



Stratigraphic significance of the transgressive surface in a sandstone-hosted uranium system: South Tortkuduk Field, Chu- Sarysu basin, Southern Kazakhstan.

Bachelor of Science in Geology

Abaidildin Abildakhanov

Prof. Milovan Fustic

School of Mining and Geosciences, Nazarbayev University

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Abstract

This thesis investigates the stratigraphic and hydrogeological significance of the transgressive interval in the South Tortkuduk uranium field, Chu-Sarysu Basin, southern Kazakhstan. The study focuses on the uppermost Paleocene to lowermost Eocene succession and aims to identify the preserved transgressive surface, characterize its internal architecture, and evaluate its practical importance for in-situ recovery (ISR) uranium production.

The research is based on an integrated workflow combining core description, acid testing, well-log interpretation, cross-section correlation, and slice-map analysis. Core observations were used to identify key sedimentological indicators of transgression, including polymictic reworked gravel, vertical facies change, and carbonate-reactive intervals. These observations were then correlated laterally using well logs and cross-sections and subsequently mapped in plan view within the Tr-MFS interval using GDE maps.

The results demonstrate that the transgressive interval constitutes a real and mappable stratigraphic feature rather than a local facies anomaly. It is best preserved in areas where the maximum flooding surface (MFS) mud is also preserved; in areas where the MFS has been eroded, the transgressive interval becomes mixed, attenuated, or difficult to recognize. The study further indicates that preserved transgressive sands may contain carbonate-cemented or carbonate-reactive material, implying that injected acid may be consumed within this interval before it can contribute effectively to uranium recovery.

The principal conclusion of this thesis is that the transgressive interval in South Tortkuduk should be treated not only as a stratigraphic surface but also as an acid-loss risk zone. Identifying where this interval is preserved provides a practical geological basis for recognizing where preferential acid injection during ISR is inadvisable, thereby helping to reduce reagent loss and improve geological support for uranium extraction planning.

Table of Contents

1. Introduction	6
1.1 Background and Significance of the Study	6
1.2 Problem Statement	9
1.3 Scope of the Study	10
2. Literature Review	10
2.1 Uranium in Geological Systems	10
2.2 Sandstone-Hosted Uranium Deposits	13
2.3 Kazakhstan and its Role in the Global Uranium Sector	14
2.4 In-Situ Recovery (ISR) Mining and the Role of Geology	15
2.5 Transgression: Definition and Significance	16
2.6 Identification of Transgressive Deposits and Maximum Flooding Surfaces	17
2.7 Sequence Stratigraphy and its Application to South Tortkuduk	19
3. Geological Setting of the Study Area	20
3.1 Regional Setting: Chu-Sarysu Basin.....	20
3.2 Uranium Geology of the Basin.....	22
3.3 South Tortkuduk and the Belt-Based Local Framework	23
4. Methodology.....	25
4.1 Core Description and Facies Analysis	25
4.2 Parallel Cross-Sections	27
4.3 Slice Maps / GDE Maps.....	29
5. Results	31
5.1 Results of Core Description and Facies Analysis.....	31
5.2 Results of Cross-Section Correlation.....	34
5.3 Results of Slice-Map Interpretation.....	36
6. Discussion.....	38
6.1 Stratigraphic Significance of the Transgressive Interval	38
6.2 Carbonate Cement, Gypsum Formation, and Acid Loss	39
6.3 Implications for ISR Optimization	40
6.4 Limitations	41
7. Conclusion.....	42

8. References	43
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1. Introduction

1.1 Background and Significance of the Study

Uranium is a fundamental resource for nuclear fuel production and is expected to remain so in the long term owing to its role in generating low-carbon electricity through nuclear power stations. The International Atomic Energy Agency ([IAEA](#)) identifies uranium as the primary fuel source for nuclear reactor operations ([IAEA, 2023](#)). According to the World Nuclear Association, nuclear electricity generation accounts for approximately 10% of total global electricity production, underscoring the continuing strategic importance of uranium in long-term energy planning ([World Nuclear Association, 2025](#)).

From a geological perspective, uranium is notable because its concentration into economically recoverable deposits depends on the interaction of redox conditions, groundwater flow, host-rock permeability, and basin architecture. In Kazakhstan, the dominant uranium resource base consists of sandstone-hosted roll-front deposits, in which oxidized uranium-bearing groundwater migrates through permeable sedimentary aquifers and precipitates uranium at reduction fronts. [Petrov \(1998\)](#) described these deposits as epigenetic stratified-infiltration uranium deposits associated with regional fronts of layered oxidation developed in Cretaceous and Paleogene sedimentary horizons. These deposits form the industrial basis of Kazakhstan's uranium sector and are particularly suitable for in-situ recovery (ISR) mining because they occur in porous and permeable strata bounded by lower-permeability units.

Kazakhstan is the dominant producer in the modern global uranium sector. According to the [World Nuclear Association \(2025\)](#), Kazakhstan has been the world's largest uranium producer since 2009 and holds approximately 14% of global uranium resources. The OECD Nuclear Energy Agency and the IAEA reported that Kazakhstan accounted for approximately 43% of global uranium production in 2022 ([OECD NEA and IAEA, 2025](#)).

ISR is the principal uranium extraction method in Kazakhstan's major sandstone-hosted uranium provinces. Production efficiency in ISR depends strongly on the spatial organization of sand-prone and mud-prone geobodies, because porosity, permeability, connectivity, and stratigraphic compartmentalization control the movement of injected leaching solutions through the subsurface.

In such systems, geological heterogeneity is not merely a sedimentological observation, but a primary production constraint influencing sweep efficiency, fluid losses, bypassed zones, and well-performance predictability ([Dahlkamp, 2009](#); [Abzalov, 2012](#); [Seredkin et al., 2016](#); [Smagambetov, 2024](#)).

Transgression is a stratigraphic process that develops when the rate of accommodation creation exceeds the rate of sediment supply, causing the shoreline and associated depositional environments to migrate landward. In sedimentary successions, this process is commonly expressed by landward-stepping facies, upward-deepening trends, ravinement, and the formation of key stratigraphic surfaces, including the transgressive surface, tidal ravinement surface, wave ravinement surface, and maximum flooding surface. Because transgression involves erosion, sediment reworking, condensation, and the juxtaposition of facies with contrasting petrophysical properties, it commonly disrupts simple vertical successions and generates complex internal architectures of high significance for reservoir characterization and subsurface fluid flow ([Cattaneo and Steel, 2003](#); [Hein and Kirwan, 2024](#)).

The present study is focused on the South Tortkuduk field within the Chu-Sarysu Basin of southern Kazakhstan. The primary objective is the identification and interpretation of the transgressive interval preserved within the uranium-bearing succession. In this work, transgression is treated as a geological feature of practical importance for ISR because it may control the distribution of permeable sands, flooding muds, and carbonate-bearing intervals within the reservoir architecture. [Dillinger et al. \(2024\)](#) demonstrated that the Paleocene to Eocene succession of the Chu-Sarysu Basin records the influence of fluvial, floodplain, marginal-marine, and marine depositional environments shaped by major transgressive events related to the Peri-Tethys and Turan Sea evolution. In the local South Tortkuduk (STK) framework, the succession is subdivided into Belt 1, Belt 2, the Tr-MFS Belt, Belt 3, and Belt 4, and the transgressive interval is recognized as a distinct part of the field architecture ([Dillinger et al., 2024](#)).

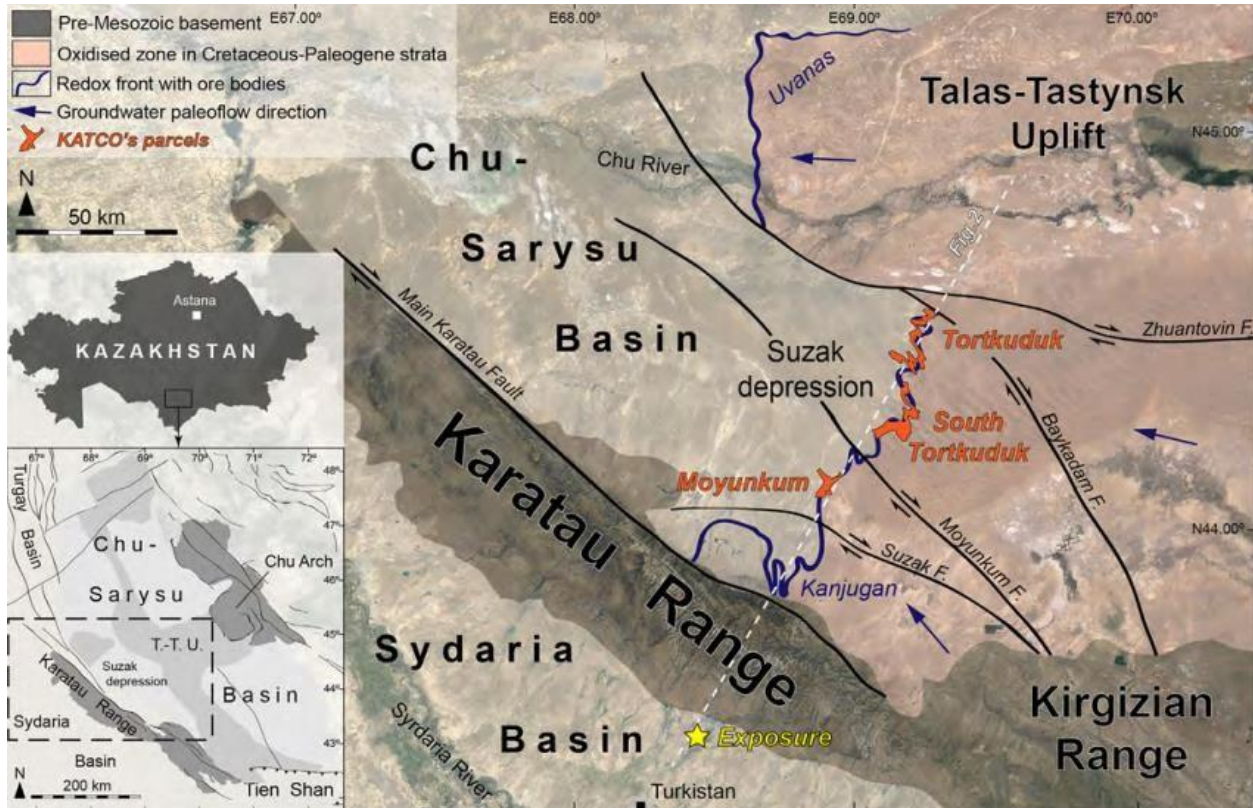


Figure 1. Regional geological setting of the Chu-Sarysu Basin showing the location of the Suzak depression, Tortkuduk, and South Tortkuduk relative to the main uranium-bearing sectors of the basin. (Smagambetov et al., in preparation).

This focus is significant because ISR performance depends strongly on geological architecture. Dillinger et al. (2024) noted that ISR is effective only where uranium occurs in a porous reservoir between impermeable sealing layers. Li and Yao (2024) further emphasized that permeability, hydraulic confinement, and host-rock mineralogy are among the key controls on ISR efficiency. In South Tortkuduk, this issue is especially relevant because internal STK interpretation reports calcite cement in the uppermost part of Belt 2 and within the Tr-MFS Belt, suggesting that the transgressive interval may also represent a zone of elevated acid consumption during sulfuric-acid ISR.

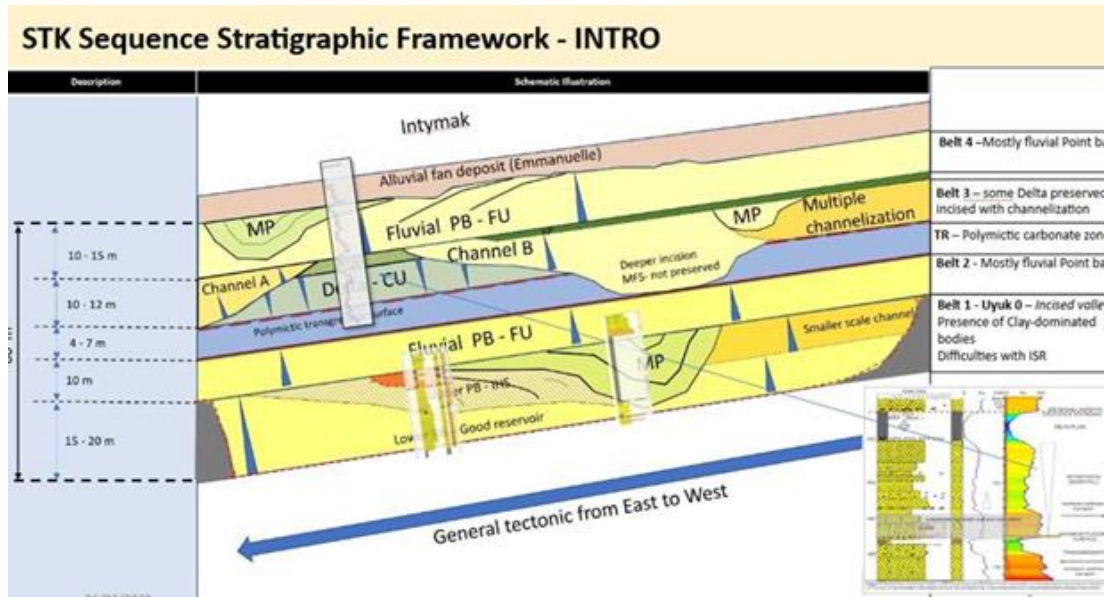


Figure 2. Belt-based sequence-stratigraphic framework of the South Tortkuduk field showing Belt 1, Belt 2, the Tr-MFS Belt, Belt 3, and Belt 4, together with the principal erosional and flooding surfaces relevant to reservoir and non-reservoir distribution. (Smagambetov et al., in preparation).

Recent ISR simulation work from the Tortkuduk–Muyunkum system supports this concern by demonstrating that sulfuric acid is consumed not only by uranium dissolution but also by side reactions with carbonates and iron-rich clays, and that carbonate-related reactions may contribute to calcium sulfate precipitation, pore plugging, and injectivity decline around injection wells (Umurzakov, 2024). The transgressive interval in South Tortkuduk is therefore important not only as a stratigraphic marker but also as a potential predictor of acid-loss risk.

1.2 Problem Statement

Despite the recognized importance of the South Tortkuduk uranium field, the transgressive interval within the uranium-bearing succession has not been adequately evaluated as a practical control on ISR behavior. Existing geological interpretation identifies a preserved transgressive interval and a maximum flooding surface within the local succession, but the significance of this interval for reservoir connectivity, internal sealing, carbonate occurrence, and acid-loss behavior remains insufficiently constrained (Dillinger et al., 2024).

This problem is especially relevant because the transgressive interval occupies a stratigraphic position where several important controls intersect. Preserved transgressive sands may provide laterally connected flow pathways; preserved flooding mud may act as an internal permeability barrier; and carbonate cement reported within this interval may increase sulfuric-acid consumption

during ISR (Fustic, n.d.). ISR simulation work relevant to the Tortkuduk–Muyunkum system further indicates that carbonate reactions may reduce leaching efficiency and contribute to permeability damage near the injector (Umurzakov, 2024).

The central problem addressed in this thesis is therefore whether the transgressive interval in South Tortkuduk can be identified and characterized in a way that improves understanding of reservoir architecture and helps explain, predict, or potentially reduce acid loss during ISR uranium extraction.

1.3 Scope of the Study

The aim of this thesis is to explain the stratigraphic and hydrogeological significance of the transgressive surface in the South Tortkuduk field and to demonstrate why this surface matters for uranium mineralization and ISR performance in a sandstone-hosted uranium system.

The study is limited to the South Tortkuduk field in the Chu-Sarysu Basin and focuses specifically on the stratigraphic and hydrogeological significance of the transgressive interval in the uranium-bearing succession. The work is not intended to provide a complete reactive transport simulation or a full mine-scale production forecast. Instead, it develops a geological interpretation designed to explain how transgression influences reservoir continuity, internal sealing, carbonate occurrence, and acid-loss behavior during ISR.

The study is based on the interpretation of published regional and basin-scale geological studies, internal STK sequence-stratigraphic and slice-map interpretation, and ISR-related technical literature relevant to acid consumption and formation damage.

2. Literature Review

2.1 Uranium in Geological Systems

Uranium is a naturally occurring radioactive element of the actinide series that is found in a wide range of geological environments. Although it is widely dispersed in the Earth's crust, its

concentration into economically significant deposits requires specific geological, geochemical, and hydrogeological conditions. In natural systems, uranium occurs principally in the isotopic forms U-238, U-235, and U-234 (Figure 4), and its geochemical behavior is strongly controlled by oxidation-reduction processes, fluid migration, mineral stability, and host-rock composition.

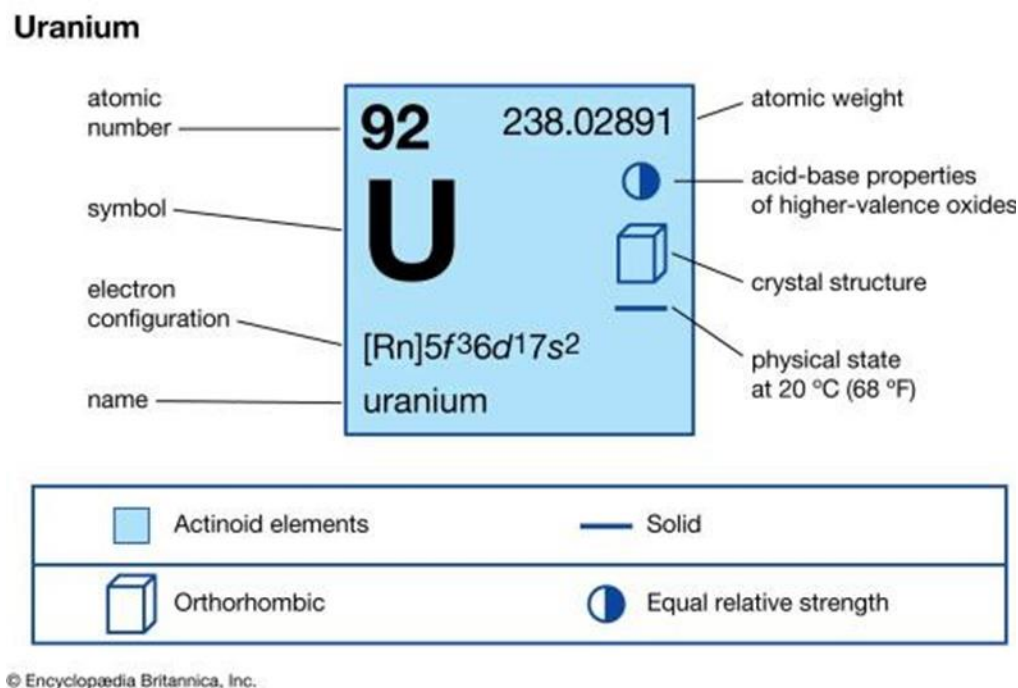


Figure 3. Uranium element and properties (Morss, 2026).

From a geological perspective, uranium is highly mobile under oxidizing conditions and relatively immobile under reducing conditions. This redox-sensitive behavior is fundamental to the formation of uranium deposits, particularly those hosted in sedimentary basins. Under oxidizing groundwater conditions, uranium is transported in dissolved form, whereas under reducing conditions it tends to precipitate as uranium minerals, commonly in association with organic matter, sulfides, or other reductants. Accordingly, the distribution of uranium mineralization is closely linked to groundwater flow systems, permeability architecture, and the spatial position of oxidation-reduction fronts (Petrov, 1998).

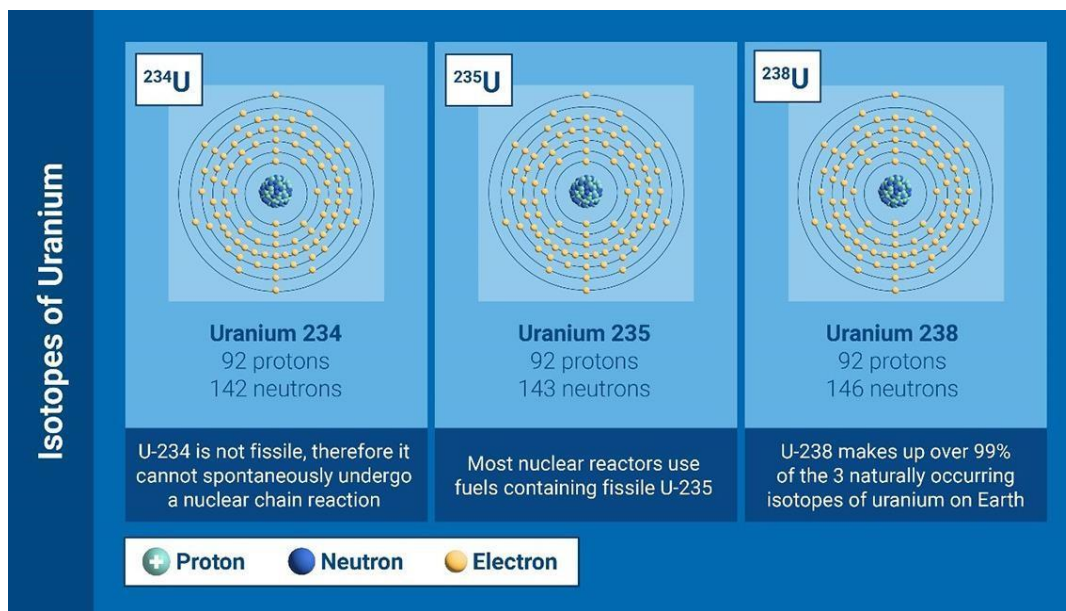


Figure 4. Isotopic forms of uranium (Morss, 2026).

Uranium occurs in a variety of minerals, of which uraninite and coffinite are among the most important ore-forming phases in sandstone-hosted deposits. These minerals typically precipitate during post-depositional fluid–rock interaction and may occur as disseminations, coatings, fracture fillings, or pore-filling phases within permeable sedimentary rocks. In most sediment-hosted uranium systems, mineralization is therefore not simply a depositional feature but the result of epigenetic processes controlled by basin hydrodynamics and redox evolution.

A wide range of uranium deposit types has been recognized worldwide, including unconformity-related, vein-type, intrusive-related, surficial, phosphorite-associated, and sandstone-hosted deposits. Among these, sandstone-hosted uranium deposits are particularly important because they constitute one of the most widespread and economically productive deposit classes. Their geometry, continuity, and ore distribution are strongly controlled by the sedimentological and stratigraphic architecture of the host succession, making them well suited to ISR mining and to interpretation using sequence-stratigraphic methods.

In Kazakhstan, sandstone-hosted uranium deposits form the basis of the national uranium industry. [Petrov \(1998\)](#) described these deposits as epigenetic stratified-infiltration accumulations related to regional fronts of layered oxidation developed within Cretaceous and Paleogene sedimentary horizons, and emphasized that uranium is localized in permeable sandstone reservoirs bounded by lower-permeability strata. This geological configuration directly shapes the significance of the

transgressive surface examined in the present study, because stratigraphic surfaces of the type investigated here exert a first-order control on the distribution of both reservoir and non-reservoir facies within the uranium-bearing succession.

2.2 Sandstone-Hosted Uranium Deposits

Uranium deposit classification provides an important framework for understanding the geological diversity of ore-forming systems and for placing sandstone-hosted uranium mineralization in a broader metallogenic context. [Dahlkamp \(2009\)](#) systematized uranium deposits according to host environment and geotectonic setting and emphasized that descriptive typology remains especially useful for exploration because it allows comparison between established deposits and newly studied mineralized systems. Within this classification, sandstone-hosted uranium deposits are treated as a distinct class characterized by strong links between sedimentary architecture, permeability contrasts, redox conditions, and groundwater flow.

According to [Dahlkamp \(2009\)](#), sandstone uranium deposits are typically confined to continental fluvial or marginal-marine environments, where uranium occurs disseminated in reduced sandstones bound by less permeable strata such as mudstones and shales. Uranium precipitation commonly takes place at redox interfaces, and the principal ore minerals are dominantly pitchblende and coffinite. Reducing conditions may be created by carbonaceous organic matter, humate, sulfides, hydrocarbons, and in some cases ferromagnesian minerals, demonstrating that ore formation in these systems depends not only on uranium-bearing fluids but also on the stratigraphic and geochemical properties of the host succession.

For the Chu-Sarysu Basin, [Dahlkamp \(2009\)](#) identified a specific roll-front subtype associated with mixed continental and marginal-marine host lithologies, referring to it as the Chu-Sarysu type. He described these deposits as similar to continental roll-front systems but developed within sedimentary successions of mixed continental and marginal-marine origin, with medium to large resources and generally low grades. This observation supports the interpretation that uranium mineralization in southern Kazakhstan cannot be explained solely by local redox conditions, but must also be examined in relation to broader depositional architecture and stratigraphic surfaces that influenced aquifer distribution and fluid pathways at basin scale ([Dahlkamp, 2009](#); [Petrov et al., 1995](#); [Dillinger et al., 2024](#)).

Roll-front uranium deposits represent one of the most characteristic styles of sandstone-hosted mineralization. They form where oxidized uranium-bearing fluids migrate through permeable sandstones and encounter reducing environments created by organic matter, pyrite, hydrocarbons, or reduced iron-bearing minerals. This redox reaction causes dissolved uranium to precipitate, commonly as coffinite and pitchblende. The resulting ore bodies are often crescent-shaped in cross-section and elongated along the direction of regional groundwater movement. [Petrov \(1998\)](#) emphasized that Kazakhstani roll-front deposits may extend for tens of kilometers along oxidation fronts and are typically localized within permeable Cretaceous and Paleogene sedimentary units.

A key characteristic of sandstone-hosted deposits is that ore distribution is not controlled only by regional basin geometry, but also by internal heterogeneity within the host succession. Facies changes, shale breaks, mud plugs, abandoned channels, channel-belt stacking patterns, erosional surfaces, and diagenetic cementation can all influence permeability and therefore both ore formation and extraction performance. This is one reason why recent studies increasingly emphasize the value of sedimentological and sequence-stratigraphic approaches to uranium geology. [Dillinger et al. \(2024\)](#) argued that detailed analysis of fluvial architecture and allogenic controls is essential to understanding how uranium-bearing reservoir bodies are organized in time and space within the Chu-Sarysu Basin.

2.3 Kazakhstan and its Role in the Global Uranium Sector

Kazakhstan occupies a dominant position in the global uranium sector owing to the combination of a large resource base, favorable geology, and an extraction method well suited to the deposit type. Most of the country's major uranium deposits are sandstone-hosted and are extracted using in-situ recovery (ISR), a method that is particularly effective in permeable sedimentary aquifers. The development of ISR in Kazakhstan commenced in the late 1960s and early 1970s, and subsequent exploration increasingly focused on sedimentary basins with ISR potential ([Dahlkamp, 2009](#)). This technological compatibility between deposit type and extraction method is a primary reason for Kazakhstan's emergence as the world's leading uranium producer.

In geological terms, Kazakhstan's most important uranium provinces include the Chu-Sarysu and Syrdarya basins, where large regional groundwater systems, thick sedimentary aquifers, and extensive oxidation fronts created ideal conditions for sandstone-hosted uranium mineralization. [Petrov \(1998\)](#) regarded the Chu-Sarysu province as one of the largest uranium provinces in Eurasia

and listed major deposits such as Mynkuduk, Inkai, Kanjugan, Moinkum, and Tortkuduk among the most significant uranium accumulations in the country. This regional setting provides the broader geological framework for interpreting the South Tortkuduk field examined in the present study.

2.4 In-Situ Recovery (ISR) Mining and the Role of Geology

ISR, also called in-situ leaching, is now one of the dominant uranium extraction methods worldwide and the principal method employed in Kazakhstan. A leaching solution is injected into a permeable uranium-bearing aquifer, uranium is dissolved underground, and the pregnant solution is pumped back to the surface for recovery. Compared with conventional open-pit or underground mining, ISR has lower surface disturbance and is particularly effective where uranium occurs in porous sedimentary rocks bounded by less permeable confining units (World Nuclear Association, 2025; Dillinger et al., 2024).

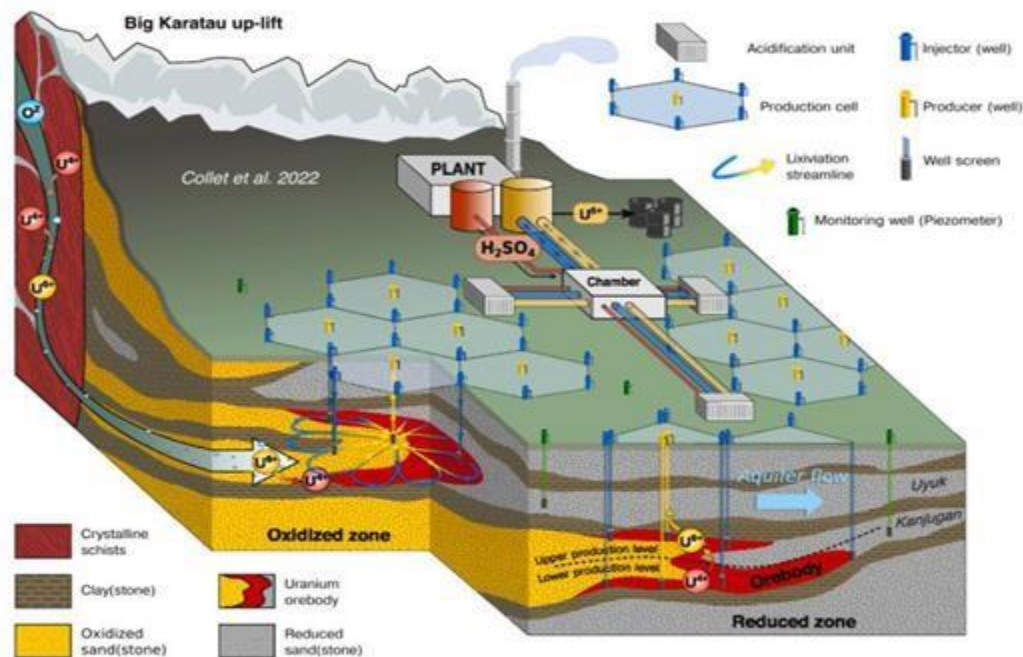


Figure 5. Schematic of the ISR process (Collet et al., 2022).

However, ISR is efficient only where geological conditions are favorable. Host rocks must be permeable enough to allow fluid circulation, laterally continuous enough to sustain hydraulic connectivity, and sufficiently confined to limit solution loss outside the target interval. Dillinger et al. (2024) explicitly stated that continuous circulation of the leaching solution is possible only

where uranium ore occurs in a porous reservoir between impermeable sealing layers, and they emphasized that sedimentological analysis and three-dimensional modelling are required to constrain fluid behavior and optimize production scenarios (Figure 5). ISR performance therefore depends directly on the geometry of reservoir and non-reservoir facies.

This dependence makes geological heterogeneity one of the central practical problems in ISR. Mud plugs, floodplain fines, abandoned channels, inclined heterolithic strata (IHS), carbonate-cemented layers, erosional incision, and stratigraphic truncation may all alter permeability, redirect flow, isolate compartments, or increase reagent consumption. In practical terms, ISR operates as a hydrogeological process within a stratigraphically complex sedimentary system, which is why understanding depositional architecture is essential for mine planning and why sequence stratigraphy has direct operational value in uranium fields.

A second major issue is acid consumption. In acidic ISR systems, sulfuric acid reacts not only with uranium-bearing minerals but also with non-ore minerals, especially carbonates. Carbonate-bearing intervals consume acid before it reaches the target uranium minerals, reducing leaching efficiency and increasing reagent costs. In addition, reactions involving calcium and sulfate may promote gypsum precipitation, which can further reduce permeability by coating pore walls or narrowing pore throats. This problem is both geochemical and stratigraphic, because carbonate cementation is commonly concentrated in specific facies belts or near key surfaces rather than uniformly distributed throughout the orebody.

This point is directly relevant to South Tortkuduk. Internal stratigraphic work from the study area indicates that weak calcite cement occurs near the uppermost parts of Belt 2 and within the Tr-MFS Belt and is likely associated with marine influence during transgression. If correct, this implies that acid consumption risk may be predictable from sequence-stratigraphic architecture rather than treated as random local variability - an insight that constitutes one of the central conceptual foundations of the present thesis.

2.5 Transgression: Definition and Significance

Transgression refers to the landward migration of the shoreline during relative sea-level rise. More broadly, it describes the stratigraphic and geomorphic response of coastal and shallow-marine systems when accommodation increases faster than sediment supply, causing facies belts to

backstep landward. [Hein and Kirwan \(2024\)](#) define marine transgression as a process associated with rising sea level that causes coastal erosion, landscape transitions, and landward translation of coastal environments, and emphasize that transgression reflects the inability of sediment delivery to keep pace with accommodation creation.

In sequence-stratigraphic literature, transgressive deposits are understood as sediments that accumulate during rising relative sea level and landward shoreline migration. [Cattaneo and Steel \(2003\)](#) noted that transgressive deposits may be recognized by gradual or irregular landward shifts of facies or by upward deepening culminating in a surface or zone of maximum flooding. They also stressed that transgression commonly involves ravinement, whereby wave and tidal processes erode and cannibalize earlier deposits during shoreline retreat. Transgressive successions are therefore commonly marked by erosional surfaces as well as by muddy condensed intervals.

In the context of uranium systems, transgression is significant for at least three reasons. First, transgressive sands may form laterally continuous permeable pathways favorable for fluid migration. Second, transgressive and maximum flooding muds may form low-permeability barriers that compartmentalize the aquifer system. Third, marine influence during transgression may introduce or redistribute carbonate cements that subsequently affect ISR acid consumption. In South Tortkuduk, all three of these effects are potentially present, making the transgressive interval much more than a passive chronostratigraphic marker.

2.6 Identification of Transgressive Deposits and Maximum Flooding Surfaces

Recognition of transgression in sedimentary successions generally requires the integration of multiple lines of stratigraphic and sedimentological evidence. At the facies scale, classic indicators include upward-deepening trends, retrogradational stacking, marine facies overlying non-marine deposits, polymictic lags, ravinement surfaces, shell-rich or reworked horizons, and condensed muddy intervals. [Cattaneo and Steel \(2003\)](#) emphasized that transgressive successions may be identified either by the systematic landward shift of facies or by upward deepening culminating in a maximum flooding surface (MFS) or flooding zone, and that transgression is commonly associated with erosional reworking.

The MFS is particularly important because it represents the stratigraphic position of greatest landward shoreline migration and, in many settings, the point of maximum accommodation and

maximum marine influence within a depositional cycle. In siliciclastic systems, it is commonly associated with the finest-grained, most condensed, and lowest-energy deposits within a transgressive-to-highstand transition. [Cattaneo and Steel \(2003\)](#) noted that the MFS typically corresponds to the deepest or most offshore facies within the local stratigraphic trend and commonly forms a downlap surface for overlying regressive deposits. From a subsurface standpoint, the MFS often coincides with low-permeability muddy intervals that may act as barriers to vertical flow.

In subsurface studies, the identification of transgression commonly relies on integrated analysis of well logs, core data, and regional cross-section correlation. Coarse basal lags, abrupt erosional contacts, upward-fining motifs, sharp transitions from sand-prone to mud-prone intervals, and log signatures corresponding to flooding muds are all useful criteria. Where core is available, transgressive deposits may also be recognized by reworked grain assemblages, shell or pebble lags, mixed sediment textures, abrupt facies juxtapositions, and evidence of ravinement. The reliability of interpretation increases significantly when these signals are traced across multiple wells rather than interpreted in isolation ([Cattaneo and Steel, 2003](#); [Smagambetov, 2024](#)).

This logic is directly applicable to the South Tortkuduk framework. The internal belt-based interpretation of the field identifies the transgressive interval by a coarse polymictic lower part interpreted as ravinement-related, followed by upward fining into finer-grained deposits corresponding to the maximum flooding interval, above which the succession becomes sandier again in overlying deltaic or marginal-marine deposits. This architecture is consistent with transgressive-to-regressive evolution in a low-gradient paralic setting.

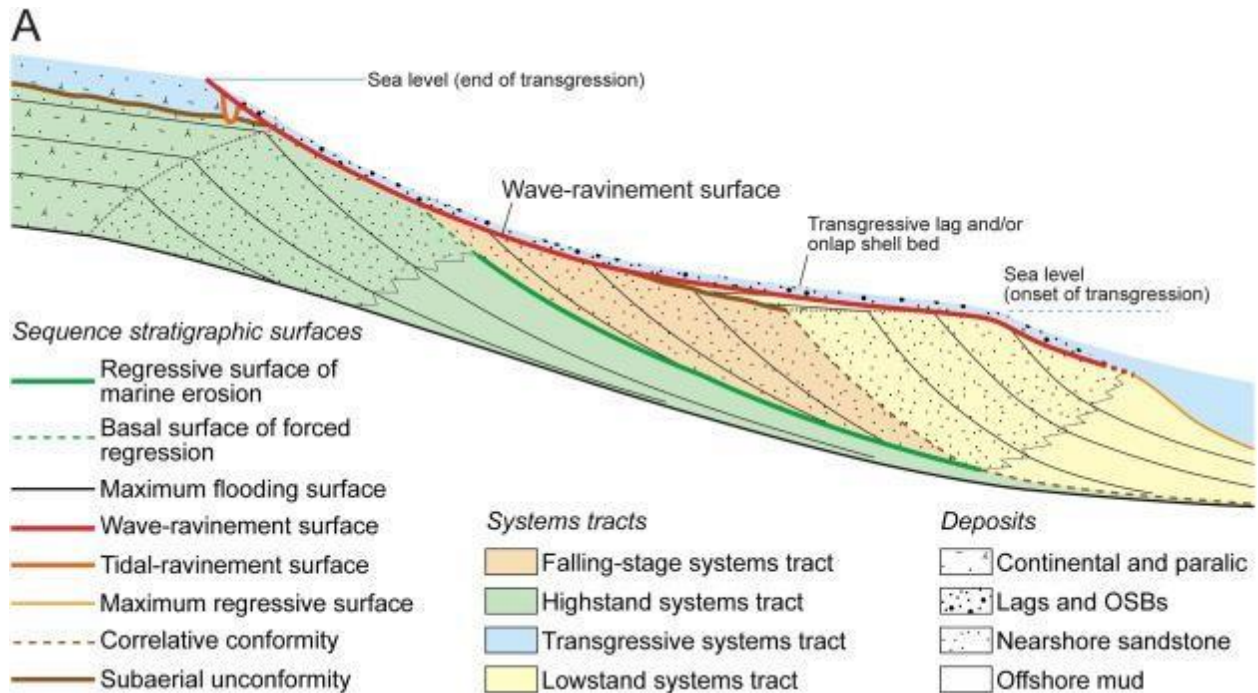


Figure 6. Idealized downdip profile of the wave-ravinement surface (WRS), truncating previously accumulated systems tracts and older surfaces (Zecchin and Catuneanu, 2013).

2.7 Sequence Stratigraphy and its Application to South Tortkuduk

Sequence stratigraphy provides a framework for organizing depositional architecture into genetically meaningful units bounded by key surfaces. In fluvial and marginal-marine successions as shown (Figure 6), this is particularly useful because sandbody continuity, floodplain preservation, channel stacking, and erosional truncation are all strongly influenced by accommodation changes, base-level fluctuations, and autogenic channel dynamics. Dillinger et al. (2024) interpreted the Paleocene to Eocene succession of the Chu-Sarysu Basin as the product of tectonics, climate, eustasy, and autogenic processes, and argued that sea-level changes linked to the Peri-Tethys and Turan Sea exerted major first-order control on reservoir architecture.

The South Tortkuduk internal stratigraphic framework applies this logic at field scale. Based on cross-sections, core-to-log correlation, and KS-log interpretation, the deposit has been subdivided into five major units: Belt 1, Belt 2, the Tr-MFS Belt, Belt 3, and Belt 4. Belt 1 is associated with the most complex reservoir heterogeneity and abundant IHS. Belt 2 is dominantly sandy but capped by an erosional transgressive surface. The Tr-MFS Belt contains polymictic transgressive

sand, flooding mud, and reported calcite cement. Belt 3 shows major thickness variation and local erosion of the MFS, and Belt 4 occupies the upper preserved succession.

This belt model links stratigraphy directly to ISR behavior. It highlights where reservoir connectivity is favorable, where compartmentalization is severe, where the MFS mud is preserved, and where carbonate-rich intervals may increase acid consumption. In this sense, sequence stratigraphy in South Tortkuduk is not simply a descriptive framework; it is the basis for understanding how geologic architecture controls mine-scale performance.

3. Geological Setting of the Study Area

3.1 Regional Setting: Chu-Sarysu Basin

The study area is located in the South Tortkuduk sector of the Chu-Sarysu Basin in southern Kazakhstan, one of the most important sandstone-hosted uranium provinces in Central Asia ([Figure 1](#)). The basin is a large northwest-trending sedimentary depression approximately 600 km long and 250 km wide, situated on the tectonically stable Turan Platform. Throughout much of its Late Mesozoic and Cenozoic evolution, the Chu-Sarysu Basin formed part of a broader sedimentary system connected to the Syrdarya Basin to the southwest; both basins are now separated by the uplifted Karatau Range. This regional relationship reflects later structural partitioning superimposed on an originally larger Cretaceous to Paleogene depositional complex ([Dillinger et al., 2024](#); [Petrov, 1998](#); [Allen et al., 2001](#)).

From a structural perspective, the Chu-Sarysu Basin occupies the eastern margin of the Turan Platform and is bounded by the Chu Arch to the northeast and the Kyrgyzian Range to the south, while the eastern part of the basin is influenced by the Talas-Tastynsk Uplift ([Dillinger et al., 2024](#)). [Dahlkamp \(2009\)](#) likewise emphasized the basin's position between uplifted basement blocks and noted the importance of the Karatau mountain belt to the southwest, the Chuily-Kendyktas Uplift to the northeast, and the Ulutau Massif to the north. These structural features influenced accommodation, sediment supply, regional groundwater circulation, and the spatial distribution of mineralized horizons across the basin.

The Tortkuduk–Moyunkum mining area lies within the Suzak depression, identified by [Dillinger et al. \(2024\)](#) as the most subsided part of the basin, likely deepened in response to uplift of the Karatau Range. The depression is bounded by the WNW-striking Suzak Fault to the south and the NW-striking Zhuantovin Fault to the north, both propagating through Paleozoic basement. This structural segmentation helps explain lateral differences in stratigraphic thickness, preservation of transgressive facies, and the geometry of uranium-bearing aquifers within the South Tortkuduk field.

The sedimentary fill of the Chu-Sarysu Basin records a long history of continental and shallow-marine deposition. [Dillinger et al. \(2024\)](#) describe the basin as containing up to approximately 800 m of Cretaceous to Quaternary strata unconformably overlying older Paleozoic and Mesozoic sedimentary rocks and Palaeozoic to Proterozoic metamorphic basement. [Dahlkamp \(2009\)](#) provides a broader regional synthesis, noting that the basin contains up to 2000 m of Quaternary to Cretaceous sediments divided by a major unconformity into an upper Neogene to Quaternary unit and a lower uranium-bearing Upper Cretaceous to Eocene unit. The lower unit is most relevant for the present study because it contains the permeable sand and gravel-sand horizons that host uranium mineralization and that later became targets for ISR exploitation.

The uranium-bearing lower basin fill consists mainly of unconsolidated to weakly consolidated alluvial, fluvial, deltaic, lacustrine, and marginal-marine sediments of Late Cretaceous to Eocene age. These deposits were laid down on a broad low-gradient alluvial plain along the eastern margin of the Turan Platform, where high-permeability arenitic units alternated with finer-grained clayey and silty intervals acting as aquitards. [Dahlkamp \(2009\)](#) notes that an Upper Eocene clay horizon acts as the upper regional confining unit, while older lithified rocks below the pre-Cretaceous unconformity form the lower boundary. This combination of permeable host beds and confining mudstone intervals is one of the essential geological reasons why the basin became favorable both for sandstone-hosted uranium mineralization and for ISR mining.

During the Paleogene, the Turan Platform formed part of the north-south-trending Central Eurasian epicontinental seaway system that connected the Arctic and Peri-Tethys oceans through shallow marine passages, including the West Siberian Sea, the Turgay Strait, and the Turan Sea. Following a major regression at the Cretaceous–Paleogene boundary, the region experienced several important transgressions during the Paleocene and early Eocene before the Turan Sea began to

retreat in the middle Eocene. [Dillinger et al. \(2024\)](#) argue that these eustatic events, together with climate shifts and local accommodation changes, exerted first-order control on the architecture of the Paleocene to Eocene reservoir succession. This regional marine connectivity is fundamental to the present study because it provides the context for the development of transgressive deposits, ravinement surfaces, and flooding muds within the South Tortkuduk succession.

3.2 Uranium Geology of the Basin

Uranium mineralization in the Chu-Sarysu Basin is dominantly of roll-front type. Ore bodies occur along redox fronts within permeable sandstone aquifers and are commonly hosted in quartz arenites separated by impermeable clay-rich units. [Dillinger et al. \(2024\)](#) note that ore bodies in the Moyunkum and Tortkuduk sectors are typically contained within sandstone intervals less than 1 to 25 m thick at depths of approximately 230 to 500 m, and that the regional lower and upper confinement of these ore-related hydraulic systems is provided respectively by Paleozoic rocks and middle Eocene shales.

[Petrov \(1998\)](#) described the ore bodies as epigenetic stratified-infiltration deposits related to regional fronts of layered oxidation, emphasizing that their formation depended on post-depositional groundwater circulation through porous strata rather than on syndepositional concentration. In this model, uranium was mobilized in oxidizing groundwater, transported through permeable sand-dominated units, and precipitated where those fluids encountered reducing conditions within the basin-fill architecture.

[Dahlkamp \(2009\)](#) characterized ore bodies in the Chu-Sarysu Basin as ribbon-like and sinuous in plan view and as roll-shaped, lenticular, or tabular in cross-section, often aligned with dynamic regional oxidation fronts. A defining feature of the basin is the multilevel nature of uranium mineralization; rather than being confined to a single stratigraphic bed, mineralization occurs in several permeable Cretaceous to Paleogene horizons separated by lower-permeability units, allowing uranium to accumulate over very large areas within a stratified hydrogeological framework.

Mineralogically, the dominant uranium minerals in the Tortkuduk mining area are coffinite and pitchblende, while associated minerals commonly include pyrite, hematite, and goethite. [Smagambetov \(2024\)](#) noted that mineralization is hosted mainly in unconsolidated quartz-rich

sands with low clay content, and that ore mineral precipitation occurred in permeable horizons during post-depositional fluid–rock interaction. The industrial development of the basin is directly tied to its geology; ISR methods were tested successfully beginning in the late 1960s and early 1970s, after which exploration and production increasingly focused on deposits with favorable hydrogeological confinement ([Dahlkamp, 2009](#)).

For South Tortkuduk specifically, the basin-scale uranium geology provides the essential context for interpreting local reservoir behavior. The field belongs to a province where ore formation depended on the interaction between permeable fluvial to marginal-marine sands, layered oxidation systems, and regional groundwater circulation. However, local reservoir architecture is highly heterogeneous. [Smagambetov \(2024\)](#) demonstrated that mud plugs, floodplain bodies, delta-plain facies, and inclined heterolithic strata can significantly influence fluid migration during ISR. This means that the uranium geology of the basin cannot be separated from the stratigraphic architecture of the host succession, especially where major surfaces such as the transgressive interval may have reorganized aquifer geometry and facies continuity.

3.3 South Tortkuduk and the Belt-Based Local Framework

At the local study scale, the South Tortkuduk succession is most effectively described using a belt-based sequence-stratigraphic framework derived from cross-section interpretation, well-log correlation, core observations, and internal geological mapping ([Figure 8](#)). This framework translates regional stratigraphy into mining-relevant architectural units that directly reflect reservoir geometry, non-reservoir distribution, and hydrogeological behavior during ISR. The studied interval is subdivided into five principal units: Belt 1, Belt 2, the Tr-MFS Belt, Belt 3, and Belt 4. Together, these belts organize the upper Paleocene to lowermost Eocene succession into a field-scale framework suitable for evaluating the transgressive surface as a first-order control on reservoir architecture ([Smagambetov, 2024](#); [Dillinger et al., 2024](#)).

Belt 1 forms the lower part of the studied interval and is the most internally complex unit in terms of heterogeneity. It is associated with an incised-valley style of organization and contains abundant clay-dominated geobodies, including mud-filled abandoned channels and widespread inclined heterolithic strata in upper point-bar settings. These features reduce lateral connectivity within otherwise sand-prone intervals and create anisotropy at scales relevant to ISR flow behavior.

Belt 2 is more dominantly sandy and is composed mainly of fluvial point-bar and channel-fill deposits with better reservoir continuity than Belt 1. It preserves a generally fining-upward fluvial architecture but is capped by a major erosional transgressive surface — one of the most important stratigraphic relationships in the study area, marking the transition from primarily fluvial organization below to transgressive reworking above. The uppermost part of the belt also contains weak calcite or carbonate-reactive material interpreted as being associated with marine influence during transgression.

The Tr-MFS Belt is the key unit for the present thesis because it contains the central transgressive and flooding elements of the local succession. This belt begins with a polymictic sand-rich interval at the base, interpreted as ravinement-related transgressive deposits, and fines upward into a muddy interval interpreted as the maximum flooding surface or zone. The local framework explicitly identifies this belt as a polymictic carbonate zone, which is significant because it suggests that transgression introduced carbonate-reactive material with later implications for ISR chemistry. The interval therefore combines two contrasting hydrogeological functions: permeable transgressive sand that may favor lateral fluid movement, and overlying flooding mud that may act as a vertical barrier.

Belt 3 displays the greatest local thickness variation and records strong post-transgressive incision and channelization. In deeply incised areas, erosion may remove part of the flooding mud and compromise the underseal, creating direct implications for vertical containment and fluid prediction during ISR. Belt 3 therefore defines the main zone in which preservation versus erosional loss of the MFS must be evaluated spatially.

Belt 4 forms the upper part of the preserved succession and is described as mostly fluvial point bars, indicating that the upper succession returns to predominantly fluvial organization above the more complex transgressive and incisional architecture below. Belt 4 defines the upper architectural boundary of the studied succession. Taken together, the belt model links sequence stratigraphy directly to mine-scale geological behavior. It shows where reservoir connectivity is likely to be favorable, where internal compartmentalization is strongest, where flooding muds are preserved, where the underseal may have been removed by erosion, and where carbonate-reactive intervals are most likely to increase acid consumption or promote secondary mineral precipitation. For the present thesis, the most important implication of this framework is that the transgressive

surface and associated Tr-MFS Belt are best understood within their full local stratigraphic context.

4. Methodology

4.1 Core Description and Facies Analysis

The first stage of the methodological workflow consisted of targeted core description and facies analysis designed specifically to identify the transgressive interval in the South Tortkuduk succession. The main purpose of core logging was not only to describe reservoir lithologies in a general sedimentological sense, but to recognize the sedimentological and diagenetic criteria indicating the presence of transgression. In particular, the core-based work focused on identifying evidence for a ravinement-related transgressive surface, associated polymictic sand, upward fining into flooding mud, and possible carbonate-cemented intervals that could reflect marine or marginal-marine influence and have implications for ISR behavior.

The broader geological logic of this approach follows directly from the interpretation adopted in this thesis. If the studied interval represents a transgressive package developed across the Paleocene to Eocene transition, it should contain sedimentological indicators different from those of the underlying fluvial reservoir succession. These indicators may include an erosional or reworked basal contact, a polymictic sand-rich lower part interpreted as ravinement-related, finer-grained muddy deposits corresponding to flooding, and local carbonate-bearing material linked either to marine influence or to diagenetic modification of the transgressive interval. The core analysis was therefore designed to test whether such features could be recognized directly in the available material before being transferred to well-log and cross-sectional interpretation.

The core material available for the study consisted mainly of historical cores from the South Tortkuduk reservoir interval. Because the reservoir is hosted in unconsolidated to weakly consolidated sand-rich deposits, core preservation was often poor; many intervals were fragmented, loosely packed, or partly missing due to earlier handling, cutting, sample extraction, and long-term storage. Despite these limitations, core remained the most direct source of geological information for identifying lithological contrasts, textural variability, and cementation features that could not be resolved from logs alone. Logged intervals were aligned with available

master logs to refine depth matching and reduce uncertainty introduced by incomplete recovery or disturbed core condition.



Figure 7. Example of historical core material used for sedimentological description in South Tortkuduk, illustrating the unconsolidated character of the reservoir and the preservation challenges of the core dataset. (Smagambetov et al., in preparation).

The first objective of core description was to characterize the lithology of the studied interval and its vertical organization. Particular attention was given to grain size, sorting, textural changes, mud content, vertical fining or coarsening trends, and contact relationships between sand-dominated and mud-dominated intervals (Figure 7). This was important because recognition of transgression in the South Tortkuduk reservoir depends partly on distinguishing the transition from underlying fluvial sand bodies into the more reworked and heterolithic architecture of the transgressive interval.

The second objective was to identify features supporting the interpretation of a ravinement surface or ravinement-related deposits. In sedimentological terms, ravinement is commonly associated with erosional reworking, sharp lithological breaks, mixed grain populations, and the concentration of coarse or polymictic material at the base of a transgressive package. The core was therefore examined for evidence of abrupt facies shifts, reworked basal intervals, coarse-grained or compositionally mixed sands, and textural contrasts distinguishing a transgressive base from ordinary fluvial fining-upward architecture.

A third objective was to test for carbonate cement within the studied interval. Facies and visually cemented intervals in core were tested with dilute hydrochloric acid in order to identify whether visible cementation or lithological hardening corresponded to carbonate-bearing zones. The results showed that carbonate-reactive intervals do occur within or near the transgressive part of the succession, which is significant because carbonate-bearing material may influence ISR behavior through acid consumption. Although the acid test was not intended to replace mineralogical or geochemical analysis, it provided practical field evidence that the transgressive interval is diagenetically distinct from the underlying fluvial reservoir sands.

4.2 Parallel Cross-Sections

After the core-based recognition stage, the next methodological step consisted of correlating the interpreted transgressive interval laterally across the study area using parallel cross-sections. The purpose of this stage was to determine whether the transgressive interval recognized in core could be traced as a laterally meaningful stratigraphic body and whether its internal organization was sufficiently consistent to distinguish a basal transgressive component, a flooding interval, and zones of local erosion or non-preservation.

The correlation workflow followed a sequential procedure (Figure 8). First, the interval of interest was identified in core-controlled wells using the sedimentological observations described in Section 4.1. Second, these observations were compared with corresponding KS and gamma-ray signatures in the same wells to establish log-based criteria for recognizing the interval in uncored wells. Third, these calibrated log motifs were correlated between wells on parallel cross-sections to reconstruct the geometry of the transgressive interval and its relationship to the surrounding belts.

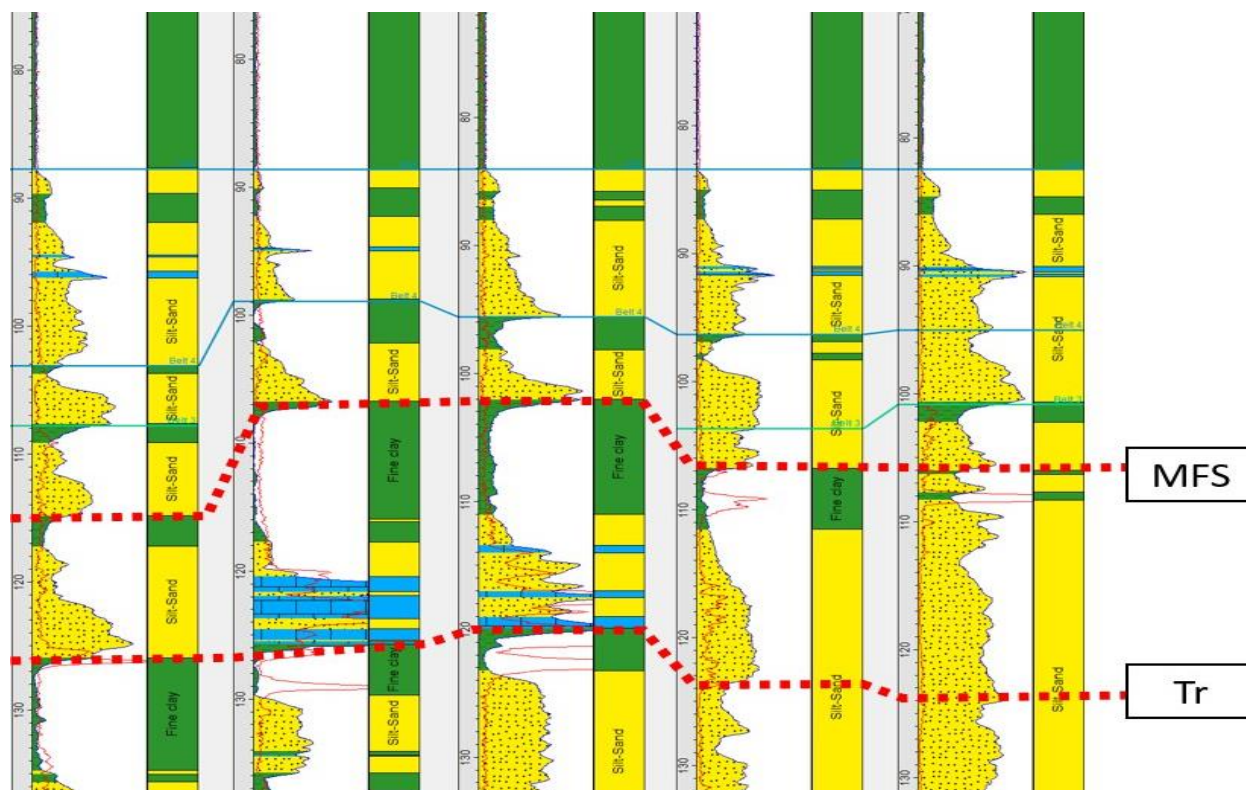


Figure 8. Representative cross-section used for lateral correlation of the South Tortkuduk succession, showing the well-to-well tracing of major belt boundaries and the stratigraphic position of the transgressive interval within the local framework.

The main geophysical basis for this correlation was the KS resistivity log, supported where necessary by gamma-ray trends and the broader internal belt framework. Lower resistivity values tend to correspond to mud-rich, low-permeability intervals, whereas higher resistivity commonly marks cleaner and more porous reservoir sands. The critical task was to identify the characteristic architecture of the transgressive interval: a lower reworked or polymictic sand-rich part followed by upward fining into a finer-grained flooding interval, with later local modification by incision or erosion.

This correlation was a geologically constrained interpretation based on four linked criteria: core-calibrated facies criteria, KS-log architecture, vertical stacking patterns, and sequence-stratigraphic logic. A sandy interval, for example, might represent either ordinary fluvial reservoir sand or reworked transgressive sand unless its position, internal texture, and overlying muddy succession were considered together. Likewise, a mud-rich zone could only be treated as a flooding interval when supported by its stratigraphic context and associated facies relationships. The use of neighbouring wells was especially important because single-well interpretation alone would not

have been sufficient to distinguish a local facies change from a broader field-scale stratigraphic relationship.

4.3 Slice Maps / GDE Maps

The third methodological component consisted of the interpretation of slice maps, also referred to in the internal workflow as gross depositional environment (GDE) maps. These maps were used to analyze the lateral distribution of lithological trends, stratigraphic surfaces, and depositional bodies in plan view, extending the cross-sectional interpretation into a field-scale geometric framework. In the South Tortkuduk workflow, slice mapping functioned as a central interpretive method for testing lateral continuity, identifying depositional patterns, and refining the geometry of the final conceptual geobodies.

After the transgressive interval had been recognized and correlated in vertical section, attention was focused on a specific stratigraphic window - the Tr-MFS interval. For each well intersecting this interval, the relative proportions of sand and mud were evaluated within the selected stratigraphic slice. These lithological proportions were then transferred to plan view. In the working mapping convention (Figure 9), sand-rich intervals were marked in red and mud-rich intervals in green. This well-by-well posting created the first level of spatial information needed to assess lateral variability within the transgressive interval.

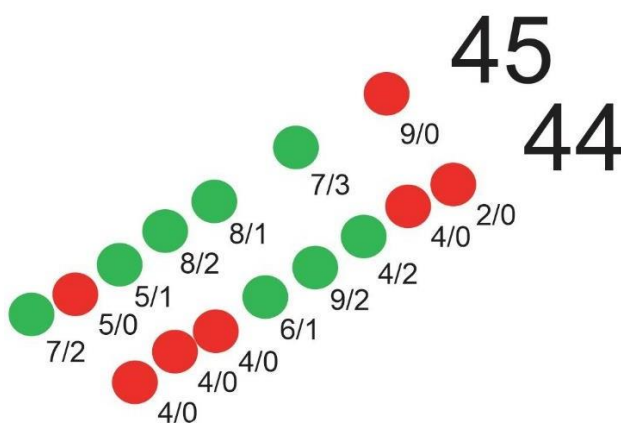


Figure 9. Initial well-based coding of sand and mud proportions within the Tr-MFS interval used as input for slice-map interpretation; red indicates sand-rich intervals and green indicates mud-rich intervals. (Smagambetov et al., in preparation).

The next step was to convert posted lithological observations into an interpretive map. Wells were compared in spatial context, and areas of similar sand/mud distribution were outlined to define

broader depositional patterns. During this process, attention was given not only to the sand/mud ratio itself but also to possible alignments, clustering, cross-cutting relationships, basinward trends, and directional elongation of mapped elements. This made it possible to distinguish preserved muddy flooding zones, eroded areas, and sectors showing an upward-coarsening or sand-prone character. In this sense, the slice maps were used to reconstruct the lateral organization of the Tr-MFS interval in geological terms.

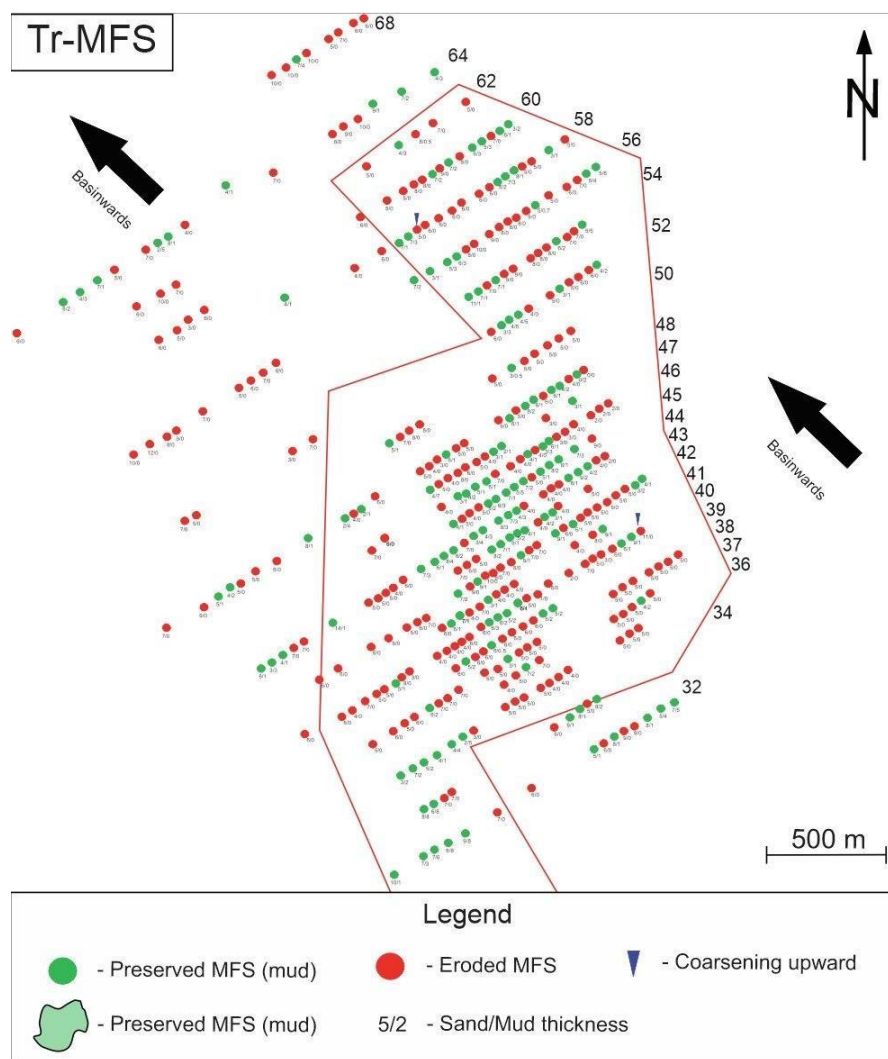


Figure 10. In this map, plotted well data are integrated into a field-wide interpretation showing the distribution of preserved maximum flooding mud, eroded areas, and local coarsening-upward sectors. This map represents the final plan-view interpretation of the Tr-MFS interval used in the methodological workflow. (Smagambetov et al., in preparation).

Although the three methodological stages were carried out separately, they formed a single integrated workflow. Core description provided the sedimentological criteria needed to distinguish

reservoir and non-reservoir facies. Cross-sections allowed those criteria to be correlated laterally and translated into a coherent local stratigraphic framework. Slice maps (Figure 10) then extended that interpretation into plan view and made it possible to evaluate the geometry and continuity of the transgressive interval across the field. In this integrated workflow, each stage constrained the next: core calibrated logs, cross-sections constrained slice maps, and slice maps refined the interpretation of field-scale architecture.

5. Results

5.1 Results of Core Description and Facies Analysis

The core-description stage provided the first direct geological evidence for the presence of a transgressive interval in the studied South Tortkuduk succession. The main finding was that the interval of interest could be distinguished from the surrounding fluvial reservoir architecture not only by its stratigraphic position but also by its internal lithological character. Core observations showed that the studied interval contains evidence of reworking, coarse-grained material, and upward facies change, supporting its interpretation as a transgressive unit rather than as an ordinary fluvial fining-upward package.

A key outcome of core logging (Figure 11) was the identification of polymictic gravel material at the base of the studied interval. This observation provided direct support for the interpretation of a ravinement-related transgressive base. The presence of gravelly and compositionally mixed clasts indicates a reworked interval produced by erosional and transport processes rather than by simple in-channel deposition alone. In the context of this thesis, the polymictic gravel is therefore interpreted as one of the strongest sedimentological indicators of transgression within the local succession.



Figure 11. Example of core from the studied interval showing coarse polymictic gravel material interpreted as evidence of a transgressive and ravinement-related base. (Smagambetov et al., in preparation).

Core description was recorded using EasyCore (Figure 12), which allowed lithology, texture, sedimentary structures, sedimentary cycles, rock colour, and sorting to be documented in a standardized vertical format. This enabled observations to be organized stratigraphically, so that key trends such as coarsening-upward and fining-upward successions could be recognized with confidence. In the transgressive interval, the logged core showed that coarse and reworked lower deposits could be followed upward into finer-grained material, supporting the broader interpretation of a basal transgressive sand overlain by a more muddy flooding interval.

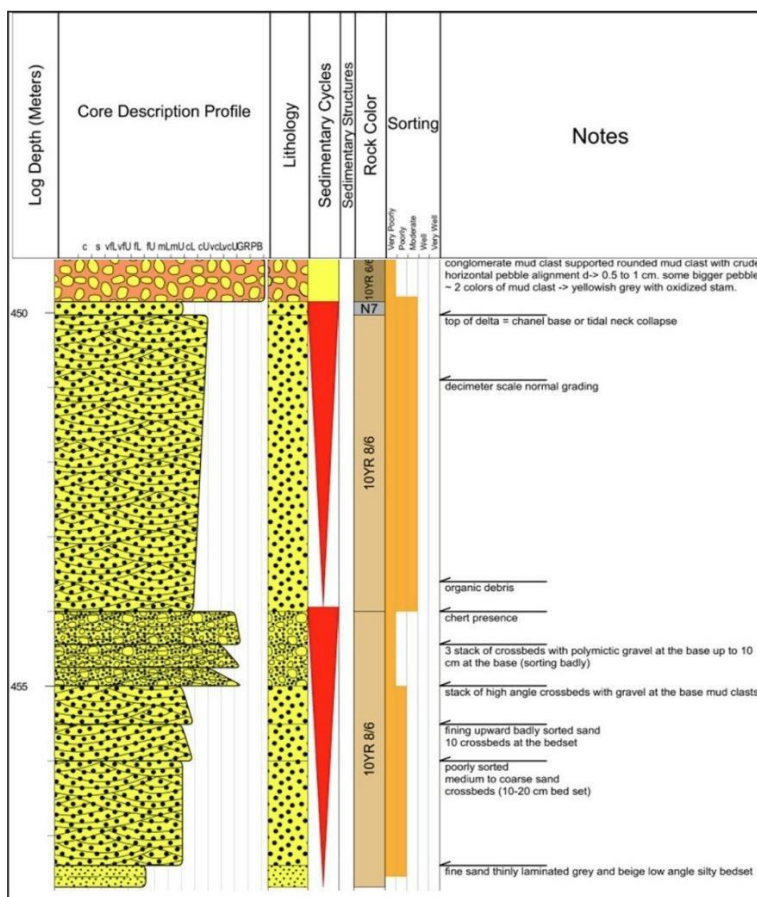


Figure 12. Easy-Core sedimentological log of the described interval showing lithology, sedimentary structures, sorting, and vertical facies organization used to identify the transgressive interval. (Smagambetov et al., in preparation).

An important additional result was the recognition of intervals suspected to contain carbonate cement or carbonate-reactive material. During description, selected facies were tested with dilute hydrochloric acid to determine whether visible cementation or lithological hardening corresponded to carbonate-bearing zones. The results showed that such intervals occur within or near the transgressive part of the succession. Although the acid test was not intended to establish a full geochemical classification, it provided practical evidence that the transgressive interval is diagenetically distinct from the underlying fluvial reservoir sands and may influence ISR behavior through acid consumption.

In summary, the core-description stage produced three major conclusions. First, the studied interval contains reworked coarse polymictic material consistent with a transgressive or

ravinement-related base. Second, the interval shows vertical facies organization compatible with a transgressive-to-flooding trend. Third, core observations identified carbonate-reactive zones, which increase the hydrogeological and operational importance of the interval.

5.2 Results of Cross-Section Correlation

The cross-section stage demonstrated that the transgressive interval identified in core could be recognized in subsurface correlation and traced laterally between wells. This was a critical result because it showed that the interpreted transgression is not restricted to one isolated core observation but forms a laterally meaningful stratigraphic feature within the local South Tortkuduk framework.

The first major result was that the core-defined interval could be tied to a recognizable log expression in neighbouring wells. The interval identified in core as showing transgressive characteristics was associated in cross-section with a distinct coarsening-upward motif and a specific position within the local belt-based architecture. Once this log motif had been calibrated against the core description (Figure 13), it became possible to search for the same interval laterally in adjacent wells and test whether it could be correlated as part of a wider stratigraphic surface or body system.

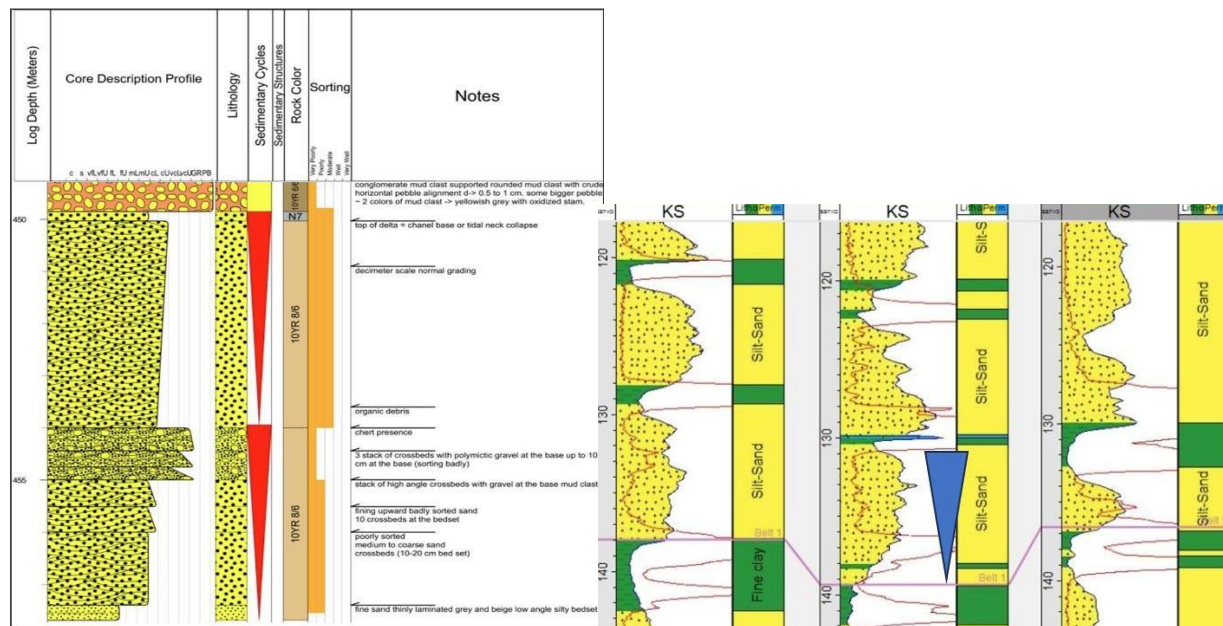


Figure 13. Example of log-based recognition of the transgressive interval, showing the coarsening-upward pattern within this interval and its relationship to the EasyCore sedimentological log. (Smagambetov et al., in preparation).

The cross-sections showed that the transgressive interval is not horizontally uniform. Instead, it varies laterally in thickness, geometry, and degree of preservation. In some wells the transgressive body is expressed clearly and can be followed with confidence, whereas in others it appears thinner, more mixed, or partly eroded. This result supports the interpretation that the transgressive interval was affected not only by original deposition but also by later erosion, incision, or differential accommodation across the field. The cross-sections therefore confirmed that the transgressive surface and overlying interval are best treated as a laterally variable stratigraphic feature rather than a flat and uniform layer.

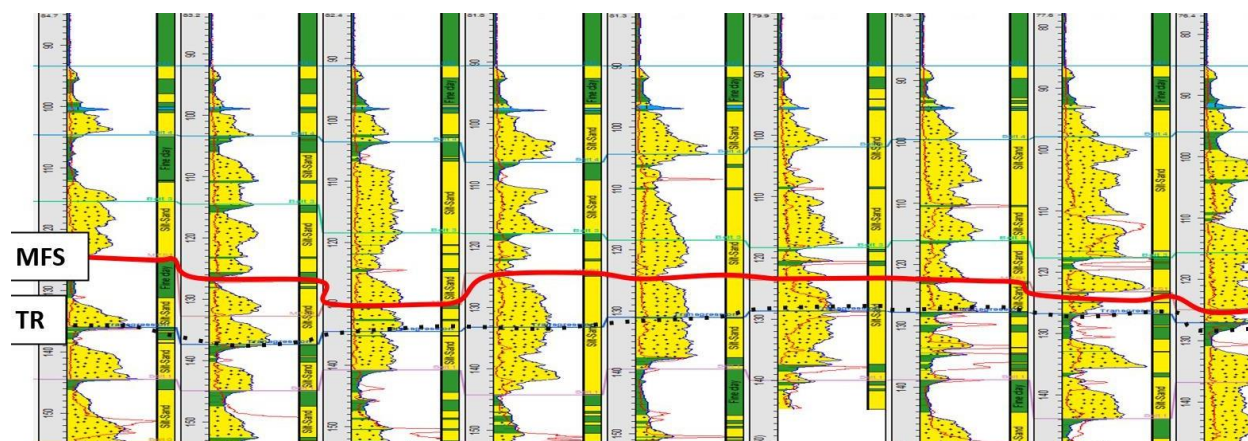


Figure 14. Representative cross-section showing the lateral correlation of the transgressive interval across multiple wells within the South Tortkuduk framework. (Smagambetov et al., in preparation).

Correlation through cross-sections also allowed the transgressive interval to be positioned more securely relative to the surrounding units. In the local framework (Figure 14), it could be recognized above the dominantly fluvial architecture of Belt 2 and beneath overlying younger deposits, helping to separate the transgressive interval from adjacent fluvial sands and clarifying that the interval occupies a discrete position within the South Tortkuduk succession.

Taken together, the results of the correlation stage show that the transgressive interval is laterally traceable but spatially variable. It can be identified in cross-section through a combination of core calibration, log architecture, and stratigraphic position, and it is preserved sufficiently well to be mapped as a distinct local element. At the same time, the cross-sections indicate clearly that

preservation is incomplete and that local erosion or mixing affects the interval in some parts of the field - providing the direct motivation for the final stage of the work.

5.3 Results of Slice-Map Interpretation

The slice-map stage produced the clearest field-scale result of the study. By mapping the Tr-MFS interval in plan view, it became possible to distinguish where the maximum flooding surface (MFS) mud is preserved and where it has been eroded or removed. This result is fundamental to the thesis because it demonstrates that preservation of the transgressive interval is spatially uneven across South Tortkuduk.

The final slice map indicates that where the MFS mud is preserved, the transgressive interval beneath it is also preserved more clearly and can be interpreted with greater confidence. In these areas, the transgressive sands remain stratigraphically organized beneath the flooding mud, and the interval retains its expected architecture of lower transgressive sand and overlying muddy flooding deposits. These preserved sectors are therefore interpreted as the most reliable parts of the field for recognizing intact transgressive architecture.

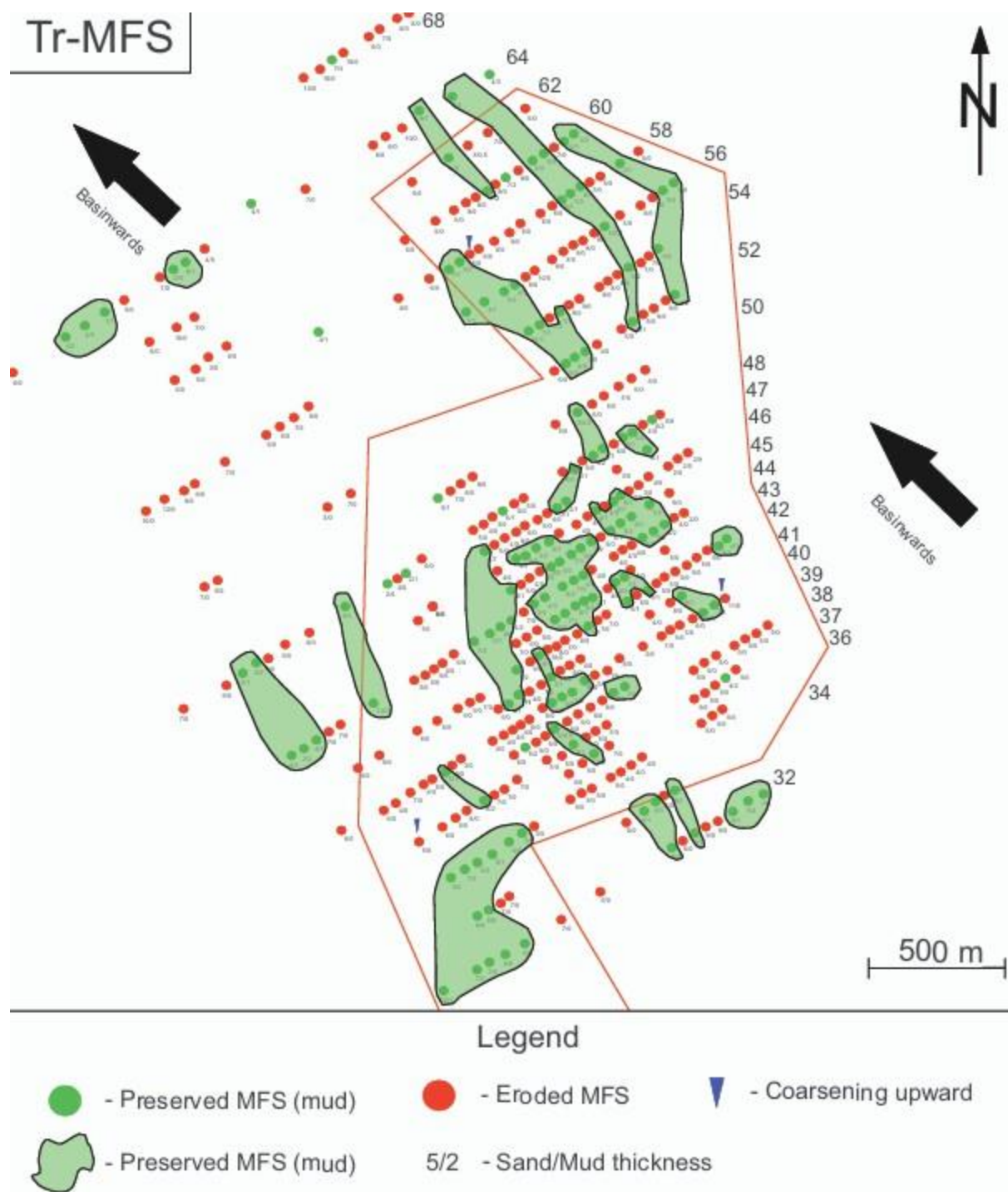


Figure 15. Final slice map of the Tr-MFS interval showing preserved MFS mud, eroded MFS sectors, and the spatial distribution of preserved transgressive architecture across the South Tortkuduk study area. (Smagambetov et al., in preparation).

By contrast, in areas where the MFS is eroded (Figure 15), the transgressive interval becomes much less distinct. In such places, the transgressive package appears thinner, more mixed, or only

weakly preserved, making its identification far less straightforward in isolated wells. One of the most important results of the entire study is that the preservation of the MFS acts as an effective indicator for whether the underlying transgressive interval has also survived in a recognizable form. Where the MFS is absent, the transgressive interval below is commonly incomplete or stratigraphically disturbed.

This result explains why the slice map was necessary. Neither core description nor cross-sections alone could reveal the full spatial pattern of preservation and erosion. The map-based approach made it possible to see that the transgressive interval is not preserved uniformly across the field but occurs in discrete preserved zones separated by areas where the flooding mud has been lost and the transgressive signal has become weak.

The slice map also allows the transgressive interval to be interpreted not only in terms of presence or absence but also in terms of preservation quality. Areas mapped as preserved MFS mud are the most likely places where the transgressive architecture below remains intact and where the lower sand body can be considered stratigraphically reliable. Areas mapped as eroded MFS, by contrast, are less favorable for confident interpretation because the transgressive body there is likely to be incomplete, mixed, or partly removed. This distinction is especially important for the hydrogeological interpretation of the field, because preserved MFS mud may represent local sealing potential, whereas eroded zones may indicate greater vertical openness and less predictable transgressive sand continuity.

6. Discussion

6.1 Stratigraphic Significance of the Transgressive Interval

The results of this study demonstrate that the transgressive interval in South Tortkuduk is stratigraphically meaningful at more than one scale. At core scale, the interval is distinguished by reworked polymictic material, vertical facies change, and transition into finer-grained flooding deposits. At cross-section scale, it can be followed laterally as a discrete interval above the dominantly fluvial architecture of Belt 2 and beneath younger overlying units. At map scale, its preservation is clearly non-uniform and depends strongly on whether the maximum flooding mud is still present. Together, these observations indicate that the transgressive interval is not simply a

local lithological anomaly but a field-scale stratigraphic element that reorganizes the upper Paleocene to lower Eocene succession.

This interpretation is consistent with the broader sequence-stratigraphic framework proposed for the Chu-Sarysu Basin. Transgression across the Paleocene to Eocene transition is expected to produce erosional reworking and ravinement-related coarse deposits, followed by finer flooding facies and subsequently overlying sandier deposits. The South Tortkuduk Tr-MFS Belt fits this general architecture well. The significance of the interval lies in the fact that it marks a change from predominantly fluvial reservoir organization below to a more complex transgressive–flooding architecture above (Dillinger et al., 2024; Cattaneo and Steel, 2003).

An equally important result is that preservation is variable. Where the MFS mud is preserved, the transgressive interval below is also more coherent and easier to interpret. Where the MFS has been eroded, the transgressive package is weaker, thinner, or mixed. This demonstrates that the stratigraphic significance of the interval depends not only on its original formation but also on its later preservation history. The transgressive surface in South Tortkuduk should therefore be treated as a preserved stratigraphic system whose expression changes laterally across the field.

6.2 Carbonate Cement, Gypsum Formation, and Acid Loss

One of the most important practical outcomes of this study is that identification of the transgressive interval is directly relevant to acid-loss risk during ISR. The results suggest that preserved parts of the transgressive interval may contain carbonate-cemented or carbonate-reactive sands, which means that these zones can consume acid before it is used effectively for uranium recovery. In this sense, the transgressive interval is important not simply because it marks a stratigraphic boundary but because it helps identify where ISR injection may be geologically unfavorable.

Core description and acid testing indicate that carbonate-reactive material occurs locally within or near the transgressive interval. Even where structural dip or hydraulic gradient appear favorable, acid introduced into such zones may be lost preferentially through reaction with carbonate-cemented sand. As a result, injected solution may be consumed at an early stage, reducing leaching efficiency and distorting the intended flow behavior. The practical implication is that mapping the transgressive surface and its preserved sands helps identify sectors where acid is likely to be spent on cement reaction rather than on productive uranium dissolution.

A further implication is that carbonate reaction may create secondary chemical effects. Where calcium is released into acidic sulfate-bearing fluids, gypsum precipitation becomes a plausible secondary process. In hydrogeological terms, this may reduce permeability locally, promote clogging, and further divert or slow the movement of leaching solution. The transgressive interval may therefore function not only as a carbonate-reactive zone but also as a location where acid loss, secondary precipitation, and reduced injectivity occur together.

By identifying where the transgressive interval is preserved, the study helps distinguish areas where acid injection may be inefficient or economically unfavorable. The main value of the methodology developed in this thesis is therefore preventive: it allows the interpreter to recognize where acid should not be preferentially injected because the solution may be lost through early reaction with carbonate-cemented transgressive sands rather than contributing effectively to uranium extraction.

6.3 Implications for ISR Optimization

From the perspective of ISR, the main value of this study is that it identifies the transgressive interval as a zone of non-uniform reservoir behavior. The results show that not all parts of the South Tortkuduk reservoir are equally favorable for fluid circulation and containment. Where the MFS mud is preserved, vertical separation is more likely to remain effective and the transgressive architecture below is more intact. Where the MFS is eroded, the interval becomes less predictable and may permit greater vertical communication or mixed flow behavior. ISR planning should therefore account for preservation state, not just ore presence or sandstone thickness.

The belt-based framework is particularly useful in this regard. Belt 1 is highly heterogeneous and likely to generate local flow diversion due to IHS and mud-dominated geobodies. Belt 2 provides the main fluvial reservoir below the transgressive surface. The Tr-MFS Belt marks the most sensitive interval because it combines transgressive sand, flooding mud, and possible carbonate-reactive material. Belt 3 is critical because incision may remove the flooding mud and weaken local confinement. In practical terms, injection and production strategy should be informed by the local preservation of the Tr-MFS interval, especially where sealing muds are absent or where carbonate-rich zones may increase acid loss.

A direct application of the slice-map results is that preserved-MFS areas may represent the most stratigraphically organized parts of the field, whereas eroded-MFS areas require more cautious interpretation. The final map therefore functions not only as a geological result but also as a screening tool for identifying areas where transgressive sand is preserved and where the local architecture is more predictable - particularly useful for acid-risk assessment, well placement, and anticipating unequal sweep efficiency during leaching.

6.4 Limitations

Several limitations should be considered when interpreting the results of this study. First, the core material consisted largely of historical and partly disturbed core from an unconsolidated to weakly consolidated reservoir. Some sedimentological observations are therefore affected by fragmentation, poor preservation, and incomplete recovery. Although master-log alignment improved confidence, some uncertainty remains at the detailed facies level.

Second, the interpretation of the transgressive interval depends strongly on indirect correlation between a limited number of core-controlled wells and a larger uncored log dataset. While this is a standard and necessary approach in subsurface studies, some lateral interpretations remain inferential rather than directly observed. The slice maps improve this significantly, but they still depend on the quality of well-based sand–mud evaluation and on the assumption that the selected stratigraphic window is correctly correlated across the study area.

Third, carbonate-reactive zones were identified by practical acid testing during core description, but this does not replace detailed mineralogical or geochemical analysis. The discussion of carbonate cement, gypsum formation, and acid loss is therefore well grounded conceptually but requires further analytical confirmation for quantitative application. Finally, the present study focuses on the upper Paleocene to lower Eocene transgressive interval and not on the full complexity of the South Tortkuduk reservoir. The conclusions are strongest for the Tr-MFS system itself and should not automatically be generalized to all parts of the field without additional work.

7. Conclusion

This thesis demonstrates that the transgressive interval in South Tortkuduk is not merely a stratigraphic marker but a preserved and operationally significant part of the uppermost Paleocene to lowermost Eocene reservoir succession. Core description, cross-section correlation, and slice-map interpretation show that the interval can be identified as a distinct body system characterized by reworked coarse material at its base, an upward transition into finer-grained flooding deposits, and strong lateral variation in preservation. The results further demonstrate that the best-preserved transgressive architecture occurs where the maximum flooding mud is also preserved, whereas in areas where the MFS is eroded the transgressive interval becomes weak, mixed, or difficult to recognize.

The main practical significance of this study is that recognition of the transgressive surface helps identify where acid injection during ISR is likely to be inefficient. Core description and acid testing indicate that preserved parts of the transgressive interval may contain carbonate-cemented or carbonate-reactive sands, meaning that acid introduced into these zones may be consumed through reaction with cement rather than used effectively for uranium recovery. Mapping the transgressive surface therefore serves not only a stratigraphic purpose but also the identification of zones where acid should not be preferentially injected. The preserved Tr-MFS interval functions as an acid-risk control zone within the South Tortkuduk reservoir.

Taken together, the study shows that the transgressive interval in South Tortkuduk should be treated as both a stratigraphic control and an ISR decision-making surface. By integrating sedimentological description, acid testing, cross-section interpretation, and slice mapping, this thesis provides a practical workflow for recognizing where transgressive sands are preserved, where the MFS remains intact, and where later erosion has reduced the predictability of the interval. The key outcome is therefore not simply the description of transgression but the demonstration that identifying the preserved transgressive interval is necessary for reducing acid-loss risk and improving geological support for ISR planning in the study area.

8. References

- Abeuov, A. (2023). Application of novel geostatistics methods on South Tortkuduk uranium roll-front deposit, Chu-Sarysu. Nazarbayev University. <https://nur.nu.edu.kz/items/f0d02f7e-a5a4-4973-9d81-b80591b4289e>
- Abzalov, M. Z. (2012). Sandstone-hosted uranium deposits amenable for exploitation by in situ leaching technologies. *Applied Earth Science*, 121(2), 55–64. <https://doi.org/10.1179/1743275812Y.00000000021>
- Cattaneo, A., & Steel, R. J. (2003). Transgressive deposits: A review of their variability. *Earth-Science Reviews*, 62(3–4), 187–228. [https://doi.org/10.1016/S0012-8252\(02\)00159-9](https://doi.org/10.1016/S0012-8252(02)00159-9)
- Dahlkamp, F. J. (2009). Uranium deposits of the world: Asia. Springer. <https://doi.org/10.1007/978-3-540-78558-3>
- Dillinger, A., Chanvry, E., Bolat, Y., & Fustic, M. (2024). Architecture and history of uranium-bearing Palaeocene–Eocene strata deposited on the eastern margin of the Peri-Tethys (Chu-Sarysu Basin, south Kazakhstan). *Sedimentary Geology*, 468, 106677. <https://doi.org/10.1016/j.sedgeo.2024.106677>
- Gabdullina, S. (2023). Reservoir architecture of the South Tortkuduk uranium field. Nazarbayev University. <https://nur.nu.edu.kz/items/903d2574-7086-4b24-808e-77c4b594f507>
- Hein, C. J., & Kirwan, M. L. (2024). Marine transgression in modern times. *Annual Review of Marine Science*, 16, 55–79. <https://doi.org/10.1146/annurev-marine-022123-103802>
- International Atomic Energy Agency. (2023). Nuclear power and the energy transition. IAEA.
- Kraft, J. C. (1971). Sedimentary facies patterns and geologic history of a Holocene marine transgression. *Geological Society of America Bulletin*, 82(8), 2131–2158. [https://doi.org/10.1130/0016-7606\(1971\)82\[2131:SFPAGH\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1971)82[2131:SFPAGH]2.0.CO;2)
- Li, G., & Yao, J. (2024). A review of in situ leaching (ISL) for uranium mining. *Mining*, 4(1), 120–148. <https://doi.org/10.3390/mining4010009>
- Morss, L. R. (2026). Uranium. *Encyclopaedia Britannica*. <https://www.britannica.com/science/uranium>

Organisation for Economic Co-operation and Development Nuclear Energy Agency and International Atomic Energy Agency. (2025). Uranium 2024: Resources, production and demand. OECD Nuclear Energy Agency. https://www.oecd-neo.org/jcms/pl_103179/uranium-2024-resources-production-and-demand

Petrov, N. N. (1998). Epigenetic stratified-infiltration uranium deposits in Kazakhstan. U.S. Department of Energy. <https://www.osti.gov/etdeweb/biblio/344657>

Seredkin, M., Zabolotsky, A., & Jeffress, G. (2016). In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics. *Ore Geology Reviews*, 79, 500–514. <https://doi.org/10.1016/j.oregeorev.2016.06.016>

Smagambetov, A. (2024). [Internal geomodelling report, South Tortkuduk field]. KATCO JV LLP.

Umurzakov, A. (2024). [ISR simulation study, Tortkuduk–Muyunkum system]. KATCO JV LLP.

World Nuclear Association. (2025). Uranium and nuclear power in Kazakhstan. <https://www.world-nuclear.org/information-library/country-profiles/countries-g-n/kazakhstan>

Zecchin, M., & Catuneanu, O. (2013). High-resolution sequence stratigraphy of clastic shelves I: Units and bounding surfaces. *Earth-Science Reviews*, 125, 228–267.

Hein et al. (2014)