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Main Characteristics of the Geological Structure of the Evaporite Formation of the Amu Darya Syneclise

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Abstract

The geological structure of the evaporite formation in the Amu Darya syneclise is a complex system that provides valuable insights into the region's geological history and economic potential. The study aims to analyse the main characteristics of the geological structure of the evaporite formation in the Amu Darya syneclise to expand knowledge of the geological and environmental history of the region and to identify the potential of these deposits for various applications. The methods used for this study included geological mapping, mineralogical analysis, stratigraphic analysis and geochemical research. The study identifies three distinct water-bearing horizons within the evaporite complex: Sharaplinsky, Yolotan, and Sakar. These horizons exhibit varying characteristics in terms of composition, water content, and distribution across the basin. Geomorphological manifestations, such as salt lakes and salt marshes, play a crucial role in understanding the ecological and geological history of the region. The evaporite formation holds substantial economic importance, hosting valuable resources including salts, oil, and gas. This geological structure supports regional industrial development, job creation, and overall economic growth. The study also highlights the need for further research into the geology and geomorphology of the Amu Darya syneclise to better understand the formation and dynamics of evaporite deposits and their role in the region's current environmental and economic sectors. The study emphasizes the need for efficient technologies and methods for resource extraction and management to ensure sustainable development and minimize environmental impact. The research provides crucial data for optimizing mineral extraction strategies and developing effective natural resource management approaches. It underscores the importance of understanding the geological structure for sustainable ecological and economic development in the region. The practical significance of this study is a basis for developing more effective natural resource management strategies based on an understanding of the geological processes of evaporite sedimentation in the Amu Darya syneclise, which is key to the sustainable development of the region's ecological and economic systems.

Keywords

Ecological history; Geomorphological manifestations; Economic potential; Stratigraphic position; Natural resource management

Introduction

The evaporite formation of the Amu Darya syneclise is highly heterogeneous in composition, comprising mainly salt and sulphate rocks with crystalline and fine-grained textures. This structure is formed by processes of high-water evaporation in the past, which is a key factor in understanding its genesis. Geological analysis has also revealed the presence of geomorphological features such as salt lakes and salt marshes, which reflect the history of changes in climatic and tectonic conditions in the area (Maharramov *et al.,* 2023; Raxmatullaevich *et al.,* 2021). These characteristics of the geological structure of the evaporite formation are important for a deep understanding of its evolution in geological time and determining its potential in various aspects, including environmental, economic and scientific applications.

The study of the geological structure of the evaporite formation of the Amu Darya syneclise is of strategic importance in the context of understanding not only the geological history of this area but also its potential for various applications. Evaporites are important sources of minerals such as salt and sulphates, which are used in a variety of industries, from chemicals to agriculture. In addition, understanding the processes of evaporite formation was used to deepen the environmental aspects associated with these deposits and develop effective strategies for managing the region’s natural resources. This study also adds to the general scientific knowledge of geological development processes and can serve as a basis for future research in the field of geology, ecology and geochemistry of the region.

Xiong *et al*. (2021) focused on the geochemical features of evaporites and their relationship with climate change. Demir and Varol (2023) dealt with the economic importance of evaporites and the possibilities of their use in industry. Al-Halbouni *et al.* (2021) described the geomorphological aspects of evaporites within the regional context. The stratigraphy and genesis of evaporites were analysed by Mohammadi *et al.* (2022). Shields and Mills (2021) focused on global processes of evaporite formation in the context of crustal evolution. Paleoclimatic aspects were studied by Eder, Zamiralova and Yan (2023), and the influence of tectonics Bahadori *et al*. (2022).

The migration of saline solutions and their influence on the chemical composition of evaporites were discussed in Wang, Vuik and Hajibeygi (2022). Rioja, Saravias and López (2023) focused on the environmental aspects of evaporite exploitation, and Jin and Nie (2022) analysed the historical aspects of basin formation. While various studies already made some contribution to addressing these issues, gaps that still need to be explored include a more detailed study of the formation and evolution of the evaporite formation in the dynamics of climate and geological change. A more accurate assessment of the economic potential of evaporite deposits given current technological capabilities, and a deeper study of the impact of human activity on the conservation and condition of this geological formation and its surrounding environment.

This study aims to analyse the main characteristics of the geological structure of the evaporite formation in the Amu Darya syneclise to expand knowledge of the geological and environmental history of the region and to identify the potential of these sediments for various applications. Research goals include:

1. Investigation of the geological structure of the evaporite formation of the Amu Darya syneclise for a more detailed analysis of its genesis and evolution, including the study of sedimentation processes and dynamics of changes in geological time.
2. Evaluation of the potential of evaporite deposits for various applications, including their economic importance in industry, as well as the possibility of using them in agriculture, construction and other sectors.
3. Analysis of the ecological significance of the evaporite formation and its impact on the environment of the region, addressing risks and benefits for nature and humans.

Literature Review

The geological structure of the Amu Darya syneclise, particularly its evaporite formation, has been the subject of extensive research due to its complex formation history and significant economic importance. The evaporite deposits in this region have attracted attention from various scientific disciplines, including geology, geochemistry, geophysics, and environmental sciences. The evaporite formation comprises a variety of lithological rock types that were formed because of specific deposition and diagenesis processes. The main lithological components of the formation include salts such as halite, sylvite, gypsum and anhydrite, which reflect the processes of high-water evaporation and salt deposit formation (Balaev *et al.*, 2023; Shyrin *et al.*, 2018). In addition, the evaporite rocks contain carbonates such as dolomites and limestones, as well as terrigenous rocks including sandstones, siltstones and clays. The thickness of the evaporite formation in this area can reach several kms that indicates a significant amount of sediments and the importance of this formation for understanding the geological history of the region.

Shoymurotov *et al*. (2022) determined that the evaporite formation of the Amu Darya syneclise consists of salt and sulphate rocks. This indicates previous periods of high-water evaporation in the region. This fact is important for understanding the geological history of the region, as it confirms the past climatic conditions and processes that led to the formation of these rocks. The formation of evaporites in the Amu Darya syneclise is intrinsically linked to the region's tectonic history. The basin's development began in the late Paleozoic era, with major subsidence and sediment accumulation occurring during the Mesozoic and Cenozoic eras. This long-term geological evolution created ideal conditions for the cyclic deposition of evaporites, interspersed with periods of marine transgression and regression. The resulting stratigraphic sequence is a complex interplay of evaporites, carbonates, and clastic sediments, each layer telling a part of the region's geological story.

Acosta *et al.* (2023) emphasise that the identification of geomorphological manifestations of evaporites, including salt lakes and salt marshes, complements and expands the understanding of the importance of these deposits for the environmental and geological history of the Amu Darya syneclise. New knowledge of climatic conditions indicates that in the past the average temperature in this region ranged from 20°C to 40°C. Precipitation in this period was insufficient, with less than 200 mm per year. These data demonstrate the climatic conditions of past epochs and their impact on the formation of the landscape and geological formations in the area. In the context of global climate change, the Amu Darya evaporite formations offer a unique archive of past climate variations (Shirin, Korovyaka and Tokar, 2011; Shubalyi, 2023). Charton *et al*. (2021) note that the study of the stratigraphic position of the evaporite formation and related periodic changes in salt accumulation conditions is an important aspect of understanding the evolution of the region's history and the dynamics of sediment formation. The stratigraphic position can be used to reconstruct the sequence of events that took place in the region over time and to identify the influence of various factors on the formation and change of geological structures. The age of the evaporite formation in this region is estimated to be between 250 and 300 million years. This time interval indicates a long history of the formation of these deposits, which is associated with various geological processes and environmental changes over millions of years.

The economic significance of the Amu Darya syneclise's evaporite formations should not be overstated (Kerimkhulle *et al.,* 2023). These deposits represent a vast mineral resource, with potential applications ranging from common salt production to the extraction of valuable minerals. The mining and processing of these evaporites contribute significantly to the economies of the Central Asian countries, providing employment opportunities and driving industrial development (Morkun *et al.,* 2023). Moreover, the role of evaporite formations in hydrocarbon systems makes them crucial for oil and gas exploration and production in the region (Moldabayeva *et al.,* 2020; Pavliuk, 2023). González-Esvertit, Alcalde and Gomez-Rivas (2023) emphasise that the exploitation of the evaporite formation in the region not only contributes to oil and gas production but also represents a source of valuable mineral resources, which leads to strengthening economic stability and improving the socio-economic situation of the local population. The impact on the region's economy is manifested in an increase in its GDP by 5-10% per year. This process provides not only additional opportunities for economic development but also contributes to the creation of new jobs and improves the standard of living in society through increased income and investment in social programmes and infrastructure (Ismayilov, Fataliyev and Iskenderov, 2019; Mysak, Lys and Martynyak-Andrushko, 2017). The study of the Amu Darya evaporite formations also intersects with important societal challenges, particularly in water resource management. Salt dissolution from these formations can lead to salinization of aquifers, affecting both agriculture and drinking water supplies (Onopriienko *et al.,* 2023). Understanding the distribution, composition, and dissolution dynamics of evaporites is, therefore, crucial for developing sustainable water management strategies in the region (Matyushenko *et al.*, 2022; Pashaeva *et al.*, 2020). According to Oravecz, Héja and Fodor (2023), tectonic processes had a significant impact on the evaporite formation, leading to its complex deformation, and changes in its structure and properties. This has a significant impact on understanding the geological history of the region. Such tectonic deformations result in changes in the distribution of rocks, their texture, and the shape and size of sediments.

The cultural and historical significance of the Amu Darya evaporite formations adds another dimension to their study. The ancient Silk Road, which passed through this region, was partly driven by the salt trade. Studying the human interaction with these geological resources provides a perspective on the interplay between natural landscapes and cultural development. This is important for a deeper analysis of the historical processes of the region's formation and identification of factors influencing its current state.

Materials and Methods

Study Area

The Amu Darya syneclise is located in the most pubescent part of the Turanian plate, where this platform junctions with the Tien Shan and Afghanistan-Pamir Alpine epiplatform orogens. Geological mapping was a methodological approach based on a systematic survey of the earth's surface to determine the geological characteristics of the region. This method involved the following steps: a detailed survey of the territory, identification of geological structures, rock types, their distribution and relationship to each other. Fieldwork was carried out to study the landscape, mountain formations, river valleys and other relief elements to map and assess the overall geological structure of the region. Based on the data obtained, the rocks were classified according to their composition, texture, colour and other characteristics. The geological map also reflected the distribution of different types of rocks on the surface of the earth and their relationship to each other, which was used to describe the history of the region's formation and predict the availability of minerals or other geological resources. Thus, geological mapping has been an important tool for geological research, which obtained a detailed understanding of the structure and evolution of the Earth's crust in a particular region.

Figure 1: Map of the study area

Mineralogical Analysis

The mineralogical composition of the rocks was analysed by studying the mineral composition of the evaporite formation to determine the predominant minerals, their textures and characteristics. This analysis was used to identify the key minerals that make up the evaporite formation and assess their role in sedimentation processes. Texture analysis provided insight into the structure of the rock, while mineral characteristics (e.g., crystal shape, colour, transparency) indicated the conditions of deposition and the history of rock formation. This approach was used to expand the genesis of the evaporite formation and its properties, which was necessary for scientific and practical applications in geology, ecology, mining and construction.

Stratigraphic Analysis

The stratigraphic analysis was carried out by assessing the vertical and horizontal distribution of evaporite layers and associated rocks to determine the chronology of their formation and evolution. The study analysed the sequence and structure of the layers, and their location relative to other layers and rock formations, and compared them with data from other fields or regions. Assessment of the vertical distribution was used to establish the sequence of formation of the layers in geological time, and the horizontal distribution gave an idea of the spatial relationships between the sediments. These data clarified the age of the rocks and determined the history of their accumulation, including environmental changes, climatic factors and geodynamic processes. Stratigraphic analysis was used to reconstruct the geological history of the region and describe the processes that led to the formation of evaporites and associated rocks. These data are important not only for basic scientific research but also for practical use in geology, mining and natural resource assessment.

Geochemical Studies

Geochemical studies were carried out by analysing the chemical composition of rock samples to determine the content of various elements, their distribution in different parts of the formation, as well as their geochemical properties and characteristics. The research analysed rock samples for chemical elements such as metals, minerals, organic matter and other components. Hence, the chemical composition of the rock was determined, and the peculiarities of its composition in different parts of the formation were determined. The study of the distribution of elements in different parts of the formation described the processes that took place in the geological past, such as the conditions of rock deposition or changes in the environment. Geochemical properties and elemental characteristics also played an important role in analysing the impact of rocks on the environment, including aspects of ecology and geochemistry. Such geochemical studies were an important tool for understanding the geological processes that took place in the formation and had wide practical applications in geology, ecology, mining and the construction industry, as well as in other areas of geological research.

Results

The Amu Darya syneclise is a vast depression in Central Asia, located in Uzbekistan. The region is characterised by a variety of geological formations, including evaporite deposits (Komilova, 2021). Evaporites are sedimentary rocks formed as a result of high evaporation of water from seas or lakes, which resulted in the formation of mineral deposits such as salts and sulphates. These sediments often have characteristic textural and structural features that reflect the processes and conditions of their formation, which makes them interesting objects of study for geologists and other scientific researchers (Chang, Li and Lu, 2022). The process of good construction in pre-salt sediments is further complicated by the opening of high-pressure brines in the overlying saline

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sediments. The explosions were the main reason for the constraint on the development of the fuel and raw material base and the continuing uncertainty in assessing the prospects of the pre-salt complex in the southern sector of the Amu Darya oil and gas basin. Out of 29 exploration wells drilled in the XI Five-Year Plan in the radioactive region, 5 were completed, of which only 2 were in optimal conditions and produced gas.

The problem of successful construction and completion of wells in saline deposits is still relevant and economically feasible not only for Eastern Turkmenistan and Western Uzbekistan but also for other regions where saline deposits are a significant geological resource. The need to develop efficient technologies and methods for the extraction and management of these deposits is becoming particularly important in the face of the growing demand for salt and other useful components that can be extracted from these rocks. A successful solution to the problem of construction and operation of wells in saline deposits is also important for the sustainable development of the region, providing not only economic benefits but also reducing the negative environmental impact of mining and processing of minerals (Drizhd, Mussin and Alexandrov, 2019; Duffy *et al.*, 2023). The Amu Darya syneclise is in the most decertified part of the Turanian plate, in the area of its junction with the Tien Shan and Afghanistan-Pamir Alpine epiplatform orogens. The saline sediments are of the Kimeridge-Titonian age (Figure 2).

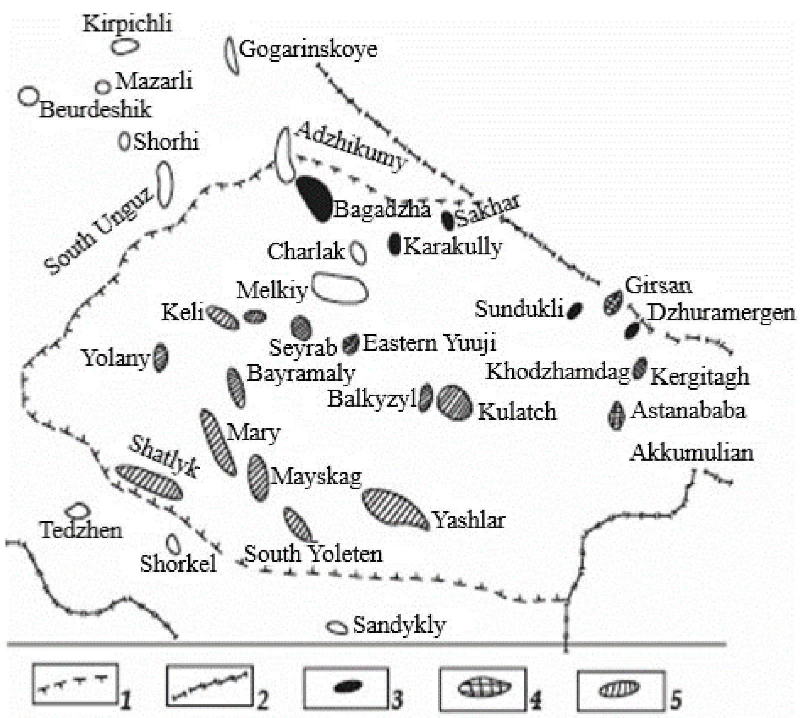

Figure 2: Overview scheme of oil and gas bearing areas in the Amu Darya oil and gas basin (Eastern Turkmenistan)

Notes: 1 – Upper Jurassic evaporite formation with a thickness of more than 500 m; 2 – border of the Republic; 3 – gas field within the structure with a rapture; 4 – gas and oil occurrences within the structure with a rapture; 5 – area with unclear prospects due to rapture.

The depth of the Kimeridzh-Tithonian roof reaches 3.5-4.0 km in the most submerged part of the Beshkent Trough and the area adjacent to the Patlyk Interbasin Eon to the north. Their capacity in the submerged part of the pool is up to 1200 m. The section of the salt mine, series consists of five formations:

- the lower one is carbonate anhydrite;
- lower halite;
- carbonate;
- upper halite; and
- carbonate-anhydrite overlapping the saline section.

The composition of the formations varies from the centre to the periphery, with sharp changes observed in the upper formation. In general, the section is composed mainly of colourless coarse crystalline salt, with brownish-red crystalline halite occurring closer to the roof, and the section is enriched with anhydrite and terrigenous material. The saturation of the sections with halite averages 65-70%, anhydrite – 25-30%, and carbonate rocks – 10% (Sirota *et al.,* 2020).

Despite the development of thick (over 200 m) "pure" halogen rocks in most of the Amu Darya region, the salt series is in a normal formation and does not form specific salt-dome shapes. The structure of sub-salt deposits is usually identical or similar to that of the super-salt sequence. In some cases, there is a shift in the sub-salt deposits relative to the super-salt deposits. This occurs along the long axis of local uplifts; this phenomenon is not observed on the wings of the uplifts. The set of local uplifts in the sub-salt sediments is shifting towards regional uplift of layers and a decrease in the thickness of the salt layer. Such phenomena are caused by the plastic properties of the salt section. Structures with pronounced salt tectonics in the Amu Darya syneclise are developed only along the Paleo-Amu Darya and Paleo-Murgab erosional sections.

The evaporite formation is considered a closed-type water supply complex, in contrast to the idea of it as a regional fluid support, meaning that there are no feeding and discharge areas. Evidence suggests that there are two types of brine occurrence in the Evaporite formation: in collector and non-collector rocks. First, brines are contained in reservoir formations composed of permeable carbonate and terrigenous rocks. These are the so-called water aquifers, which have a regional distribution controlled by the permeable rocks that make up them (Raad, Leonenko and Hassanzadeh, 2022). In addition to water occurrences associated with reservoir formations, the evaporite complex contains water occurrences directly in salt anhydrite deposits, which are fluid pores. These water manifestations are locally sporadic and tend to gravitate towards fracture systems. Two fracture systems should be distinguished among them due to fundamental differences in water flow prediction: of the first order, forming linearly elongated aeons of faults, and area development within the anticline structure. In contrast to fault zones resulting from large tectonic processes that break the continuity of the overlying and underlying rocks of the evaporite formation, the second-order fault system is smaller and is a benefit of the evaporite formation. Its formation is a consequence of the formation of an anticline fold with the involvement of plastic salt anhydrite deposits in folding (Pal *et al.*, 2023).

In the section of the evaporite formation, aquifers can be seen, separated by salt anhydrite deposits acting as fluidic retainers (Figure 3). The aquifers include carbonate and terrigenous deposits of the Sharapli horizon, inter-salt dolomites of the Iolotan horizon and sub-salt sulphate and carbonate deposits of the Sakar horizon. The aquifers are named after the typical areas where they have been discovered.

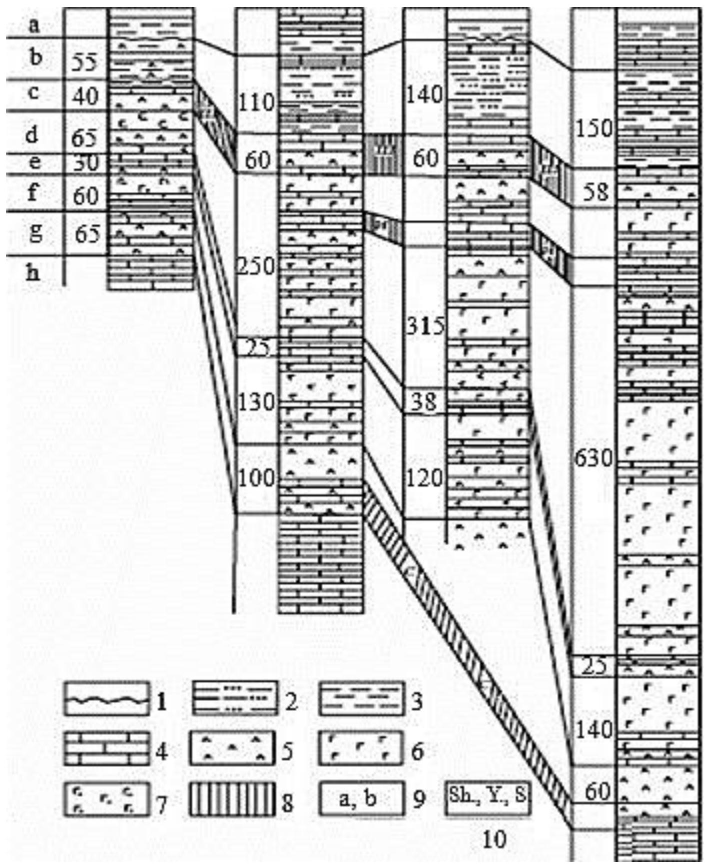

Figure 3: Scheme of comparison of sections of the evaporite formation

Notes: 1 – inter-formation erosion; 2 – siltstones; 3 – clays; 4 – limestones; 5 – anhydrites; 6 – salts; 7 – salts with terrigenous particles; 8 – aquifer: 9 – formations and age of sediments: a – Berrias-Barremian Stage (Terrigenous Red Formation); b – Titonian Stage (Karabilian Formation): c-g – formations of the Kimeridge-Titonian Stage (Evaporite Formation); c – upper anhydrite-carbonate; d – upper halite; e – middle anhydrite; f – lower halite; g – kerbonate-anhydrite; h – Oxford Stage (Carbonate Formation); 10 – aquifers: Sh. – Sharallinsky, I. – Iolotansky, S. – Sakarsky.

Aquifers have all the inherent features that allow them to be distinguished into an independent taxonomic unit (Luo *et al.*, 2022). They have a common chemical composition of brines and capacitance-filtration properties of rocks, facies ageing and hydrodynamic isolation, and common formation conditions. The clear confinement of the aquifer to the section and the commonality of the features give confidence in the reliability of the hydrogeological stratification of the section (Ismayilov, Iskenderov and Ismayilova, 2021; Murray and Power, 2021).

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The listed aquifers are closed. The Sharaplinsky water supply horizon crowns the evaporite formation. It is isolated from the overlying horizon by clays of the Valanginian age, and from the underlying horizon by the upper layers. The horizon is composed of fractured anhydrite in the eastern part of the basin or carbonates with clayey siltstone interbedded in the rest (Figure 4). The horizon is characterised by low thickness (10-20 m) in the axial zone (Sundukli). In the areas located in the southern half of the basin, its depth is 45-60 m (Karakel, Bayramali), and in the northern half – 30-90 m (Farab, Northern Balkui).

The Sharaplinian aquifer has been identified by many wells, including those that have contributed to the successful completion of the wells. During testing at the Bayramali, Sharapli, Keli, North Cheshme, Mary, East Shatlyk, South Yolotani, and Tarkhana areas, fluid inflows were obtained only at North Cheshme, Keli, and Sharapli, i.e., at areas located in the central part of the basin, where water-bearing sediments are carbonate (Table 1).

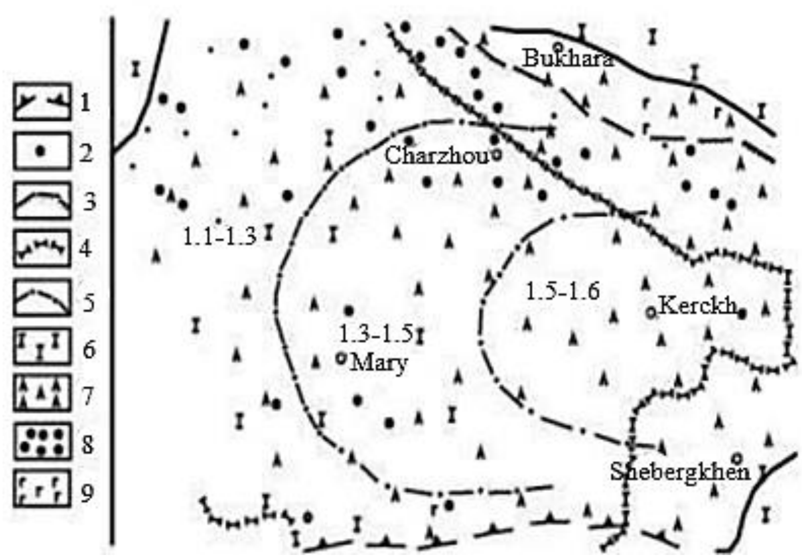

Figure 4: Schematic of the structure and distribution of the reservoir pressure anomaly coefficient (RPA) in the Sharallinsky aquifer

Notes: 1 – boundary of the evaporite basin; 2 – object carrying information; 3 – fault zone; 4 – border of the republic; 5 – RPA isolation; 6-9 – rock composition; 6 – carbonates, 7 – anhydrites; 8 – sandstones; 9 – salts.

Table 1. Test results of the Sharapla water aquifer

Area, well	*Interval, m*	*Brine flow rate, m^3/day*	*Density, g/cm^3*	*Impurity*
Sharapla, 1	2678-2738	1	1.05	Oil and gas
Sharapla, 3	283-2772	0.35	1.27	Oil
Sharapla, 4	2782-2715	0.43	1.24	-
Keli, 3	2906-2933	-	1.234	Oil
Northern Cesme	3188-3126	1.43	1.095	-

Source: Compiled by the author based on Abdullaev, Bogdanov and Eidelnant (2020)

It is noteworthy that in most areas, oil and gas inflows are obtained together with brine, but they are not of commercial importance. Brine flow rates are relatively low: 0.35-1.43 m^3/day. The reservoir pressure anomaly coefficient (RPA) in the Sharapli horizon in the central part of the basin does not exceed 1.3-1.5 (Sharapli, Keli); in the periphery, the RPA is lower, at 1.05-1.3. The brine is sodium chloride, less commonly sodium chloride-calcium chloride with a magnesium content of less than 15 g/l and a calcium content of less than 53 g/l. The density of the brine depends on the position of the object concerning the underlying halite pack. The highest density, up to 1.27 g/cm^3 (Sharapli-3), was recorded in contact with salts. Brine outflows are successfully suppressed by weighting the drilling mud to 1500-1600 kg/m^3 (Kulach-3, Astanababa-I, Keli-3). The aquifer is underlain by salts. The salts are 60-150 m thick and are composed of greyish-white or pinkish coarse crystalline rock salt. The Yolotan water supply aquifer is composed of dolomitic limestone and is developed in the central part of the basin.

Inter-salt dolomites have been tested at Bayramala, North Cheshma, East Shatlyk, Mayskoye, South Yolotan and East Uchadty. Of the above areas, fluid inflows were obtained at Bayramali, South Yolotan, and East Uchadzhi (Table 2).

Table 2. Results of testing of the Yolotan water horizon

Area, well	*Interval, m*	*Yield, m^3/day*	*Density, g/cm^3*
South Yolotan, 1	3481-3480	-	-
South Yolotan, 3	3634-3584	11.6	1.383
Vostochny Uchadzhi, 15	2680-2840	12.6	1.189

Source: Compiled by the author based Abdullaev, Bogdanov and Eidelnant (2020)

The South Yolotan field received an oil inflow of 6.8 m^3. The water content of the dolomitic limestone, as well as the Sharaplinian horizon, is low. Groundwater salinity corresponds to the water contained in the sediments formed in the salt basin. At South Yolotan-Z, brines with a mineralisation of 411.4 g/l of sodium chloride-sodium-calcium composition were obtained. Reservoir pressures at South Yolotan are 60.2 (well 1) – 58.0 MPa (well 3), with a pressure ratio of 1.73-1.61, respectively.

The aquifer is separated from the underlying Sakarskoye water supply aquifer by a substantial salt anhydrite formation. Directly beneath the Yolotan water supply horizon, there are salts up to 600 m thick. Their power is maximum in the axial zone. A well-aged bundle of inter-salt anhydrites stands out beneath the salts. Inter-salt anhydrides in the axial zone are exclusively greyish-white dense anhydrides enriched in places with inclusions and veins of carbonate material. The maximum thickness of the bundle (up to 200 m) can be traced in the Sundukla area. Inter-salt anhydrides were tested at Bayramala-2, Severny Cheshma-3, Yuzhny Yolotan-1, and Mayskoye-12. No inflows were received anywhere. The lower halite unit completes the thick salt-anhydrite fluidic support. It is represented by colourless coarse crystalline halite containing anhydrite inclusions and interlayers (Bondarev and Gheorghe, 2022; Kumar *et al.,* 2021). In the inner part of the basin, the thickness of the unit is maximum. Here, to the east of Bayramala, the thickness is up to 200 m, and in the structures of the southeastern end of the Charjou Stage – up to 200-250 m (Kultak, Pamuk). From here to the north, the capacity naturally decreases. South of the basin axial zone to the Karabilskoye uplift, the thickness of the formation varies from 65 to 140 m (Karakel, Bayramali). In the Shatlyk and Gaurdak areas, halites are replaced by sulphates and merged with the carbonate-anhydrite unit that makes up the Sakar water supply horizon.

The Sakar water supply horizon is composed of transitional carbonate-sulphate rocks and lies on the carbonate formation of the Kellaway-Oxfordian stages. The formation is composed mainly of anhydrites containing productive limestone and dolomite beds in the lower part of the section (Omidpour *et al.*, 2023). The maximum thickness is in the axial zone of the Bayramali Basin, Sundukli (80-130 m) and in the nearby structures of the Charjou Stage and Beshkent Trough (Kultak – 140 m, Shurtan – 100 m). The share of carbonate rocks is increasing in the areas of the Charjou Stage (Samantepe, Sakar, Metejan) (Figure 5). To the north, the thickness of the unit decreases from 50 m (Farab, Baba Arap) and 90 m (Bagadja) to complete wedging. Near the Badkhyz and Maimaninskoye uplifts, in the Shatlyk and Gaurdak areas, the unit merges with the overlying ones.

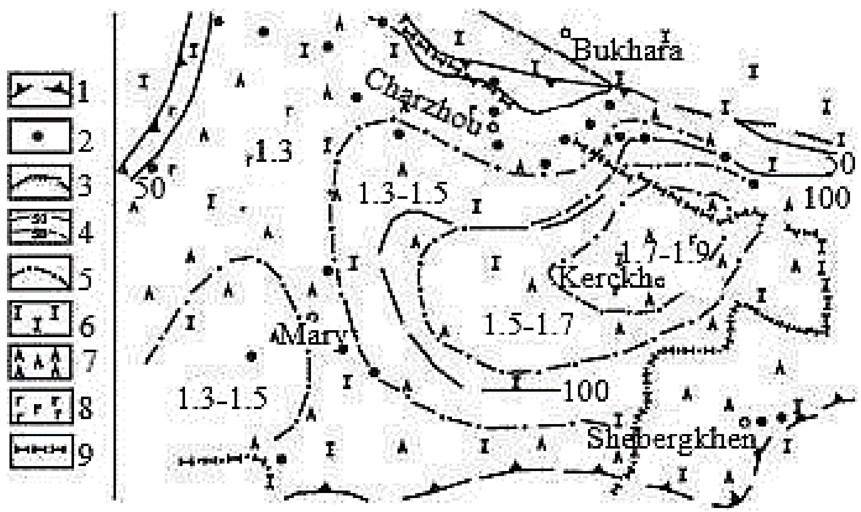

Figure 5: Scheme of the structure and distribution of the Sakara aquifer
Notes: 1 – boundary of the evaporite basin; 2 – object carrying information; 3 – fault zone; 4 – horizon thickness isolation (confident and assumed), 5 – RPA; 6-8 – rock composition: b – carbonates; 7 – anhydrites; 8 – salts; 9 – the border of the republic.

The water content of the sediments has been studied in almost all areas of the northern sector and some areas (Sakar, Uchadzhi, Khojambas, Astanababa, Sundukli, Samantepe) of the southern sector. The upper part of the aquifer, composed of sub-salt, i.e. basement anhydrite, was tested at Bayramali (wells 9, 11, 12), Severny Cheshm (wells 2, 3), and Yuzhny Yolotan (wells 1, 3). The water content of anhydrite is uneven and is caused by fractures. Of the above areas, brine inflows were obtained at Bayramali and South Yolotan (Table 3). In the Bayramali area, well 9 encountered self-pouring water with a flow rate of 86.4 m^3/day, while no self-pouring was obtained in well 12 when testing these deposits. The South Yolotan area received a joint inflow of water and gas with flow rates of 29.8 and 156 m^3, respectively. The widespread water content is associated with the underlying limestone formation with rare anhydrite and dolomite interlayers.

Table 3: Test results for basement anhydrite

Area, well	*Interval, m*	*Static brine level*	*Brine flow rate, m^3/day*	*Density, g/cm^3*	*Impurity*
Bayramali, 1	4471-4191	47-77	5.52	1982	1.227
Bayramali, 12	4312-4210		1.1	1766	1.14
South Yolotan, 3	3996-3978	166	29.8	Self-leach	1.094
Northern Cesme, 2				dry	
Northern Cesme, 3	3952-3900			dry	

Source: Compiled by the author based Abdullaev, Bogdanov and Eidelnant (2020)

For the horizon, a correlation between the RPA and the formation thickness has been established (Benincasa *et al.*, 2021). The maximum RPA, up to 1.8-1.9 and more, was obtained in the Sundukli area (Figure 5). The brine mineralisation in the Sakarska horizon is 160-340 g/l, which is significantly lower than the mineralisation of brines contained in the overlying sediments, but higher than in the underlying sediments, where the water mineralisation is 95.5-101.2 g/l. The dynamics of brine mineralisation change with depth can be seen in the Sakar field (Table 4).

Table 4: Variation of mineralisation with depth in the Sakar aquifer of the Sakar deposit

Well	*Interval, m*	*Mineralisation, g/l*
5	2698-2707	340.3
	2731-2729	260.9
	2750-2754	238.6
2	2601-2545	151.6
	2754-2673	141.9
	2814-2790	93.3
4	2668-2646	208.7
	2690-2696	187.4

Source: Compiled by the author based Abdullaev, Bogdanov and Eidelnant (2020)

Drilling experience shows examples of successful suppression of brine manifestations arising from the Sakara horizon. For example, at Astanababa, brine formation began at a drilling mud density of 1700-1800 kg/m^3. The manifestation was suppressed by weighting the drilling mud to 2200 kg/m^3. At Sundukli, Girsan and Tangykuduk, gas and water emissions were also prevented by weighted solutions (up to 2200 kg^3). In the evaporite water supply complex, three water supply horizons are distinguished, which are manifested in the central part of the basin, forming the full volume of water supply horizons. However, the Yolotan and Sharaplinian horizons are absent from the section towards the periphery of the basin. This indicates the nature and distribution features of the water-bearing horizons, which correspond to the facies zonation and conditions of formation of the saline formation in this region. This correspondence emphasises the importance of addressing geological factors when studying and exploiting aquifers as part of geological and engineering works.

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Discussion

The study of the geological structure of the evaporite formation of the Amu Darya syneclise has provided valuable results that are important for understanding the geological history of this region. The analysis of the main characteristics established that the evaporite formation consists mainly of salt and sulphate rocks with a characteristic crystalline and fine-grained texture. This indicates high evaporation of water in the past, which is a key factor in the formation of these deposits.

The facies zonation of the evaporite formation is an important aspect of its geological structure. Within the formation, several facies zones are distinguished, each characterised by a specific type of rock and the peculiarities of its accumulation (Kruglov *et al.*, 2023). The central zone is represented by thick salt strata, indicating high salt concentration in the past and intensive water deposition. The coastal zone is characterised by a predominance of carbonate and terrigenous rocks, indicating more coastal or marine deposition conditions. The transition zone between the central and coastal zones is characterised by a mixed carbonate-sulphate rock composition, reflecting transitional conditions during sedimentation. The study of facies zonation determined the conditions of evaporite formation and their distribution in the geological past of the area.

The results of the research conducted by Saidmambiyevna and Ugli (2021) found that geomorphological manifestations of evaporites, such as salt lakes and salt marshes, play a significant role in the ecological and geological history of the Amu Darya syneclise. These natural formations complement and deepen the understanding of sedimentation processes in the region, adding important aspects to its geological evolution. The data obtained coincide with the main statements made in the previous section and confirm the importance of high-water evaporation processes in the formation of evaporite deposits in the Amu Darya syneclise. These data complement and clarify the understanding of how these processes influenced the geological evolution of the region. Furthermore, the study confirmed the presence of geomorphological manifestations of evaporites, such as salt lakes and salt marshes, which underlines their importance for the ecological and geological history of the region. These observations are consistent with previously known information on geological processes in the area and deepen the understanding of sediment formation in the Amu Darya syneclise.

Brown *et al*. (2021), who studied the same geomorphological aspects, confirm the conclusion that the presence of salt lakes and salt marshes in the region is indicative of past climatic and geological processes. This is important for a deeper understanding of the formation of sediments in this syneclise. Geomorphological features, such as salt lakes and salt marshes, can serve as a kind of “archive” of past climatic and geological conditions, reconstructing the history of the region and assessing the impact of various factors on its formation. Such studies help expand knowledge of the geological and climatic history of the region, which is important for understanding its current state and developing effective strategies for managing its natural resources. It is worth noting that the discovery of these geomorphological features not only expands the understanding of the formation of evaporite deposits but also indicates the importance of regional climatic and geological processes for the formation of a unique geological and ecological environment in this area. The stratigraphic position of the evaporite formation indicates periodic changes in salt accumulation conditions, related to climatic fluctuations or tectonic activity in the region. These conclusions contribute to the understanding of the processes of sediment formation in this syneclise and their dynamics in geological time, which is relevant for further reconstruction of the history of this area.

Borrelli *et al*. (2021) determined that the identification of the significance of the stratigraphic position of the evaporites and its relationship with climatic and tectonic processes highlights an important aspect for a deeper understanding of the history and development of the geological structure of the Amu Darya syneclise. As such, studying the position of the evaporites in the context of stratigraphy can be used to assess the influence of various factors, such as climate change and geological shifts, on the formation and development of this region. These results confirm the above study, as they complement and deepen the understanding of sediment formation processes in the Amu Darya syneclise, as well as their connection with changes in salt accumulation conditions, which is an important factor for reconstructing the history of this geological area and the dynamics of its development in geological time.

The evaporite formation plays a key role in the region's economy due to the extraction of various valuable resources. In particular, the region is home to the extraction of salts, oil, gas and precious building materials, which contributes to the development of industry and job creation, as well as to the economic sustainability and prosperity of the region (Kondrat and Matiishyn, 2023). Xiao *et al.* (2021) emphasize that the economic significance of the evaporite formation is revealed not only through the extraction of salts and oil but also by creating conditions for the development of industry and infrastructure, which has a positive impact on the overall economic growth of the region. This includes creating new jobs, attracting investment, expanding production capabilities, increasing export flows and stimulating the development of small and medium-sized businesses. These results confirm the above study, as they demonstrate the importance of the economic contribution of the evaporite formation to the region, supporting its infrastructure, providing jobs and contributing to the development of industry and raw materials, which is a key factor for the economic sustainability and growth of the region. Tectonic processes had a significant impact on the formation of the evaporite formation. It is positioned in a folded platform cover, which indicates that it has been deformed by folds and faults of different ages and amplitudes. These structural changes in the geological past of the region were essential for shaping the distribution and properties of evaporite deposits.

Habiballah, Witam and Ibnoussina (2022) note that the impact of tectonic processes on the evaporite formation is reflected in various types of deformation, which enriches the understanding of its formation and the dynamics of geological processes in this area. These deformations may include shear, folds, faults, and other changes in the structure and shape of the rock. Horizontal landslides are characterized by the movement of rock blocks over a distance of up to 10 km. Vertical shifts involve the uplift or down lift of rock blocks by up to 500 m. These two types of deformation reflect different aspects of tectonic processes that can occur in a geological area and affect its structure and properties. The diversity of deformation types indicates the large amounts of tectonic processes occurring in the region over time. Analyzing the results and conclusions obtained, it is possible to conclude that tectonics hold substantial position in the formation and deformation of the evaporite formation in this area. These data underline the need for further research into tectonic processes to better understand the geological history of the region and its impact on the formation of natural resources and geological structures.

In the context of practical application, the results of the study are of significant importance for various industries and spheres of science. For instance, the data obtained on the composition and structure of the evaporite formation can be used to optimize the extraction of minerals from these deposits. In addition, an in-depth understanding of the geological structure can be used to develop more effective strategies for natural resource management, which is substantially relevant for the further improvement of sustainable development of the ecological and economic systems of the region.

Conclusions

Analysis of the lithological composition of the evaporite formation showed a predominance of salt rocks such as halite, sylvinite, gypsum and anhydrite. These findings indicate processes of high-water evaporation and salt deposits in the past. In addition, the evaporite formation contains carbonates (dolomites, limestones) and terrigenous rocks (sandstones, siltstones, clays), which indicates a variety of deposition processes and rock evolution. Another important aspect of the study is the stratigraphic analysis, which was used to determine the vertical and horizontal distribution of evaporite and associated rocks. This distribution indicates periodic changes in the conditions of salt accumulation, possibly related to climatic fluctuations or tectonic activity in the region. Geomorphological occurrences of evaporites, including salt lakes and salt marshes, have also been identified, confirming their importance to the environmental and geological history of the region.

The evaporite formation plays a key role in the region's economy as it contains various valuable resources. It produces salts such as halite, sylvite and gypsum, which are widely used in industry, agriculture, medicine and other sectors. Oil and gas are also important resources extracted from the evaporite formation, which contributes to the development of the oil and gas industry and energy supply in the region. The studies revealed that in the Sakar field, the change in mineralisation in the Sakar aquifer with depth is variable: for instance, in hole 5 mineralization was 340.3 g/l in the interval 2698-2707 m, 260.9 g/l in the interval 2731-2729 m and 238.6 g/l in the interval 2750-2754 m, while in hole 2 it was 151.6 g/l in the interval 2601-2545 m, 141.9 g/l in the interval 2754-2673 m and 93.3 g/l in the interval 2814-2790 m. There is also a difference in brine flow rate and density in different wells: for example, in the Bayramali 1 well, the brine flow rate was 47-77 m^3/day, with a density of 5.52 g/cm^3 and an impurity of 1.227, and in the Sharapli 3 well, the brine flow rate was 1.43 m^3/day, with a density of 1.095 g/cm^3. It is also worth noting the presence of various impurities, such as oil and gas, in the Sharaplinka water aquifer, which is important for assessing the field's potential and developing appropriate production technologies.

The findings have important implications for environmental management strategies. Understanding the lithological composition and stratigraphic distribution of the evaporite formation aids in predicting areas of high resource potential and guides sustainable extraction practices. The identification of geomorphological occurrences, such as salt lakes and marshes, informs the conservation of these unique habitats and their ecological functions. Additionally, recognizing the impact of historical climatic and tectonic events on salt accumulation patterns can help anticipate future changes and develop adaptive management plans. Effective environmental management strategies should incorporate this geological and environmental knowledge to balance resource utilization with ecological preservation

For a more complete understanding of the evolution and dynamics of the evaporite formation of the Amu Darya syneclise, additional research is needed to analyses palaeoclimatic data, interrelationships with the tectonic history of the region, and the underlying geological processes that determine the formation and alteration of rocks over time.

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Author's Declarations and Essential Ethical Compliances

Author's Contributions (in accordance with ICMJE criteria for authorship)

This article is 100% contributed by the sole author. He conceived and designed the research or analysis, collected the data, contributed to data analysis and interpretation, wrote the article, performed critical revision of the article, edited the article, and supervised and administered the field work.

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Research involving human bodies or organs or tissues (Helsinki Declaration)

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