mineralisation ranges from 308 to 367 g/L with a chloride-magnesium composition. Chloride predominates in the anionic composition (95-99% equivalents). The content of sulfate ions ranges from 0.9 to 4.5% equivalents, magnesium from 37 to 77%, and sodium from 15 to 54% equivalents. In most cases, magnesium predominates (50-60% equivalents). Calcium is present in the range of 520 to 3117 mg/L, which is 0.42-3% equivalents, while potassium varies from 13125 to 41923 mg/L (6.6-17.4% equivalents). The brines of the Orenburg deposit contain dissolved hydrogen sulfide, ranging from 11 to 59.5 mg/L. The gas content of the brines is low, ranging from 200 to 350 cm³/L, consisting mainly of nitrogen-methane

gas. In the Orenburg deposit, five zones of brine manifestations are distinguished: Western, Northwestern, Northern, Southeastern, and Southern. Wellhead pressures vary significantly, from 1.2 MPa (Western area) to 6 MPa (Northwestern area). It is characteristic that there are no brine manifestations in the vault, where elements of salt tectonics are more actively developed, likely leading to the dissipation of reservoir energy into the overlying strata.

The Astrakhan arch is located in the southwest marginal zone of the Caspian Depression. The main productive horizon, lying at depths of more than 3900 m, consists of Middle Carboniferous limestones, characterised by ACRP up to 1.7 (well 1.5 – Shirayevskaya). They are overlain by a thick saline fluid barrier of the Kungurian stage of the Lower Permian. The thickness of the saline deposits reaches 1230 m and is predominantly composed of sulfate-halogen rocks. The salt is coarse-crystalline, granular, massive, with numerous inclusions of carbonates, gypsum, and anhydrites. Lens-shaped brine deposits with AHPD are found within the saline deposits, and salt flows are noted (Gu et al., 2022). Brine blowouts in saline deposits tend to occur in layers and lenses of terrigenous rocks lying within the thick sulfate-halogen layer of the Kungurian stage and represent highly mineralised brines. Mineralisation reaches 430 g/L. Brine flow rates on the Astrakhan arch reach 336 m³/day, with a density of up to 1.26 g/cm³ and a temperature of 98-101°C. At the Astrakhan Gas Condensate Field, brine flow rates reach 29 m³/day, with a density of up to 1.3 g/cm³. Brine blowouts hinder drilling operations. During prolonged self-discharge of rapa, a constant flow rate is observed. The constancy of the brine flow rate is explained by the stability of the rock skeleton to the mountain pressure for a certain period of time. Then, as a result of discharge and disturbance of the established equilibrium, the brine flow rate decreases to a certain level, after which it remains constant. For example, at well 3 Shirayevskaya, the brine flow rate remained at 9 m³/day for one and a half years.

Irkutsk Amphitheater

The Irkutsk Amphitheater is the largest salt-producing basin. The salt-bearing deposits are mainly associated with the Usolsk suite and, to a lesser extent, the Belsk and Angara suites of the Lower Cambrian. A characteristic feature of the salt-bearing section is the frequent alternation of layers of rock salt with layers of dolomite, anhydrite, sandstone, limestone, and marl (Liu et al., 2023). Out of the 2500 m thickness of salt-bearing rocks, the rock salt layers account for 900 m, i.e., salts make up 35% of the total volume of the salt-bearing formation. The geological structure of the salt-bearing deposits in the Irkutsk Amphitheater has influenced salt tectogenesis. Unlike other known areas of salt-bearing deposit development, such as the Caspian and Dnieper-Donetsk depressions, typical diapiric salt tectonics has limited development within the Irkutsk Amphitheater, as the Lower Cambrian salt layers are frequently interspersed with strong limestones and dolomites, forming a rigid skeleton that impedes the movement of salt and particularly its breakthrough from one horizon to another. The structure of the section has left its mark on the hydrogeological conditions. The frequent alternation of salts with limestones, dolomites, predetermined the early stages of diagenesis and compaction of sediments to squeeze out highly concentrated brine from the salts, forming pressurised aquifer horizons in the reservoirs (Bharti et al., 2021).

In the Lower Cambrian salt-bearing deposits section, lithological horizons are well maintained across a vast territory of the Irkutsk Amphitheater. In areas with increased rock fracturing, these horizons serve as a hosting medium for underground water, oil, and gas. The following aquifer horizons are observed in the territory of the Irkutsk Amphitheater (from top to bottom): in the Angara suite – Sheloninsky, Ziminsky, Ustkutsky; in the

Belsky suite – two horizons; in the Usolsk suite – Balykhtin, Osin; in the Motsky suite – Verkhnyemotskiy, Parfenovsky, and Markovsky. Thus, aquifer horizons occupy a relatively large volume in the salt-bearing formation. The character of pressure distribution in the aquifer horizons has much in common with the Amu Darya syncline. For example, in the inter-salt Osin horizon, represented by bituminous limestones lying among layers of rock salt, formation pressures vary from 1.6 to 36.3 MPa and exceed hydrostatic pressure by 5-13 MPa across most of the basin. Maximum values are associated with areas where the thickness of rock salt increases. The formation pressures approach hydrostatic levels only near the framing, where the salt wedges out. For example, in the Markovskaya area, where aquifer horizons in salt-bearing deposits lie at depths of 300 m, the results of testing inter-salt deposits indicate relatively low ACRP values (no more than 1.1).

Brines have a mineralisation of up to 500-600 g/l. In the composition of maximally saturated brines, in addition to calcium chloride, magnesium and potassium chlorides also play a significant role. Occasionally, the presence of hydrogen sulfide is noted in the brines (Backer et al., 2022). Thus, the manifestation of brine during drilling in salt-anhydrite deposits is possible in any saline basin if evaporite formation layers, lens-shaped collectors, or disjunctive disruptions are present in the section, which provide or have provided the penetration of fluid into salts and anhydrites from inter- and subsaline fluid-saturated horizons. The level of brine formation energy varies from conditionally hydrostatic to geostatic and is determined by the tightness of the evaporite formation (thickness, distance from the area of regional unloading) and the specific properties of the salts (solubility, tightness, plasticity, fluidity).

The technology for conducting wells and the tactics of drilling that ensure the effectiveness of exploration activities are formed based on the level of geological information and natural conditions of the region. As the geological model is refined and new information appears, the tactics of drilling operations should be reviewed and adapted to more modern conditions. In brine-prone regions, which should include all saline basins with an evaporite formation thickness of more than 450-500 m and a formation energy level in subsaline deposits above 1.1, drilling tactics must anticipate encountering brine. This involves using well designs that ensure the uncovering of brine in accordance with the mining-geological conditions in the expected brine manifestation zone.

Discussion

During the study, results were obtained that allowed for predicting the zones of brine manifestations in the Amu Darya syncline and conducting an analysis of brine manifestations in oil and gas fields. The analysis of lithological-facies maps and sections enabled the identification of various geological formations and the determination of their formation conditions. This provided a basis for predicting potential brine manifestation zones, which is important for geological exploration and the development of hydrocarbon fields. According to a recent study by H. Rahimi et al. (2021), controlling the planning of mineral exploration plays a key role in optimising the process of resource development and exploitation. This is important not only from an economic but also from an ecological perspective, as the wrong choice of deposits can lead to unnecessary ecological consequences, as well as inefficient use of financial and time resources. This is particularly relevant in situations where resources are limited or when a high degree of precision is necessary in selecting sites for exploration. These data are consistent with the theses presented in the previous section. The problem of select-

ing sites and non-sites can arise due to various factors, including insufficient knowledge of the region's geological structure, unreliability of geological data, and economic and environmental constraints. For example, in the case of minerals such as oil or natural gas, site selection can be complicated due to the heterogeneity of their distribution in the Earth's crust or because of the complexity of their extraction due to geological or geotechnical features. It is also important to consider social and environmental aspects to minimise negative impacts on the environment and society (Buzhyn, 2023; Sadykov et al., 2024).

The analysis of tectonic disruptions has also played a considerable role in the analysis of brine manifestations. Understanding the deformation processes of the Earth's crust has helped identify structural features that influence the formation and accumulation of hydrocarbons and assess the region's geological stability. Referring to the definition by K. Kassymkanova et al. (2023), improving the geophysical method of determining the boundaries of ore-bearing rocks, considering tectonic disruptions, is an important task in the geological and mining industry. Tectonic disruptions, such as faults and folds, can significantly alter the geological structure and properties of rocks, which complicates the accurate determination of mineral deposits. It should be noted that in refining this method, various factors, such as the types and characteristics of tectonic disruptions and the geophysical properties of rocks, must be considered, and appropriate data processing algorithms must be developed. The use of modern technologies, such as geophysical modelling and data processing using artificial intelligence, can significantly improve the efficiency of this method. Such an approach will allow for more precise determination of the boundaries of ore-bearing rocks even in conditions of complex geological structure.

The analysis of the chemical composition of minerals and dissolved substances in rock formations and water sources has provided insight into the geochemical features and possible presence of minerals, including hydrocarbons. Q. Li et al. (2022) found that improving the long-term conductivity of hydraulic fracturing by altering the minerals of the rock is a strategically important task in the mining industry, especially in the development of shale deposits and other oil and gas projects. One method used to enhance conductivity is the chemical treatment of the rock aimed at altering its structure and characteristics. Various chemicals that can break down or alter the minerals composing the rock can be employed for this purpose. For instance, acidic solutions can be used to dissolve carbonate minerals such as calcite, which leads to the creation of additional channels for the flow of fluid and gas. Other chemical additives can be used to break down clay particles or create voids in the rock, which also helps increase conductivity. However, it is necessary to consider potential negative consequences of chemical treatment of the rock, such as water pollution or changes in the physical and chemical properties of the rocks. Therefore, it is important to develop and apply treatment methods that are effective in increasing conductivity but have minimal impact on the environment and are highly safe.

The examination of the isotopic composition of waters has also proved informative, allowing the determination of the origin of water resources and the assessment of the degree of pollution. K. Wang et al. (2021) showed that the analysis of the isotopic composition of water is an important analytical method that provides information about the origin of water resources, their circulation, and interaction with the geological environment. Water isotopes, such as oxygen-18 and deuterium, can be used to determine the source of water, its age, temperature regime, and even the climatic conditions at the time of its formation. It can be agreed that using isotopic analysis can reveal differences in the composition of water in different geo-

graphic areas and identify sources of water resource contamination. For example, changes in the isotopic composition of water may indicate the influence of anthropogenic factors, such as industrial pollution emissions or the use of fertilisers in agriculture. Thus, the analysis of the isotopic composition of water plays an important role in assessing the quality of water resources and developing measures for their protection and management (Malchyk, 2024).

Gas geochemical studies have allowed the evaluation of geochemical processes in the Earth's crust and the identification of potential hydrocarbon deposits. As noted by S. Huang et al. (2022), the use of light hydrocarbons in the geochemistry of natural gas is an important tool for determining the geological characteristics of gas deposits and assessing their potential. Light hydrocarbons, such as methane, ethane, propane, and butane, are the main components of natural gas, and their content and composition can vary depending on different geological conditions. Examining the content of light hydrocarbons in natural gas can help in determining the source of the gas, its age, and the geological conditions of its formation. For example, isotopic analysis of methane can help determine its origin – biogenic or abiogenic. Furthermore, the chemical composition of the gas can be used to detect the presence of impurities or contaminants that may affect its quality and usage. Analysing the obtained results and conclusions, the use of light hydrocarbons in the geochemistry of natural gas is an important tool for researching and assessing gas fields and for developing strategies for their extraction and use.

Research of the regime of underground waters and mapping hydrogeological zones provided an understanding of the dynamics and distribution of underground waters, which is crucial for water resource management. R. Zhao et al. (2024) determined that mapping the potential of underground water sources plays a key role in hydrogeological studies, as it allows for identifying the opportunities and limitations of using underground water resources. The assessment of the contribution of hydrogeological factors involves analysing various parameters such as geological structure, rock types, structural features, and hydraulic properties of rocks. Furthermore, regional hydrogeological conditions are examined in mapping the potential of underground water sources, including hydrogeological structures, aquifers, the chemical composition of water, and its dynamics. These factors interact with each other and determine the distribution and quality of underground water resources in the region (Skarbøvik et al., 2010). Therefore, understanding the contribution of hydrogeological factors not only helps to determine the potential of underground water sources but also contributes to the development of effective strategies for their management and protection.

To summarise, the analysis of brine blowouts in the Amu Darya Basin and their impact on oil and gas fields has provided valuable data on the geological processes and resources of this region, which is a noteworthy step in understanding and developing its natural resources.

Conclusion

The analysis of forecasting brine blowout zones in the Amu Darya basin and brine blowout in oil and gas fields provided valuable insights, enhancing the understanding of the geological nature and potential of this area. Firstly, the analysis allowed identifying the characteristics of the brine blowout distribution and establishing their relationship with the region's geological structure. Natural gas fields in the Amu Darya basin play a key role in meeting the energy needs of the region, especially for Turkmenistan and Uzbekistan. The potential for oil extraction in this basin also remains significant. To improve the efficiency of drilling opera-

tions in areas with mud volcanoes, attention must be focused on improving technical and economic aspects by identifying the most likely fields with such complications.

The results of the study confirm the presence of prospective zones of brine blowout in the Amu Darya basin, providing new opportunities for more detailed analysis and subsequent geological exploration. The analysis of brine blowout in oil and gas fields revealed common patterns and unique features of their geological structure, which is a key factor for the successful development and sustainable operation of these natural resources. One of the key conclusions of this study is the need to consider the influence of tectonic processes when predicting brine blowout and assessing prospective areas for further geological exploration. In addition, a noteworthy result is the identification of potential oil and gas fields based on the analysis of brine blowout, which contributes to the further development of the oil and gas industry in this region.

The study highlights the importance of geological data and analysis methods in predicting brine blowouts and assessing the region's oil and gas potential. The results obtained can be used as a basis for developing strategies for further development and management of natural resources in the Amu Darya basin. The study provides insights into the most promising zones for hydrocarbon exploration, leading to more efficient and cost-effective drilling operations. Understanding brine blowouts and their impact on hydrocarbon deposits helps develop better management strategies for sustainable exploitation. The research emphasizes the need for a multidisciplinary approach in geological studies, combining hydrogeology, geochemistry, and geophysics. Future research should focus on analysing the environmental impact of hydrocarbon extraction, investigating innovative extraction technologies, and comparing the research with similar formations globally. One limitation of this study is the restricted availability of data, and the limited area studied, which may reduce the generalizability of the obtained results. It is necessary to further examine the influence of geological processes on the formation of brine and the distribution of oil and gas fields for more accurate forecasting of the resource potential of the Amu Darya basin.

Conflicts of Interest: The author declares no conflict of interest.

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