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Transgressions and Regressions of the Mesozoic and their Role in the Formation of Bar Reservoirs in the Northern Part of the Turan Plate: New Prospects for Hydrocarbon Exploration

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Abstract

The depletion of conventional structural traps necessitates exploration of lithologically and stratigraphically controlled hydrocarbon reservoirs. This study examines the genesis and distribution of sand bar reservoirs formed during Mesozoic transgressive–regressive cycles in the northern Turan Plate, including Mangyshlak, Buzachi, Northern Ustyurt, and the northwestern Aral Sea. Integrated sedimentological, paleogeographic, and tectonic analyses reveal key transgressive phases in the Middle–Late Jurassic and Late Cretaceous that led to the formation of high-quality bar complexes in nearshore, shelf, estuarine, and deltaic environments. These sand bodies exhibit favorable reservoir properties but significant heterogeneity and complex architecture. Most research in this region has focused on petroleum geology, reservoir characterization, paleogeography, and stratigraphy, while gaps remain in coastal–marine geology, geophysics, and environmental–geochemical studies. The most favorable reservoirs occur in the Middle and Late Jurassic, whereas the Early Cretaceous and Triassic are less prospective. A new methodological framework is proposed, integrating high-resolution seismic stratigraphy, geochemical profiling, machine learning, and digital twin technologies. Mesozoic bar-type reservoirs represent promising exploration targets, underscoring the need for coordinated efforts among scientific, governmental, and industrial sectors to unlock their hydrocarbon potential.

Keywords: Mesozoic transgressions and regressions; Sand bar reservoirs; Turan plate; Lithological traps; Hydrocarbon exploration.
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1. Introduction

In the current stage of development of the oil and gas industry, marked by the depletion of conventional structural traps and the increasing significance of lithologically and stratigraphically controlled hydrocarbon accumulations.[1] The study of lithological natural hydrocarbon reservoirs has acquired particular scientific and practical importance.[2] Among the most effective lithological traps are sandy bars and dunes formed in shallow marine settings, coastal accretion zones, and terrestrial shoreline complexes.[3] These sedimentary bodies develop in dynamic depositional environments influenced by currents, wave action, and tidal processes, which contribute to the reworking, sorting, and redeposition of terrigenous material.[4] The genetic features of their formation, internal architecture, grain-size distribution, and spatial isolation of bar complexes, together with favorable reservoir properties such as porosity and permeability, result in a highly complex reservoir structure.[5]

The formation of lithological traps is associated with successive stages of sediment accumulation and stratigraphic evolution, which necessitates the application of an integrated approach to their study.[6] The most informative methods include high-resolution seismic stratigraphy, detailed sedimentological analysis of core material, petrophysical investigations, and geostatistical modeling of reservoirs.[7] The integration of data across various scales enables the identification of prospective zones for the development of bar and dune reservoirs and the refinement of models describing their spatial variability within sedimentary basins.[8,9] Several

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Table 1: Bar-type hydrocarbon traps: Classification and global examples.

S. No	Type of Bar Trap	Example Field	Basin / Region	Age	Reference
1	Shoreface-marine bars	Cotton Valley	East Texas, USA	Jurassic	Hamlin, 1988
2	Shoreface-marine bars	Yates Field	Permian Basin, USA	Permian	Galley, 1958
3	Shoreface-marine bars	Pohokura Field	New Zealand	Pleistocene	King *et al*., 2004
4	Deltaic bars	Brent Group	North Sea, UK	Jurassic	Spencer & Plint, 1995
5	Deltaic bars	Statfjord Field	North Sea	Jurassic	Tyler *et al*., 1991
6	Estuarine bars	Alwyn North	North Sea	Triassic–Jurassic	Emery & Myers, 1996
7	Fluvial bars	Marmaton Sandstone	Oklahoma, USA	Permian	Brown, 1969
8	Intra-facies lateral traps	Panoma Gas Field	Hugoton, USA	Permian	Franseen *et al*., 2004
9	Supra-facies bars beneath seals	Norphlet Formation	Gulf of Mexico, USA	Jurassic	Salvador, 1987
10	Isolated submarine bars (turbidites)	Deepwater Gulf of Mexico	Gulf of Mexico	Cenozoic	Weimer, 1989

techniques can aid in the identification and development of deposits in Bar-type traps, including 3D seismic exploration and modern drilling methods.[10]

Bar-type traps are often characterized by complex internal heterogeneity (varied lithologies within a single bar), which must be carefully considered in reservoir modeling.[11-14] In this context, it is appropriate to examine the types and classifications of bar traps based on contemporary approaches developed from stratigraphic, sedimentological, and geophysical studies.[15-18] The complex nature of bar reservoir formation has necessitated the development of various classification schemes that reflect not only their structural and stratigraphic characteristics but also the patterns of their spatial distribution.[19] For a more comprehensive understanding of the mechanisms of hydrocarbon accumulation in bar-type traps, it is essential to refer to the classification of sandy bars that takes into account the influence of depositional dynamics, tectonic setting, lithological heterogeneity, and subsequent diagenetic alteration of reservoir rocks.[20] Sandy bars that serve as oil and gas traps can be classified according to their genetic origin into the following types: shoreface-marine, deltaic, estuarine, fluvial, and deep-water turbiditic formations.[21,22] For each of these categories, there are well-documented field examples worldwide that demonstrate the high hydrocarbon potential of bar-shaped reservoirs (Table 1).

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1.1 Examples of oil and gas fields associated with sandy bars

North Sea Basin Fields (United Kingdom, Norway). Fields such as *Brent*, *Statfjord*, and *Oseberg* are associated with ancient barrier sand bodies and shoreface bars of Jurassic age. The characteristic of these fields can be summarized as follow: Hydrocarbon accumulations are localized within high-porosity sandstones of ancient coastal and bar complexes overlain by marine shales.[23-25]

Permian Basin Fields (USA). Significant oil and gas accumulations have formed within Permian-age sandy bars and barrier islands (*e.g.*, in the *San Andres* Formation). The combination of porous bar sandstones and effective seals (compacted carbonate layers) creates favorable conditions for trap formation.[26,27]

Book Cliffs Formation Fields (Utah and Colorado, USA). Oil-bearing sandy bodies are associated with paleobars and barrier systems along the shorelines of Mesozoic seas. Large lithostratigraphic traps formed within coastal sandy bars.[28,29]

Norphlet Formation Fields (Gulf of Mexico, USA). In the well-known *Norphlet Sandstone* formation, gas accumulations are associated with ancient eolian-marine bars of Late Jurassic age. High-quality sandy reservoirs derived from ancient dunes and bars, sealed by salt domes and marine deposits.[30]

Eastern Pre-Urals Fields (Russia). In the Eastern Pre-Urals region, oil accumulations are known to be associated with lower Permian shoreface bars and barrier islands (*e.g.*, fields in the Solikamsk area). A combination of paleogeographic bars and lithostratigraphic traps (Fig. 1).[22,31,32]

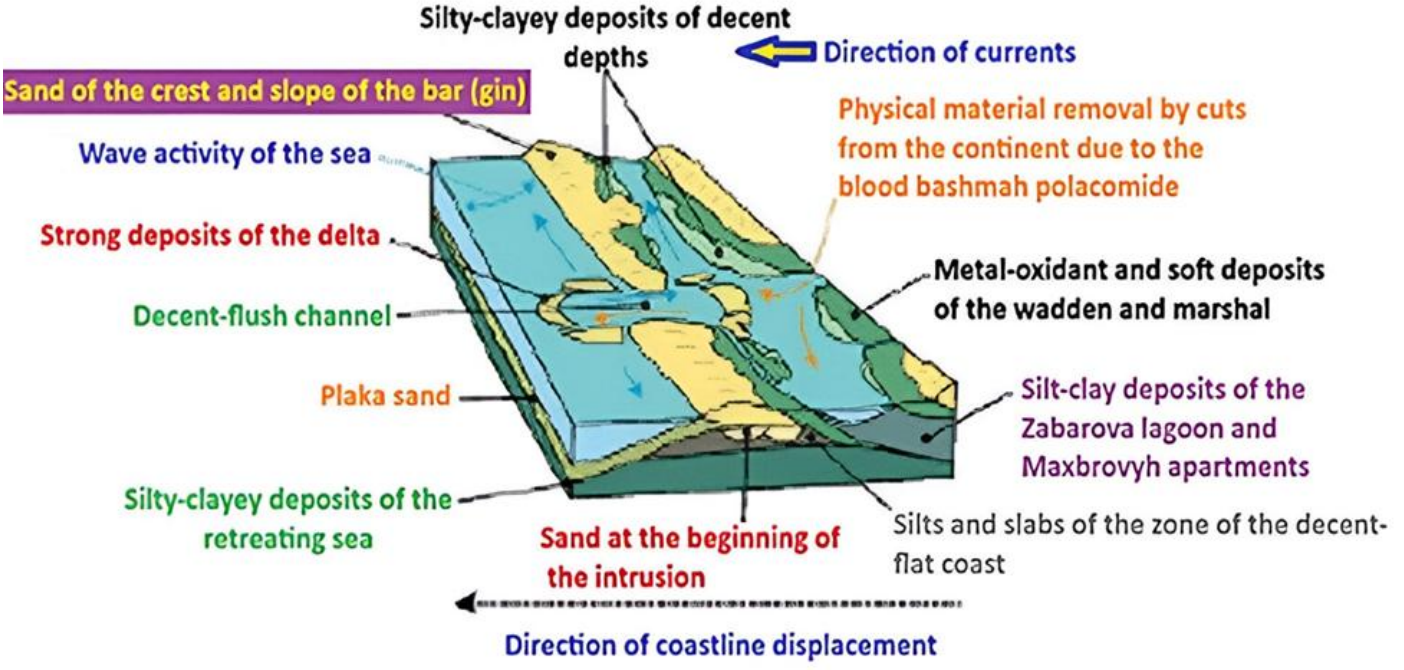


Fig. 1: Conceptual model of the coastal shallow water zone under conditions of sea regression, reflecting the sedimentation conditions in the territory of the Lodochny Val at the time of formation of the deposits of the Lower Kheta suite (Berriasian – Early Valanginian) Reproduced from.[33]

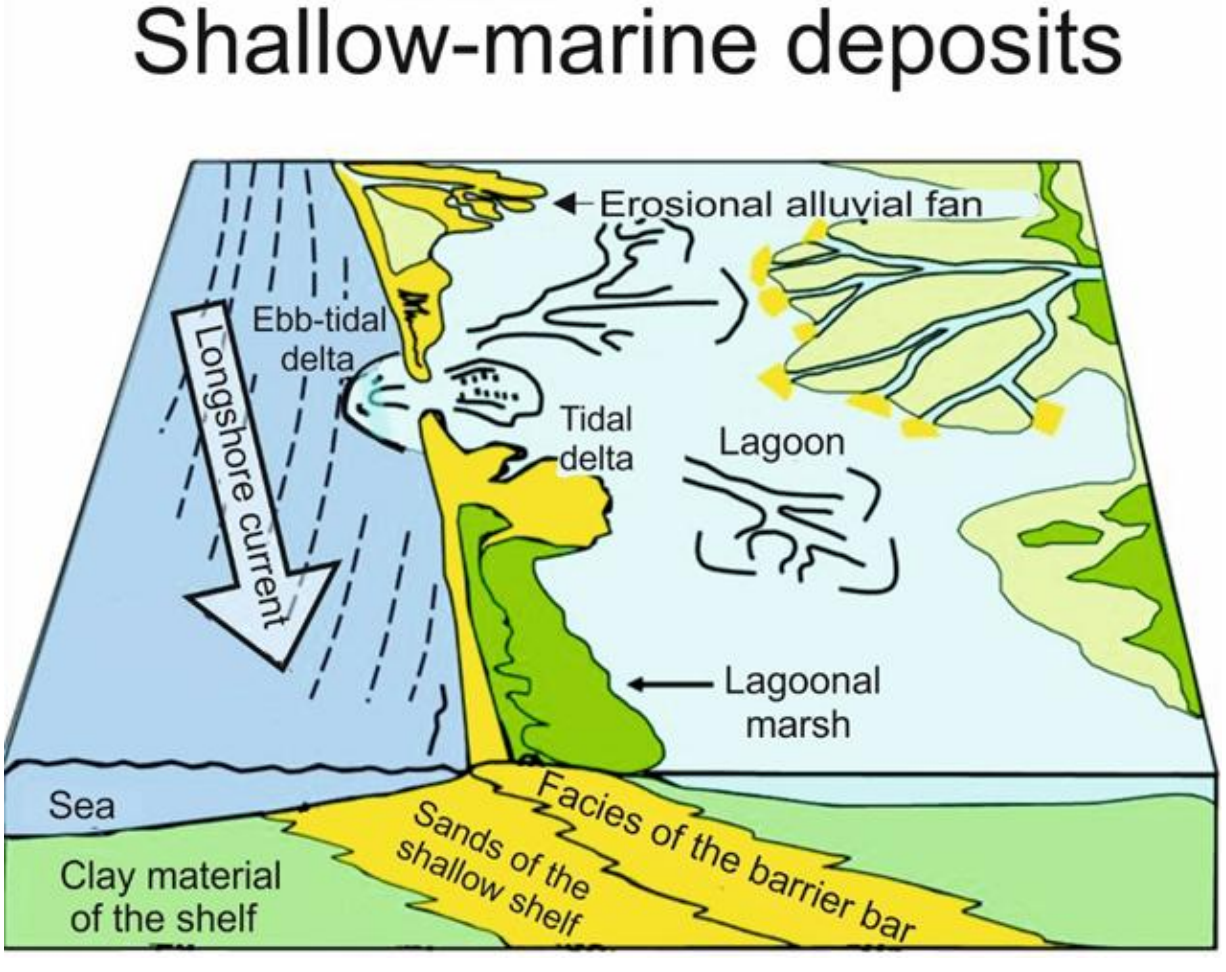


Fig. 2: Role of sedimentological models in Electrofacial Analysis of Terrigenous Deposits Reproduced from.[34]

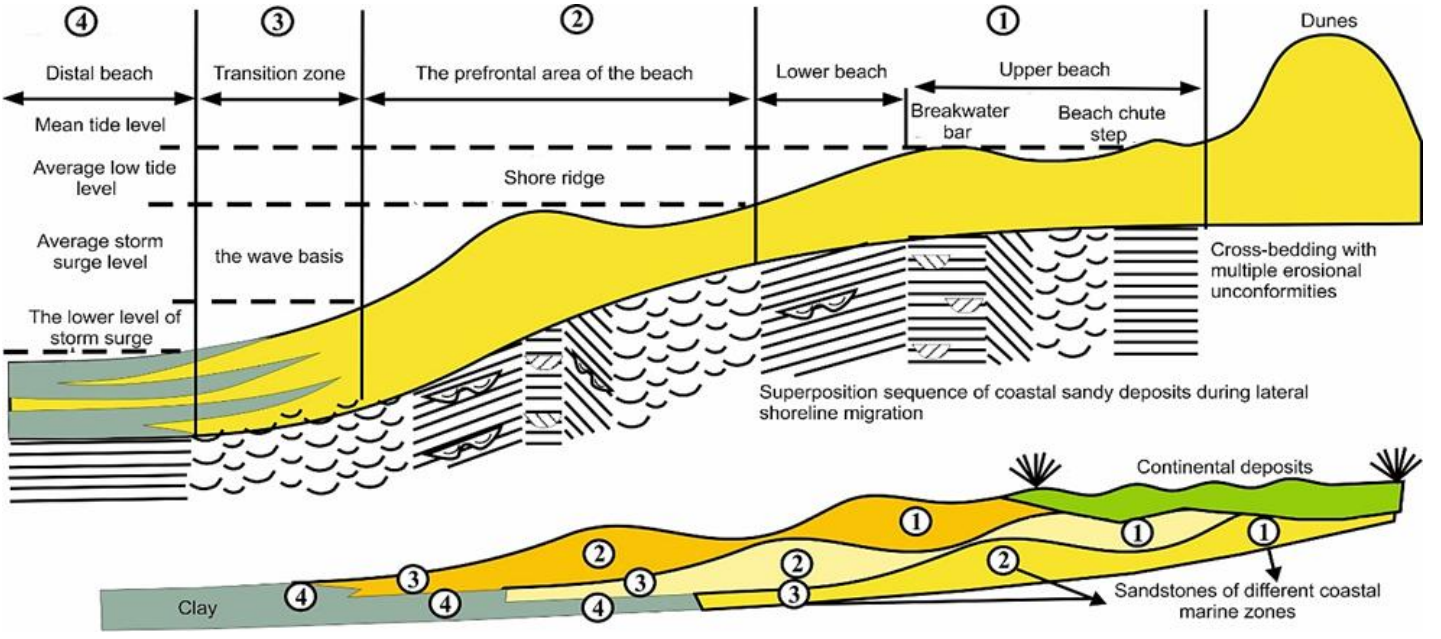


Fig. 3: Scheme of geomorphological units of the coastal zone and the relationship between the textures of seabed sediments in the coastal zone reproduced from.[34]

1.2 Deposits of transitional and marine facies

When interpreting deposits of transitional and marine facies groups, it is necessary to count the stages of tectonic development of the sedimentary basin (transgressive, regressive) and the hydrodynamic regime of the sea coast (wave, tidal, storm).[34] Transgressions and regressions affect the volumes of clastic material supplied to the sedimentation basin and the "expressiveness" of facies settings in the sedimentary section.[35] Under regression conditions, the supply of terrigenous material increases due to a decrease in the erosion base. The predominantly slow development of regressions is accompanied by successive layering of sediments in the section formed within the distant, transitional, pre-frontal and beach zones of the sea coast (Figs. 2 and 3).[34]

The spatial relationship of specific facies settings in the conditions of a stable sea coast (Fig. 4) is controlled by the type of its hydrodynamic activity (storm, wave, tidal), which also predetermines the type of deltas of the sea basin (tidal, wave, river).[36] Thus, predominantly tidal processes are capable of redistributing terrigenous material over large areas both in the landward direction and in the seaward direction, forming sandstones of the cover type within the beach, pre-frontal, transitional zones and reservoirs of the "laced" type in the shelf area (tidal bars) and tidal plain (tidal channels).[37] Wave processes with a deficit of clastic material are favorable for the formation of far-zone bars, barrier bars and lagoons. The storm coast is characterized by the formation of a community of sandy bar structures of the erosional-accumulative type, tidal deltas and storm sandstones[38] (Fig. 5).

Thus, sandy bars represent one of the most significant lithological traps, characterized by considerable variability in formation conditions, morphology, and lithological composition.[39-41] Their successful development in the North Sea, the Permian Basin (USA), and the Gulf of Mexico shelf confirms the potential of such objects for exploration and prospecting operations.[42] The classification of bar formations and their role in the formation of hydrocarbon lithological traps allow for the analysis of the conditions of their development in specific geological settings.[43-45]

The Turan plate has traditionally been studied from the standpoint that the tectonic structures were based on the ultimate folding period.[46-50] The tectonic development of the Caspian Depression and the Turan Plate, located in the northern part of the Caspian Sea, has been regarded as distinct. The only similarity between these structures is their shared oil and gas resources.[51-53] Many studies have been focused on structural constructions on the sidelong movement of vast lithosphere plates over giant distances.[54-56] Two-level plate tectonics in the expansion of Paleozoic constructions of the Turan territories was explored to bind the formation of regional folded structures with global plate tectonics in the Paleozoic.[57-60] The tectonics of plates in the Paleozoic (Neoproterozoic-Paleozoic) at its global manifestation in the Mesozoic-Cenozoic was discussed based on the ophiolitic zones of the Paleozoic.[61-63] The tectonic zoning issues and geodynamics of the jointed tectonic structures formation within the North Caspian oil and gas basin in the East European Precambrian Craton and the Turan plate of

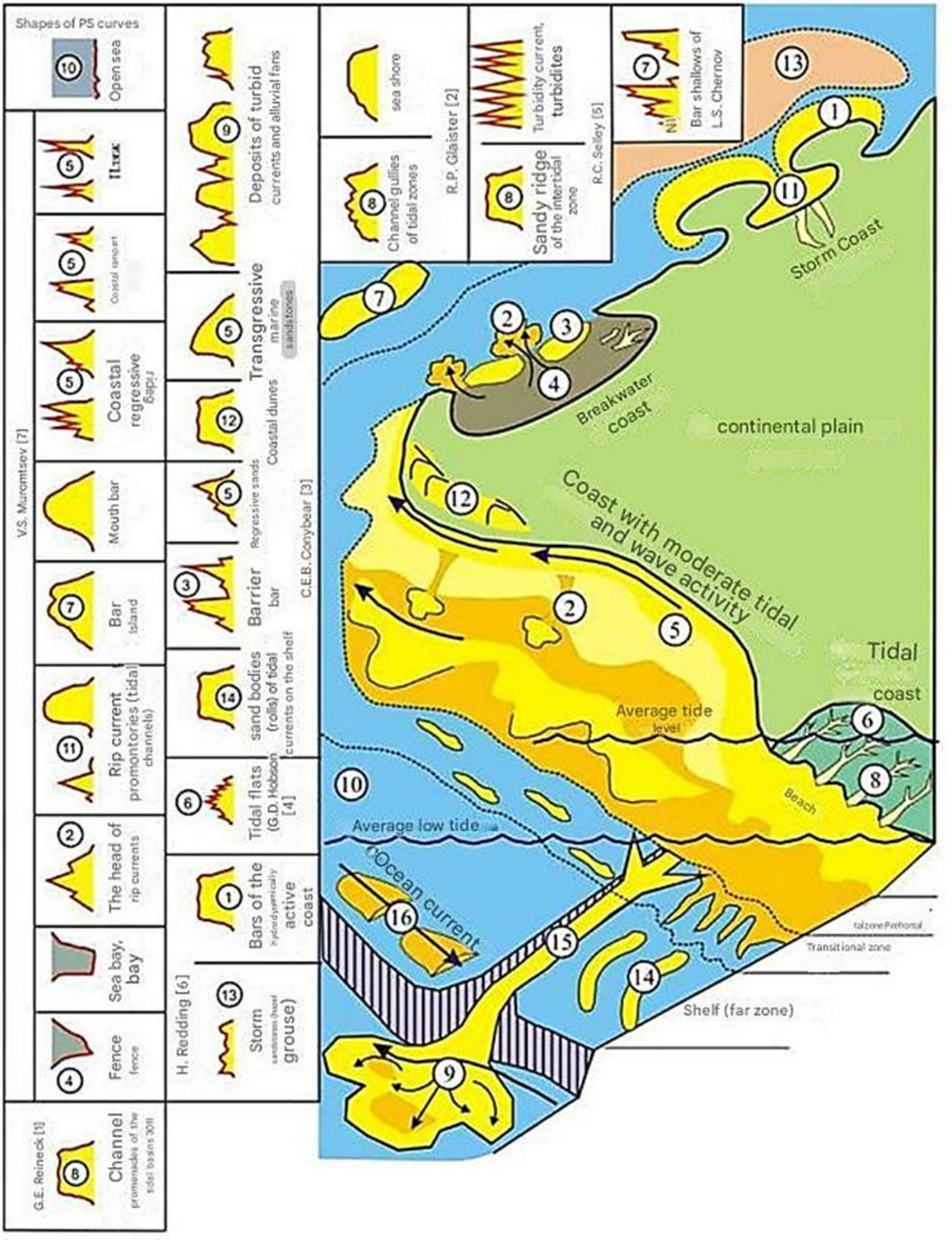


Fig. 4: Facies interpretation of the PS curve for marine sediments: 1) bar island; 2) gullies and rip current heads; 3) barrier bar; 4) behind-bar lagoon; 5) beach, coastal ridge (transgressive and regressive beach sands); 6) tidal zone with a sleeve-like system of channel gullies; 7) far-zone bars and sand banks; 8) tidal channels and ridges; 9) deep-water alluvial fan; 10) clayey shelf sediments; 11) tidal deltas; 12) dunes; 13) storm sands; 14) sand bars of tidal currents; 15) submarine valley; 16) submarine dunes Reproduced from.[34]

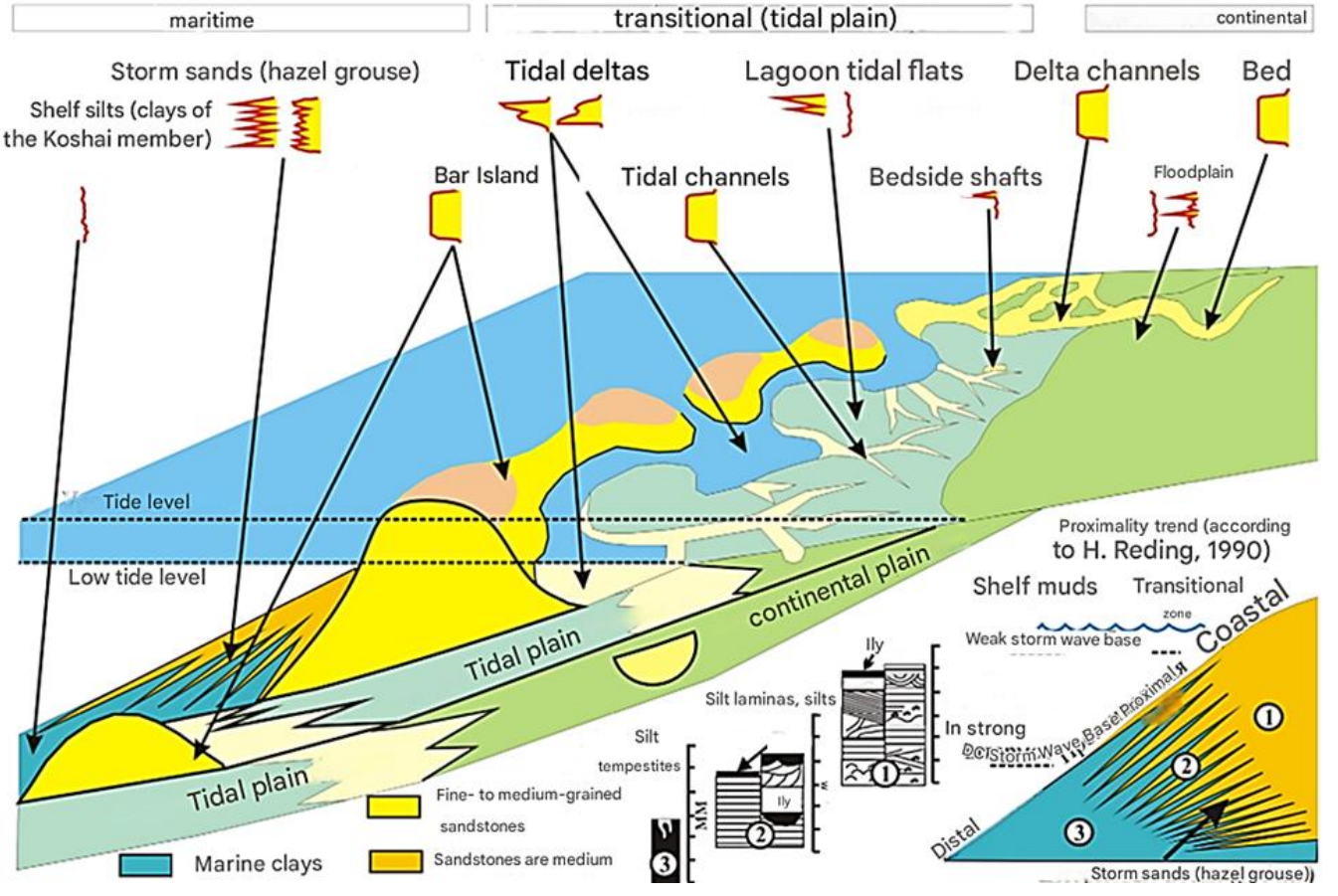


Fig. 5: Sedimentation model of the storm coast (conditions of formation of the Barremian-Aptian sand layers of group A1 of the West Siberian Lowland) reproduced from.[34]

Cimmerian (Mesozoic) folding.[64-66]

The relevance of this research direction is driven by the need to expand the mineral resource base through the involvement of hard-to-recover resources, as well as by the increasing complexity of the geological structure of prospective targets, where classical structural elements are weakly developed or entirely absent. The aim of this article is to conduct a comprehensive analysis of the Mesozoic transgressions and regressions in the territories of Mangyshlak, Buzachi, North Ustyurt, and the northwestern Aral Sea region, identify the patterns of lithological trap formation within bar complexes, and substantiate their potential in the hydrocarbon system of the region. It is important to note that the studied area has been unevenly explored, which necessitates further detailed investigations to gain a more accurate understanding of its geological structure and hydrocarbon potential.

2. Geological setting

Within the northwestern part of the Turan Plate, the Mesozoic era provided all the necessary tectonic and paleogeographic conditions for the formation of bar complexes,[67] which are prospective from the viewpoint of hydrocarbon potential. The northwestern part of the Turan Plate, encompassing the territories of Mangyshlak, the Buzachi Peninsula, North Ustyurt, and the northwestern Aral Sea region, represents a unique geological area, characterized by complex interactions of tectonic, paleogeographic, and climatic factors throughout the Mesozoic era[68-71] (Figs. 6 and 7). These regions, located within modern Kazakhstan, demonstrate a variety of lithofacies complexes shaped by active tectonic processes that resulted in alternating transgressions and regressions.[72] The Mesozoic era (252–66 million years ago) was a time of significant geodynamic changes, including the breakup of Pangaea, the formation of new oceanic basins, and the activation of tectonic processes, which had a profound impact on the paleogeography of the region.[73-75] The alternation of marine transgressions and regressions led to the formation of diverse sedimentary complexes, including bar and dune formations, which possess potential as hydrocarbon reservoirs.[76-78]

Despite significant progress in the study of hydrocarbon-bearing complexes in the region, many aspects of the formation and spatial distribution of lithological traps,

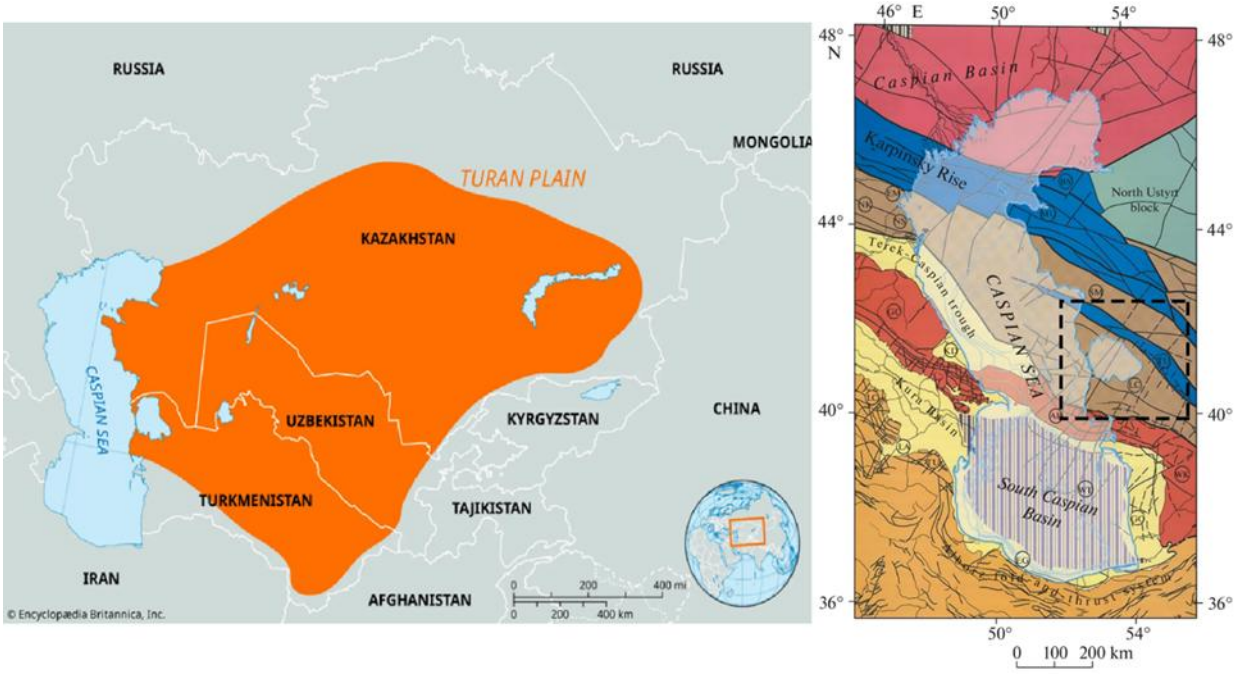


Fig. 6: A- Location of the Turan Plate (https://www.britannica.com/place/Turan-Plain), B- Tectonics of the Basement of the Turan Plate reproduced from.[46]

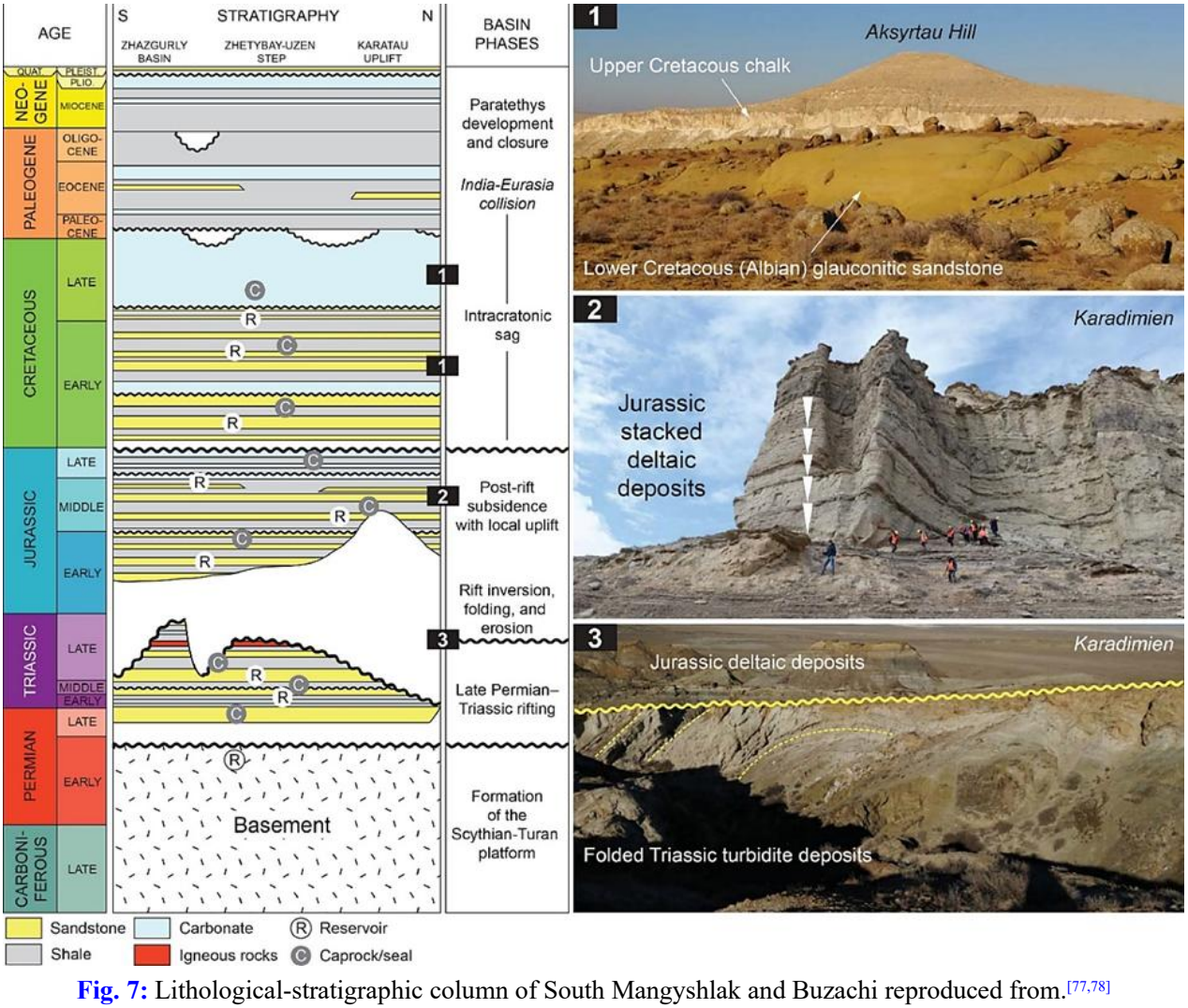


Fig. 7: Lithological-stratigraphic column of South Mangyshlak and Buzachi reproduced from.[77,78]

particularly bar reservoirs, remain insufficiently explored.[79,80]. This is partly due to the high complexity of the geological structure and the multiple changes in sedimentary environments in response to Mesozoic tectonic processes.[81,82] Of particular interest are the bar complexes that formed under conditions of dynamic alternation between marine transgressions and regressions, as their spatial distribution and reservoir properties are largely controlled by large-scale geodynamic events. Given the above, an important step in the research is the reconstruction of the main geodynamic factors that determined the transgressive-regressive cycles in the northwestern part of the Turan Plate throughout the Mesozoic era. Analyzing the evolution of the tectonic regime, sea-level changes, and associated sedimentary systems will allow for a more substantiated identification of promising areas for the development of bar reservoirs.

3. Surveying of the studies related to the bar reservoirs for the mesozoic era in the northern part of the turan plate

3.1 Dynamics of transgressions and regressions during the mesozoic and conditions for the formation of bar complexes

Throughout the Mesozoic era, the territory of Mangyshlak, Buzachi, North Ustyurt, and the northwestern Aral Sea region underwent significant paleogeographic changes associated with alternating transgressive and regressive phases.[83-86] These changes determined the sedimentary environment, controlled sedimentation processes, and consequently influenced the formation of lithological traps of the bar type.[87,88]

Triassic – Lower Jurassic: Dominance of Continental Conditions. During the Triassic period and the early Jurassic (from the Lower Jurassic to the second half of the Middle Jurassic), continental sedimentary conditions dominated the majority of the study area, with coastal plains observed only in the extreme western part of the region[89,90] Sedimentary processes were primarily alluvial and lacustrine-alluvial in nature.[91,92] The formation of bar complexes during this period was absent, as the marine environment had not yet extended into the region. In the context of plain river systems, sandstones, clays, and aleurites accumulated, but these deposits generally lacked the typical structure and texture characteristic of bar formations.[93] Thus, the Triassic and early Jurassic periods are characterized by the absence of shallow marine bar formations, which can be attributed to the isolated position of the region from the global ocean and the dominance of landmasses.[94]

Middle Jurassic (Late Bathonian and Kimmeridgian): Onset of Transgression. The situation changed during the second half of the Middle Jurassic, when the first significant transgression began. The sea advanced onto the territory of Mangyshlak and Buzachi, creating coastal and shelf sedimentary environments.[95,96] The sedimentary systems became more complex due to the influence of wave reworking and tidal currents.[96,97] In the developing shallow shelf environment, coastal tidal-wave bars started to form. It can be assumed that these bars were characterized by the

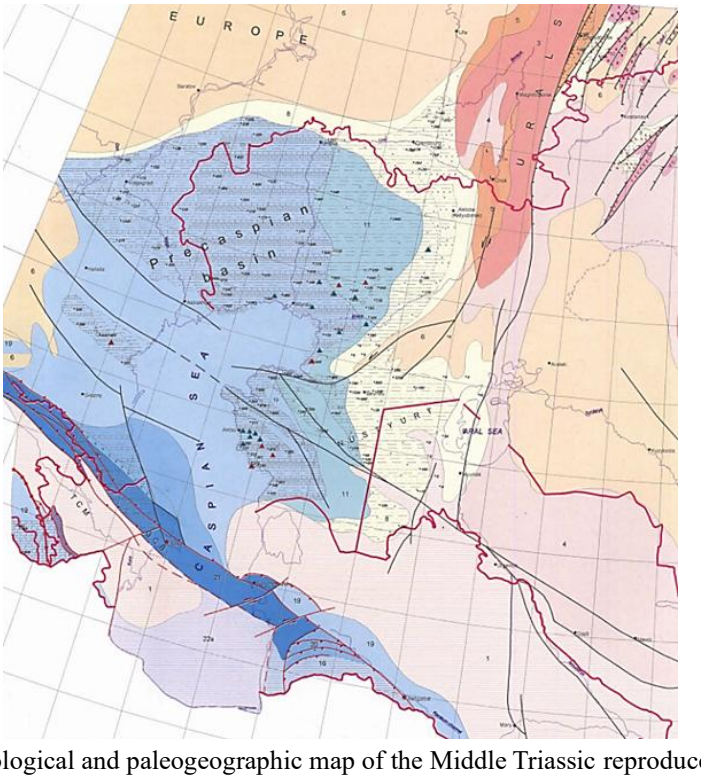


Fig. 8: Lithological and paleogeographic map of the Middle Triassic reproduced from.[96]

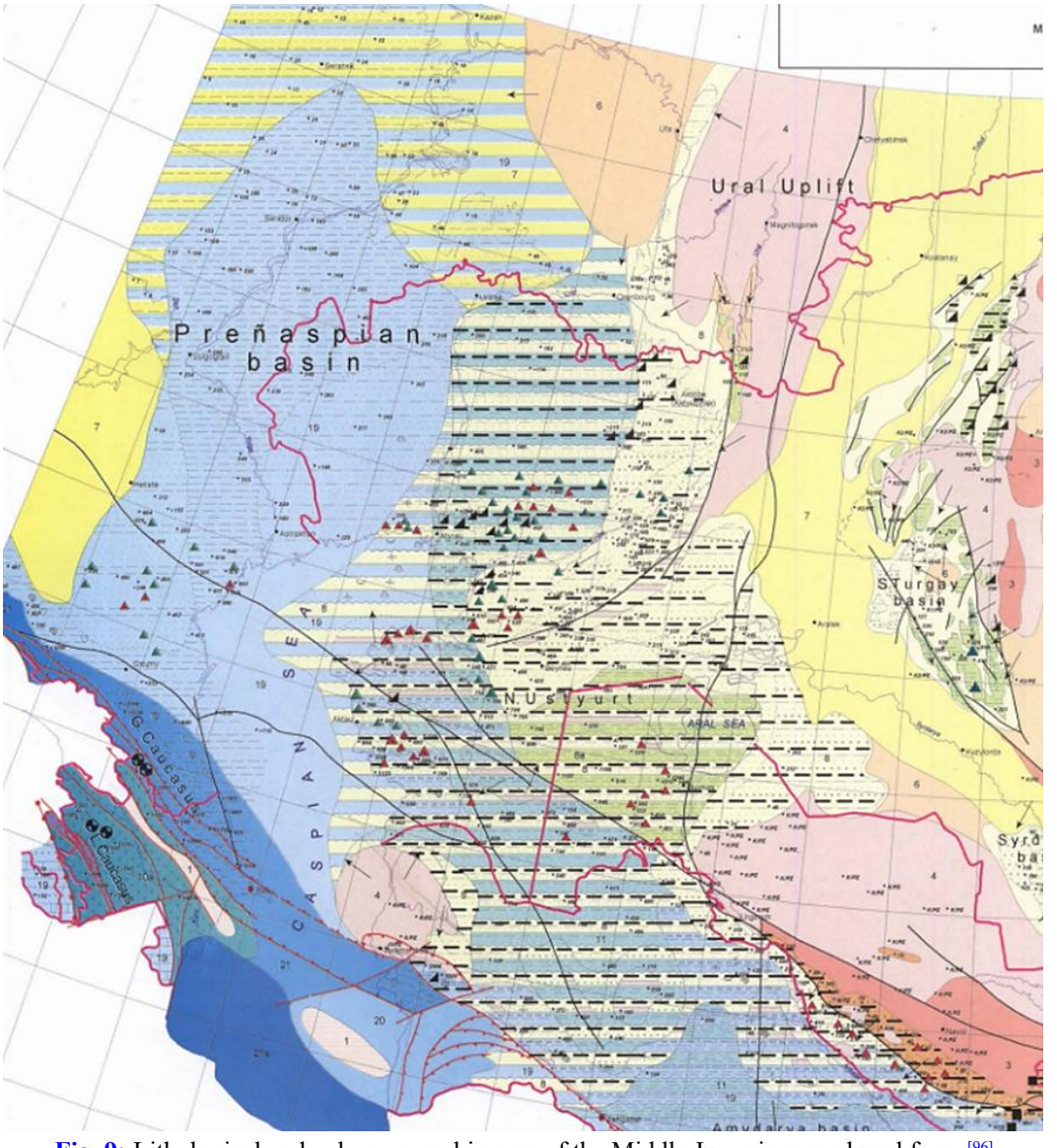


Fig. 9: Lithological and paleogeographic map of the Middle Jurassic reproduced from.[96]



Fig. 10: The coastline of the Caspian Sea reproduced from.[98]

following features (Fig. 8):

- High sorting of sand material;
- Clearly expressed layered textures with signs of wave ripple marks;
- Subordinate sedimentation dynamics influenced by tidal currents and coastal wave action.

These bars formed parallel to the shoreline and could have acted as primary lithological traps in subsequent hydrocarbon-bearing complexes (Fig. 9).

The actualistic approach allows the consideration of ancient transgressive-regressive cycles as direct analogs of contemporary sedimentary processes.[98] For clarity, an image of a modern bar, forming under similar conditions, is provided (Fig. 10).

Late Jurassic (Oxfordian–Tithonian): Intensification of Transgression. During the Late Jurassic, transgressive processes intensified.[99] The marine waters expanded, covering almost the entire territory of Mangyshlak, Northern Ustyurt, and Buzachi.[100-102] Extensive shallow shelf areas formed, with active wave reworking of sedimentary material (Fig. 11).[96]

The conditions of the Late Jurassic transgression contributed to the formation of several types of bars:[103]

Shelf wave bars, forming on the advancing shelf under the influence of persistent wave action and tidal currents.[104-106]

Coastal lens-shaped bars, occurring along the shoreline due to the reworking of terrigenous material by waves and littoral currents.[107,108]

Shelf wave bars were characterized by significant length, relatively uniform granulometric composition, and moderate sorting potential.[109] They could take the form of long parallel ridges stretching along the paleo-shoreline[110] (Fig. 12).

In this phase, the most promising sandstone reservoirs with high porosity and permeability were formed, which could be capped by thinner clayey covers created during periods of relative sea-level rise. Examples include: Cotton Valley, Yates Field, Pohokura Field.[112]

Early Cretaceous (Berriasian–Aptian): Regression and Reduction of the Marine Waters.

At the boundary between the Jurassic and Cretaceous, a period of regression began.[113] During the Early Cretaceous, the marine waters gradually retreated, giving way to continental, lagoonal, and estuarine sedimentation conditions.[96,114] This contributed to the reduction of shelf bar formation zones and the increased role of riverine and estuarine processes (Fig. 13).

In the estuarine environments of the Early Cretaceous, the formation of estuarine bars occurred, developing at river mouths under the influence of mixed fluvial and marine processes.[115] These bars were characterized by poorly sorted

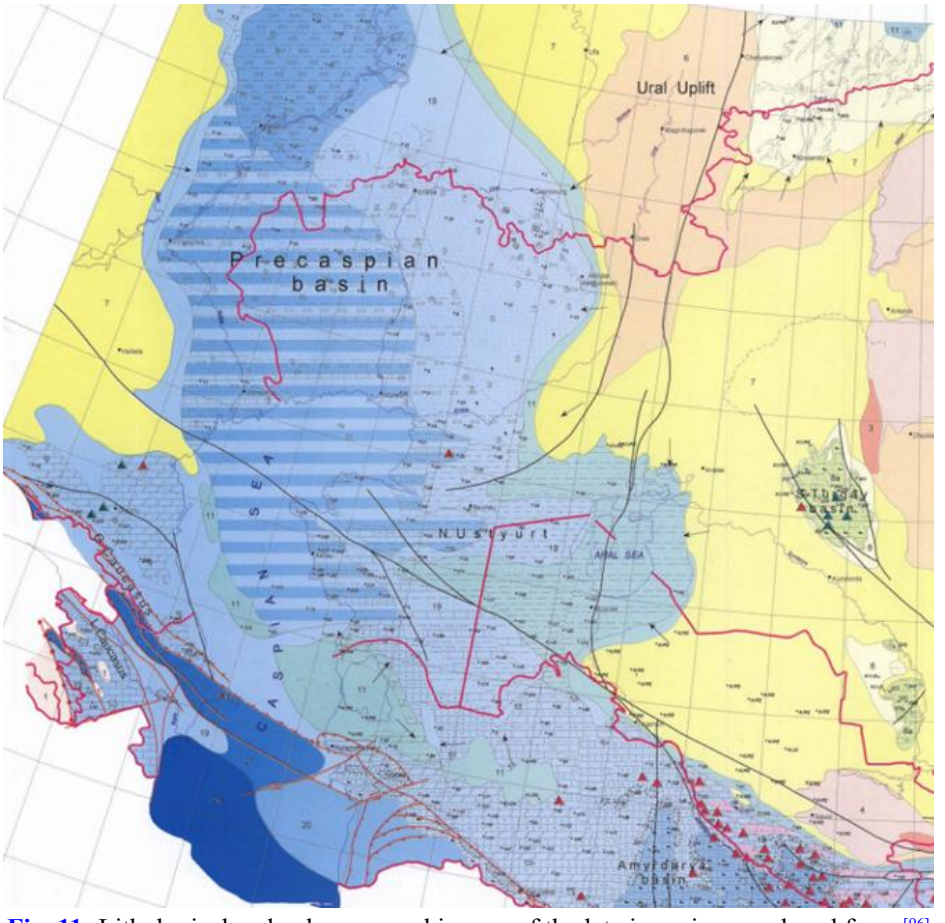


Fig. 11: Lithological and paleogeographic map of the late jurassic reproduced from.[96]

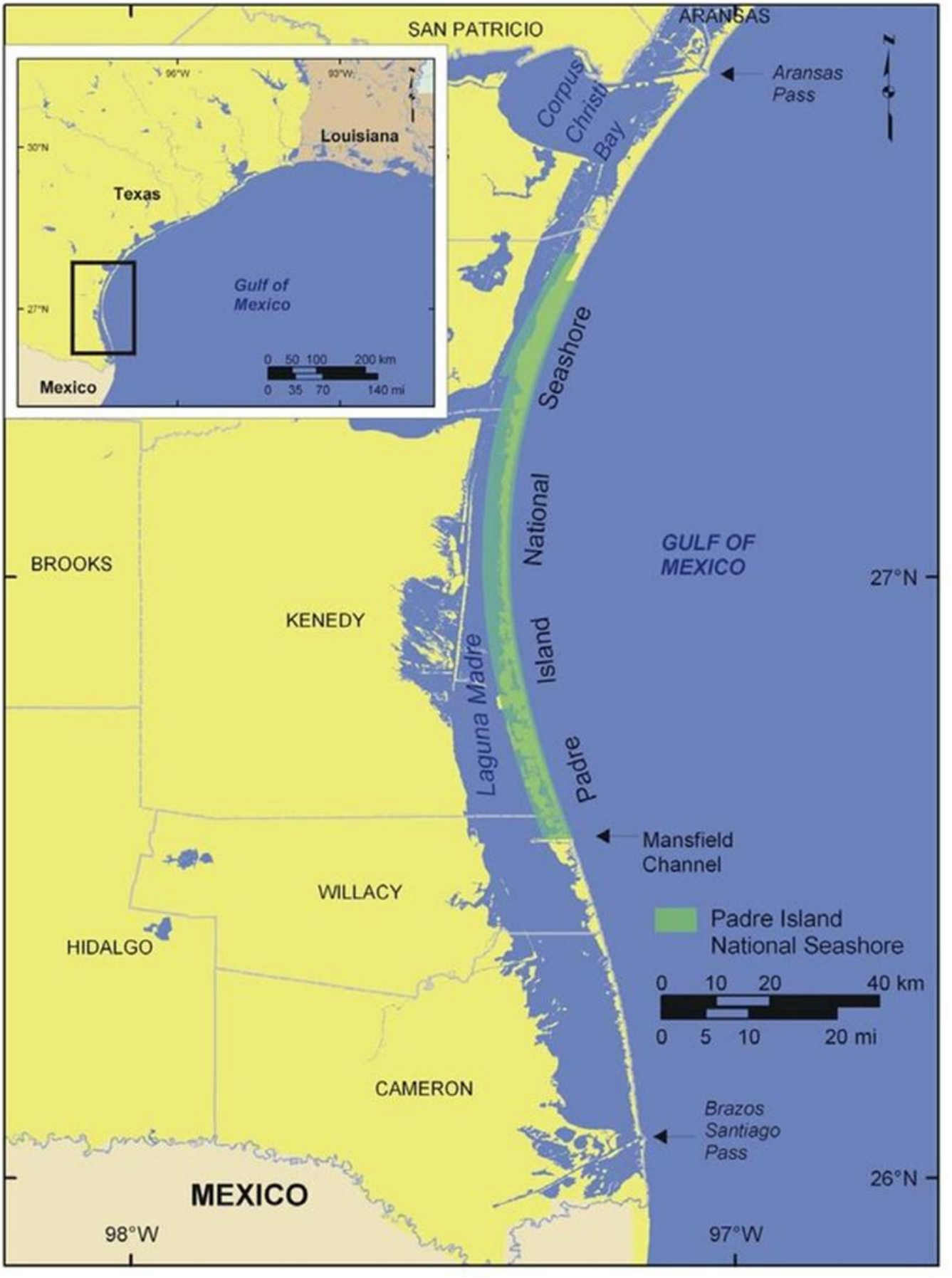


Fig. 12: Offshore wave bars reproduced from.[111]

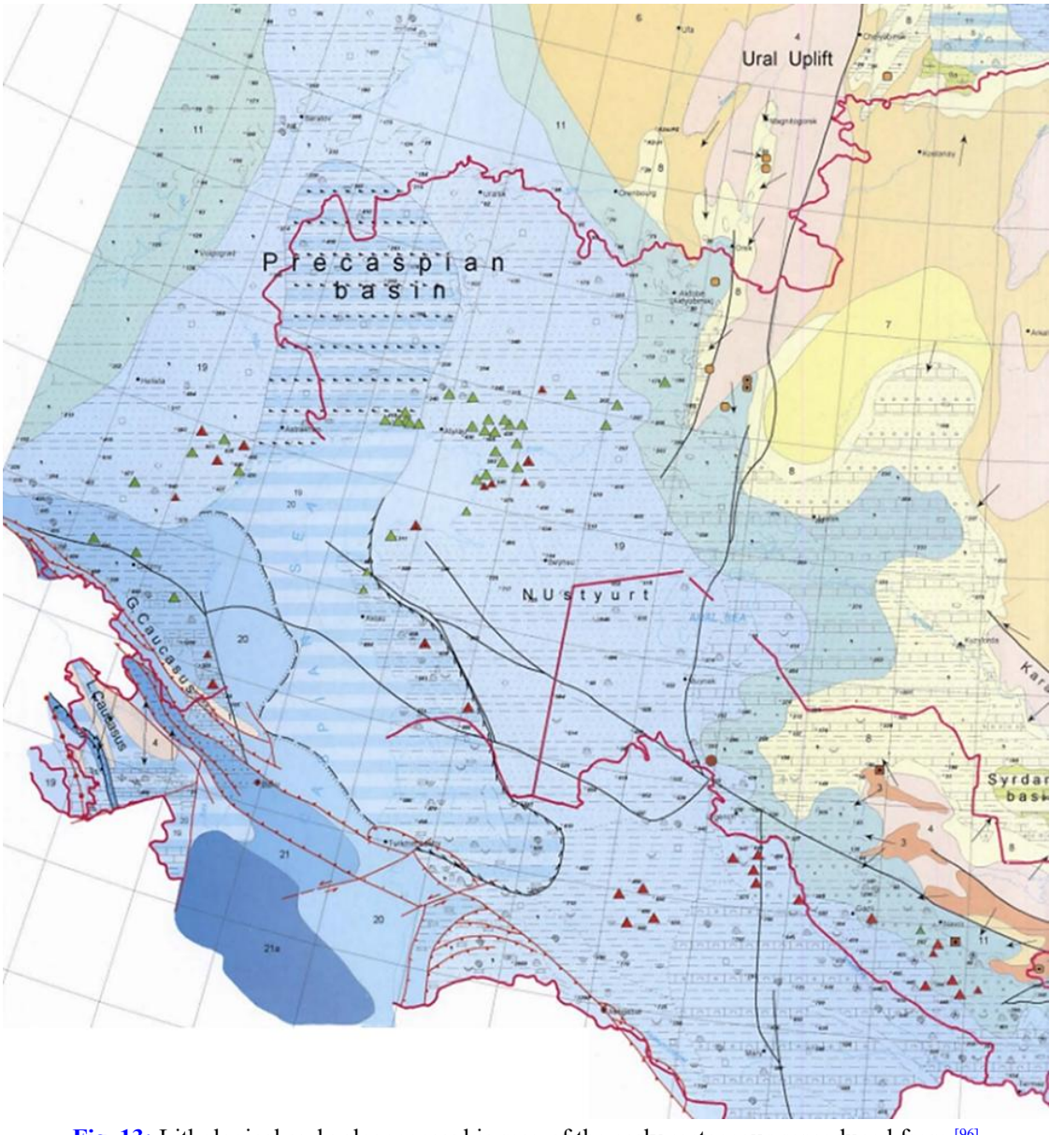


Fig. 13: Lithological and paleogeographic map of the early cretaceous reproduced from.[96]

sediments and interbedding of sandstones with siltstones and argillites. Such bars could act as localized lithological traps, particularly when overlain by lagoonal clayey deposits.[116]

Late Cretaceous (Cenomanian–Maastrichtian): the second transgression. In the second half of the Cretaceous period, a renewed marine transgression took place. During the Cenomanian–Maastrichtian, new flooding of the territories of Northern Ustyurt, Mangyshlak, Buzachi, and the Aral Sea region occurred, leading to the development of inner epicontinental sea conditions [47,51,96] (Fig. 14).

In the Late Cretaceous, the dominant formations were:

Inner shelf bars, developing in the calm shallow shelf zone.[117]

Tidal bars, forming under the influence of powerful tidal currents within estuarine and lagoonal systems.[118]

The sandstone bodies of Late Cretaceous bars can be characterized by high sorting and significant development of secondary reservoir properties (*e.g.*, due to early diagenetic cementation followed by cement dissolution).[119] Late Cretaceous complexes have become of great importance in the petroleum-bearing sections of the region due to the combination of high-quality reservoir properties of the rocks and the presence of reliable caps, represented by marine argillites and clays.[120] To further analyze the evolution of sedimentary conditions in the northern part of the Turan Plate in the regions of Mangyshlak, Northern Ustyurt, Buzachi, and the northwest part of the Aral Sea region and a summary table has been compiled (Table 2). It reflects the dynamics of transgression and regression processes during the Mesozoic, the nature of sedimentation, and their role in the formation of prospective bar reservoirs.[121]

Thus, the analysis of the sedimentation history shows that the most favorable conditions for the formation of bar reservoirs occurred during the Middle and Late Jurassic transgressions. It was during this time that active accumulation of shelf sandstones and carbonate formations with high

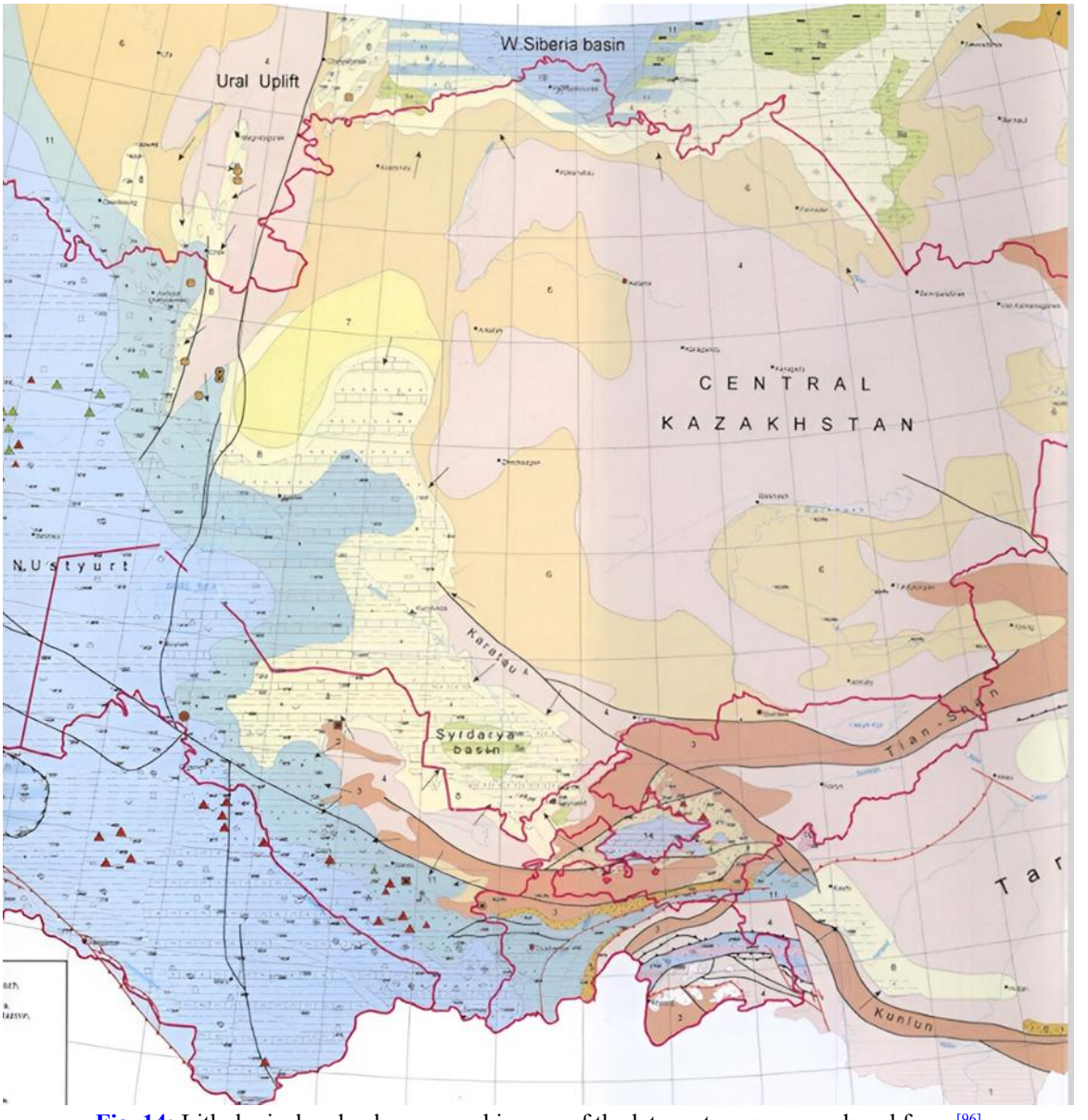


Fig. 14: Lithological and paleogeographic map of the late cretaceous reproduced from.[96]

Table 2: Sedimentation History of the Mesozoic and Formation of Bar Reservoirs in the Mangyshlak, Northern Ustyurt, Buzachi, and Northwest Aral Sea Regions.

Period	Region	Sedimentation Conditions	Process Type	Main Deposits	Role in Bar Formation
Triassic (~252–201 million years ago)	Mangyshlak, Northern Ustyurt, Buzachi, NW Aral Sea	Continental conditions: rivers, lakes	Regression	River sandstones, lake clays	Accumulation of terrigenous layers; no potential for bar formation
Early Jurassic (~201–174 million years ago)	Mangyshlak, Northern Ustyurt, Buzachi, NW Aral Sea	Continental conditions persist	Regression	River and lake deposits, weak boggy conditions	No bar formations present
Middle Jurassic (~174–163 million years ago)	Mangyshlak, Northern Ustyurt, Buzachi, NW Aral Sea	Beginning of marine transgression	Transgression	Marine sandstones, initial bars	Formation of first bar complexes, beginning of petroleum exploration interest
Late Jurassic (~163–145 million years ago)	Mangyshlak, Northern Ustyurt, Buzachi, NW Aral Sea	Peak marine transgression	Transgression (Peak)	Shelf sandstones, carbonates, lagoons	Formation of high-capacity bar reservoirs with potential oil and gas saturation

Period	Region	Sedimentation Conditions	Process Type	Main Deposits	Role in Bar Formation
Early Cretaceous (~145–100 million years ago)	Mangyshlak, Northern Ustyurt, Buzachi, NW Aral Sea	Marine retreat, continental conditions	Regression	Aeolian sands, dune deposits	Pause in bar formation, unfavorable conditions for reservoir accumulation
Late Cretaceous (~100–66 million years ago)	Mangyshlak, Northern Ustyurt, Buzachi, NW Aral Sea	New marine transgression	Transgression	Young shelf sandstones, new bar formation	Creation of additional prospective objects for oil and gas exploration

reservoir properties took place in the Mangyshlak, Northern Ustyurt, Buzachi, and northwest Aral Sea regions. The Late Cretaceous transgression also contributed to the formation of additional prospective targets, though their oil and gas potential requires further detailed study.

4. Results and discussion

Contemporary conditions in the oil and gas industry require high-tech methods, innovative solutions, and a comprehensive approach to organizing exploration and prospecting (E&P) activities, which is associated with the need for significant financial investment. Due to private capital's limited resources and scale, it does not fully support the implementation of such large-scale projects. Therefore, there is a need for extensive collaboration with the state, which can provide the necessary funds for carrying out large and expensive exploration programs.

The cooperation between the state and private companies becomes a crucial factor in the success of discovering new deposits. This is particularly relevant for regions such as the northern part of the Turan Plate, where significant investments and highly qualified resources are required for comprehensive exploration. It is important to note that the involvement of scientific personnel, including staff from the relevant departments at Satbayev University, plays a key role in the successful implementation. Satbayev University, with its deep scientific potential and extensive experience in geology and oil and gas technologies, can serve as a scientific moderator and executor, providing qualified specialists for the advanced exploration methods in the development and implementation.

Departments specializing in geophysics, geochemistry, and modeling will not only develop theoretical models but can also actively participate in the practical application of the latest technologies. By the framework of partnerships with the state and private sectors, Satbayev University can offer unique scientific developments and innovative approaches that will significantly improve the efficiency of exploration activities.

Thus, it is the comprehensive approach, which includes both state funding and private capital involvement, with active engagement of Satbayev University's scientific personnel, that creates the foundation for the effective implementation of exploration and prospecting activities in promising regions. The next stage in the exploration process is the selection and implementation of the latest exploration techniques that will ensure high accuracy in predictions and open new opportunities for discovering hydrocarbon deposits.

Given the increasing complexity of geological challenges and the growing demands for accuracy in forecasting the hydrocarbon potential of territories, the methodology for exploration and prospecting (E&P) should be based on the integration of classical geological and geophysical methods with modern digital technologies. For the regions in the northern part of the Turan Plate (including Northern Ustyurt, Mangyshlak, Buzachi, and northwest Aral Sea), the following comprehensive E&P algorithm is proposed:

Regional Analysis and Modeling:

1. Comprehensive analysis of regional geological, paleogeographic, and paleotectonic data using GIS technologies.
2. Creation of digital geological models based on existing archival materials, seismic survey data, drilling data, and remote sensing data (RS).
3. Identification of areas with potential for the development of bar sandstones associated with transgressive and regressive phases of the Mesozoic.

Next-Generation Seismic Survey:

1. High-density 3D seismic surveys in promising areas with the potential for subsequent 4D monitoring (tracking subsurface changes over time).
2. Application of depth migration, attribute analysis, spectral decomposition, and data inversion techniques for detailed mapping of thin lithological traps (bars).
3. Use of Full Waveform Inversion (FWI) technology to enhance the resolution of geological models.

Geophysical and Geochemical Profiling:

1. Detailed electro-exploration studies (MTZ, VES) for refining the sedimentary cover structure.
2. Application of microseismic, gravimetric, and magnetometric methods to detect hidden structural and lithological traps.
3. Conducting exploration geochemistry (gas surveys, porosity and hydrocarbon saturation analysis of core material) to identify direct signs of fluid-saturated reservoirs.

Machine Learning and Artificial Intelligence:

1. Development and training of machine learning models for predicting lithological rock types and identifying prospective targets based on seismic and geophysical attributes.
2. Implementation of Big Data processing technologies for the

automated interpretation of large volumes of heterogeneous data.

Drilling of Exploration Wells:

1. Programming the drilling of control and parametric wells with integrated logging data, borehole geophysical studies (BGS), and core material.
2. Implementation of directional drilling technologies to increase the likelihood of uncovering bar structures.
3. Evaluation of hydrocarbon potential at early stages using digital sensors and borehole monitoring systems.

Development of Digital Twins:

1. Creation of "digital twins" for prospective areas to conduct virtual drilling, optimize well design, and simulate extraction processes.
2. Forecasting reservoir productivity using hydrodynamic modeling.

Economic Evaluation and Preparation for Pilot Development:

1. Conducting technical and economic assessments of prospective targets.
2. Planning the transition to the pilot industrial development stage for the most promising areas.

The coordination of the activities should be carried out within the framework of state subsoil exploration programs, involving private capital and the active participation of scientific personnel, primarily specialists from the relevant departments of Satbayev University. The university can assume the role of scientific support, model validation, core sample analysis, and field testing of new technologies. This type of collaboration between the government, private business, and the scientific community will enable the effective and innovative implementation of large-scale projects aimed at discovering new hydrocarbon deposits in the northern part of the Turan Plate.

Given the scale of the tasks at hand and the high demands for justifying prospective objects, a comprehensive methodology for exploration and prospecting has been developed. This methodology integrates advanced digital technologies with traditional geological and geophysical research. The structure of the methodology is presented in the Table 3.

Thus, the proposed methodology combines modern digital solutions and advanced geophysical technologies with the fundamental principles of petroleum geology. The involvement of academic personnel from specialized departments of Satbayev University as moderators, researchers, and experts at all stages of exploration activities will not only enhance the scientific validity of decision-making but also foster a sustainable link between science, industry, and governmental interests.

The implementation of this approach within the framework of a large-scale governmental program or through joint public-private initiatives establishes a solid foundation for the efficient development of new hydrocarbon-prospective targets in the northern part of the Turan Platform.

In South Mangyshlak, 84% of the total hydrocarbon reserves are oil. The Middle Jurassic terrigenous deposits, located on the Zhetybai-Uzen step to the south of the Mangyshlak folded belt, represent a high percentage of the hydrocarbon deposits.

According to the period of study achievement, it is clear that the studies dealing with Bar Reservoirs in the northern part of the north Turan Plate expanded with time, from only 2 in the period pre-1960s to 14 during the 1990s, and 47 in the 2020s (Fig. 15).

Fig. 16 illustrates that the studies for the north Turan plate had a high percentage compared with other areas, equal to approximately 23% (21 out of 91). One possible reason is that the researchers concentrated on a specific area while the others were used for additional acknowledgment and comparison.

According to Fig. 17, most studies explored the Petroleum Geology and Reservoir Characterization, Paleogeography, and Stratigraphy. In a smaller percentage, basin analysis and tectonics, the Sedimentology & Depositional Environments. In the Coastal & Marine Geology, Geophysics & Seismic Studies, and Environmental & Geochemical Studies, the gap will be noticed and increases respectively.

Table 3: Stages of the integrated methodology of prospecting and exploration work.

Stage	Scope of Work	Applied Technologies
1. Regional Analysis	Analysis of geological and geophysical data, basin modeling	GIS technologies, remote sensing (RS), digital modeling
2. 3D/4D Seismic Survey	Detailing lithological traps (bars), structural analysis	High-density 3D seismic survey, depth migration, spectral decomposition, Full Waveform Inversion (FWI)
3. Geophysics and Geochemistry	Refinement of sedimentary cover structure, identification of reservoir indicators	Electrical prospecting (MT, VES), gravimetry, magnetometry, exploration geochemistry
4. Artificial Intelligence	Prediction of bar zones and hydrocarbon accumulations, automated interpretation	Machine learning, Big Data analytics, neural network models
5. Exploratory Drilling	Penetration of prospective bar structures, core sampling, and well logging	Directional drilling, digital well monitoring systems
6. Digital Twins	Virtual drilling, reservoir and production modeling	Digital twins of target areas, hydrodynamic modeling
7. Economic Evaluation	Feasibility study for the development of promising targets, planning of pilot production	Integration of techno-economic models

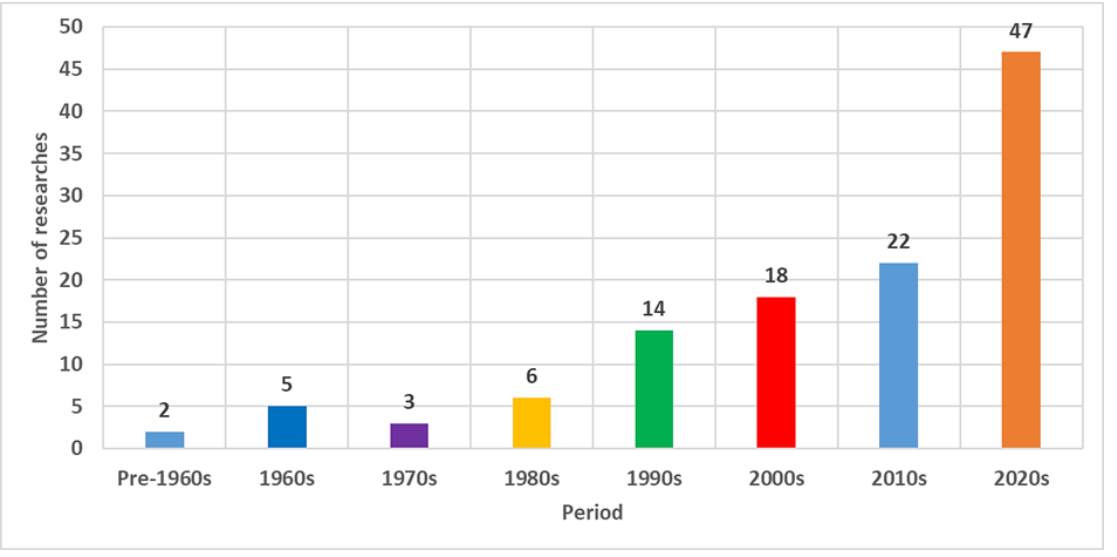


Fig. 15: The growth of studies dealing with bar reservoirs in the northern part of the Turan Plate from the 1960s to the 2020s.

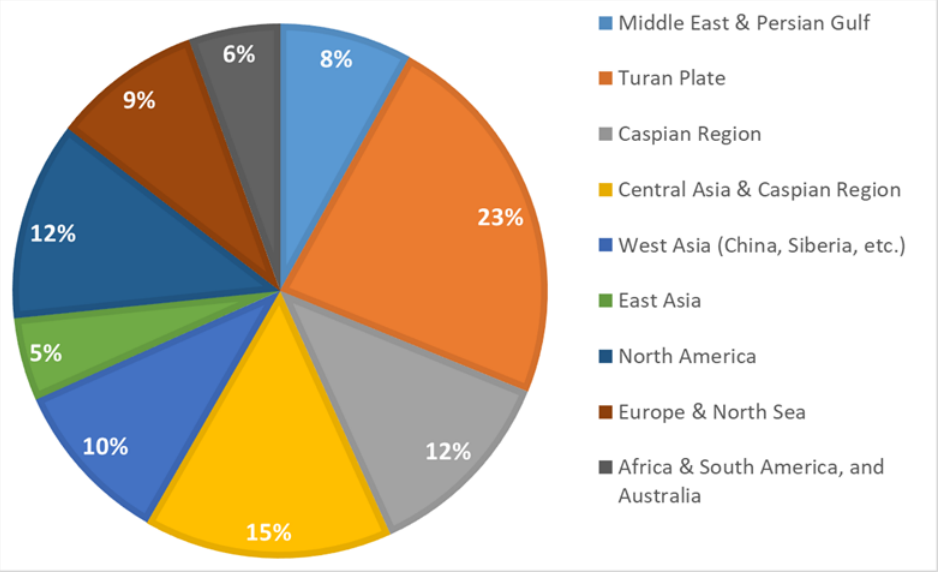


Fig. 16: Percentages of studies according to the applied study area.

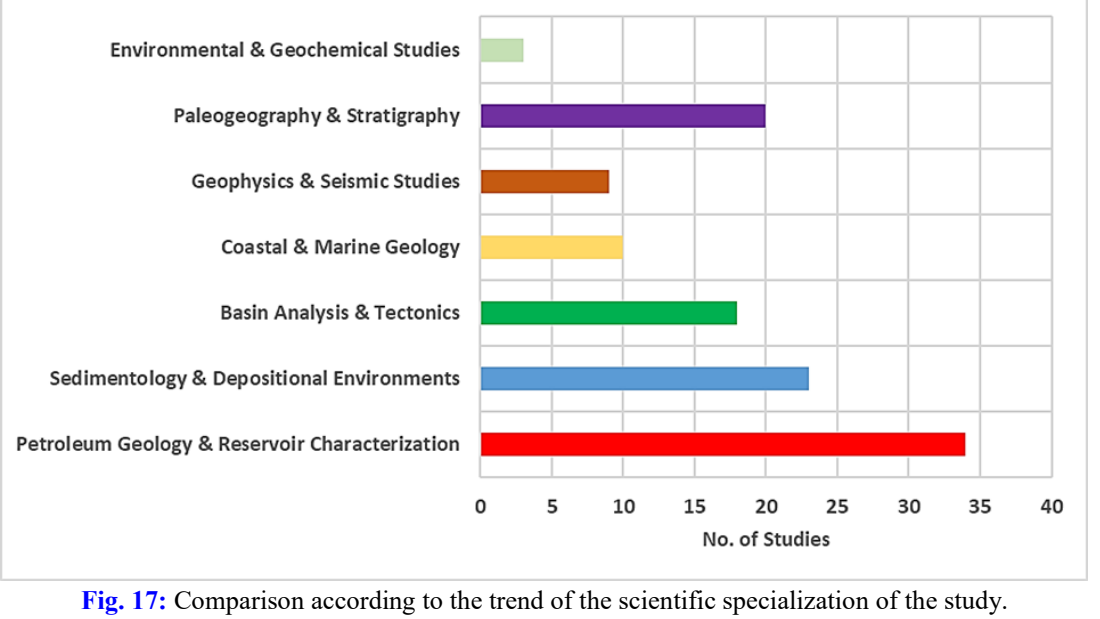


Fig. 17: Comparison according to the trend of the scientific specialization of the study.

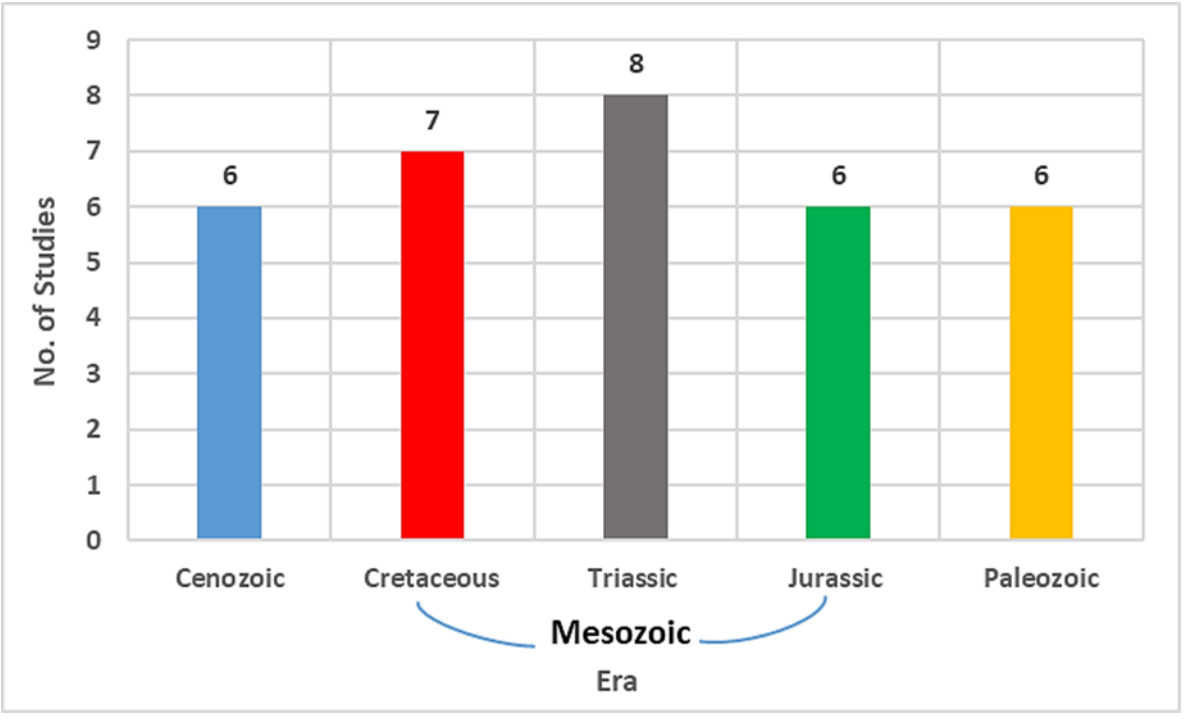


Fig. 18: Division of the studies applied for the north Turan Plate according to the sedimentation stratigraphic period.

According to Table 2, the favourable reservoirs are in the Middle and Late Jurassic of the Mesozoic era; on the other hand, the ancient period of the Early Cretaceous and the Late period, represented by the Triassic, were identified as unfavourable for generation and holding hydrocarbons. More studies are required on the Middle and Late Jurassic in new sites for the north Turan plate, in addition to enhancing the information about the formations of those periods, with the continuity of the exploration of other geological periods in all the Turan plate to increase the reserves in this area (Fig. 18).

5. Conclusions and perspectives

This study focused on the genesis and spatial distribution of sand bar reservoirs for Mesozoic transgressive–regressive cycles in the northern part of the Turan Plate, encompassing regions such as Mangyshlak, Buzachi, Northern Ustyurt, and the northwestern Aral Sea area. The conclusions and recommendations can be summarized as follows:

Mesozoic transgressive-regressive cycles led to the formation of multiple types of bar reservoirs.

Middle and Late Jurassic periods were the most favorable for bar development and The northern Turan Plate holds high potential for hydrocarbon exploration based on these formations.

A complex, tech-integrated exploration strategy is essential for success.

A growth in the studies of the Bar Reservoirs for the northern part of the north Turan Plate expanded with time from the pre-1960s to the 2020s.

Most studies for the North Turan Plate explored petroleum Geology and Reservoir Characterization, Paleogeography, and Stratigraphy. In a smaller percentage, basin analysis and tectonics, the Sedimentology & Depositional Environments, the gap in Coastal and Marine Geology increases, and more in Geophysics and Seismic Studies, and Environmental and Geochemical Studies, progressively.

The favorable hydrocarbon reservoirs are in the Middle and Late Jurassic of the Mesozoic era; on the other hand, the Early Cretaceous and the Triassic were identified as unfavorable for the generation and holding of hydrocarbons. More studies are required on the Middle and Late Jurassic in new sites for the north Turan plate, with the exploration continuity of the other geological periods in all the Turan plate to increase the potential reserves.

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Conflict of Interest

Not conflicts

Supporting Information

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