



SCHOOL OF
MINING AND
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**Geological Assessment of Kempirsay Ophiolite Massif and its paleo-drainage system
for Carbon Mineralization**

BSc in Geology

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ABSTRACT

Climate change driven by rising atmospheric CO₂ concentrations necessitates the development of reliable and permanent carbon storage solutions. Among the available approaches, geological CO₂ storage through mineral trapping in mafic and ultramafic rocks represents a particularly secure long-term pathway, as CO₂ is converted into stable carbonate minerals. This study investigates the occurrence of ultramafic fragments within sedimentary successions and evaluates their potential for CO₂ mineral trapping.

Although ultramafic fragments are commonly considered highly unstable during transport and burial, this study documents their abundance in both outcrops and subsurface cores. Experimental CO₂–water–rock interaction experiments conducted on ultramafic samples under elevated CO₂ pressure (60 bar) and moderate temperature (40 °C) demonstrate rapid Mg release, progressive alkalization, and geochemical conditions favorable for carbonate precipitation. These findings support the hypothesis that ultramafic-derived sediments retain significant reactivity after burial.

Based on geological, geochemical, and experimental constraints, we propose that burial depths of approximately 1000 m provide optimal pressure–temperature and fluid conditions for efficient CO₂ storage and in situ mineral trapping. The results highlight the significant potential of ultramafic-bearing sedimentary successions for carbon capture and storage (CCS) and carbon mineralization strategies.

Key words: CO₂ mineral trapping; Source-to-sink processes; Ural Mountains; Pre-Caspian Basin; Zharkamys zone; Carbon capture and storage (CCS); Carbon mineralization; Geological CO₂ storage; Olivine-rich sediments

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ORIGINALITY STATEMENT

I, Aruzhan Duisen, hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at Nazarbayev University or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at Nazarbayev University or elsewhere is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged

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1. Introduction

1.1 Climate changes

Climate change is as a serious global problem (IPCC, 2021; Friedlingstein et al. 2023), which means that reliable and scientifically based solutions are urgently needed (UNEP, 2020). Atmospheric CO₂ comes from both natural processes, like decomposition, ocean release, and respiration, and human activities, such as agriculture and burning fossil fuels since the Industrial Revolution (Metz et al. 2005). Natural systems are no longer able to absorb enough CO₂ to balance these emissions, which has caused a sharp rise in atmospheric CO₂ levels. This rise is a major cause of global warming, climate change, and related environmental and social issues (Ripple et al. 2020). Geological CO₂ storage is an important carbon mitigation strategy aimed at reducing greenhouse gas emissions and slowing climate change. The method involves capturing carbon dioxide from industrial sources and injecting it into deep underground geological formations for long-term storage. According to the Intergovernmental Panel on Climate Change, properly selected geological formations can retain more than 99% of injected CO₂ for over 1,000 years (IPCC, 2005).

The main types of geological CO₂ storage include depleted oil and gas reservoirs, deep saline aquifers, unmineable coal seams, and basalt formations. Depleted reservoirs are widely used because they have already demonstrated the ability to trap fluids naturally over geological timescales. Deep saline aquifers are considered the most promising option due to their large global storage capacity, estimated by the IPCC to range from hundreds to thousands of gigatonnes of CO₂ (IPCC, 2005). Unmineable coal seams can store CO₂ through adsorption processes, while basalt formations provide highly secure storage through mineral carbonation reactions. These geological storage methods play a significant role in carbon capture and storage (CCS) technologies and contribute to international efforts to mitigate the impacts of climate change.

1.2 CO₂ mineral trapping

Mineral trapping is the process of converting CO₂ gas into solid minerals through geochemical or biogeochemical reactions (Wang et al. 2018). Mineral trapping of CO₂ is a promising technology for permanent and safe carbon storage.

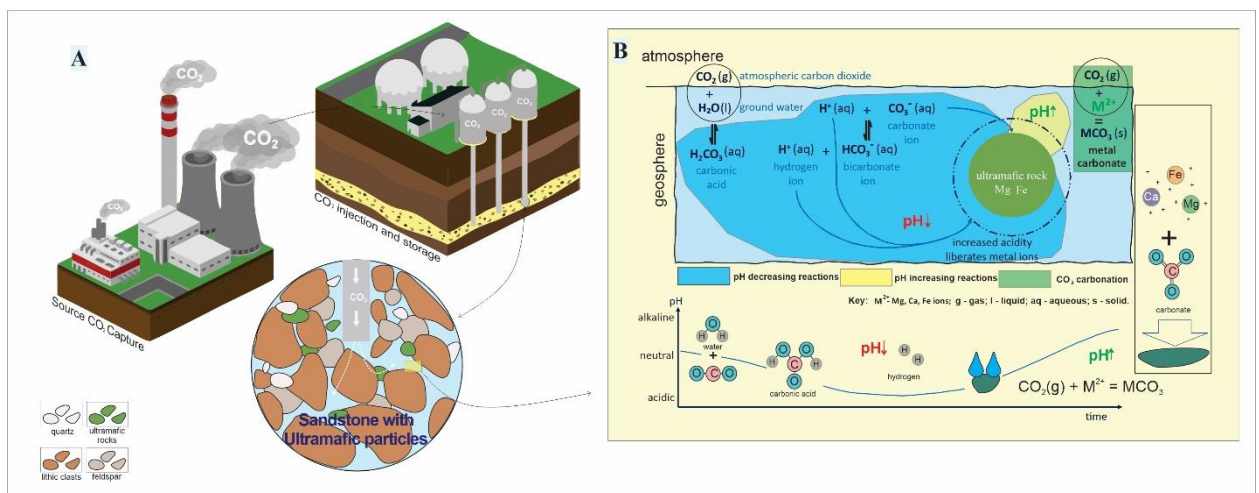


Figure 1. (A) Schematic presentation of CO₂ capture from an emitter and its geological storage in deeply buried (>800m) porous reservoirs characterized by polycrystalline grains including

chemically reactive ultramafic clasts / grains, adapted from [Kim et al. \(2023\)](#); (B). Proposed schematic of CO₂ carbonation in sedimentary reservoirs with ultramafic fragments showing liberation of metal ions caused by CO₂ injection and related acidification (drop in pH) followed by pH swing towards increased alkalinity and CO₂ precipitation as carbonate minerals, adapted from [Leila et al. \(2025\)](#).

The technology is limited to reactive silicate minerals able to release divalent cations (metal ions), such as Ca²⁺, Mg²⁺, and Fe²⁺ ([Goff, Lackner, 1998](#); [Snæbjörnsdóttir et al. 2020](#); [Stokreef et al. 2022](#); [Nisbet et al. 2024](#); [Taksavasu et al. 2024](#)). These minerals are commonly hosted by mafic (eg basalts), and ultramafic (eg peridotites and serpentines, rocks and glaucuronite enriched sediments ([Kelemen et al. 2019](#); [Kelemen, Matter, 2008](#); [Lacinska et al. 2017](#); [Rieli et al. 2021](#); [Yusuf, Ibrahim, 2023](#); [Nisbet et al. 2024](#); [Khandoozi et al. 2023](#); [McLaughlin et., 2023](#); [Rigopoulos et al. 2018](#))).

1.3 Trapping by mafic and ultramafic

The technology is based on observations that water acidized by CO₂, dissolves certain minerals and liberates cations which move to porous media, where it reacts with excessive CO₂ and precipitates as stable carbonate phases ([Xiong et al. 2018](#); [Rieli et al. 2021](#)). Natural examples of this process can be observed in alkaline springs located in ultramafic geological settings, where spontaneous mineral carbonation occurs over time, as shown in Figure 1 (part B).

Olivine and pyroxene being primary igneous minerals, as well as their aqueous analogues (e.g. serpentine group minerals and brucite) provide the chemical components necessary for the formation of carbonates such as calcite (CaCO₃), magnesite (MgCO₃), siderite (FeCO₃), and ankerite [Ca(Fe, Mg, Mn)(CO₃)₂], ([Paukert et al. 2012](#); [Gill et al. 2024](#), [Nisbet et al. 2024](#)).

The extensive distribution and abundance of mafic and ultramafic rocks-comprising approximately 10% of the continental crust and the majority of the seafloor ([Matter et al. 2016](#))-make them ideal candidates for carbon storage. The research community on CO₂ storage believes that this approach can safely, rapidly, and permanently store CO₂ in large quantities, with minimal effort required for verification and monitoring post-disposal ([Helps et al. 2024](#)).

1.4 Current CO₂ mineral trapping projects

The carbon sequestration industry is still in its early stages, with pilot projects running in various countries at sites with different geological and mineral characteristics. ([Oelkers, Gislason, 2023](#)). Successful testing at pilot projects, including those with mafic rock systems in the Nordic region and the CarbFix Project in Iceland ([Anthonson et al. 2013](#); [Pogge von Strandmann et al. 2019](#)), as well as the Wallula Basalt Pilot Project in Washington, USA ([McGrail et al. 2014](#); [Cao et al. 2024](#)), gives us confidence in the potential for future technological upscaling. This is particularly true because ultramafic rocks are believed to be more chemically reactive than mafic rocks, potentially enabling faster carbonate mineralization ([Gill et al. 2024](#)). Moving forward, experiments and pilot projects are aimed at establishing the foundation for a global carbon sequestration industry, with increasing attention directed toward ultramafic-bearing sandstone reservoirs as promising geological formations for enhanced mineral carbonation and long-term CO₂ storage ([Oelkers & Gislason, 2023](#)).

1.5 Kazakhstan's decarbonization opportunities

Central Asian countries, particularly Kazakhstan, are increasingly advancing carbon capture and storage (CCS) and carbon capture, utilization, and storage (CCUS) technologies,

including carbon mineral trapping. Owing to its vast territory and diverse geological setting, Kazakhstan offers strong potential for the development of large-scale decarbonization projects. In particular, the southern margins of the Ural Mountain Belt host extensive ultramafic and ophiolitic complexes, including chromium-rich mining districts, and which are highly prospective for carbon mineralization due to their abundance of reactive Mg-rich silicate minerals. These ophiolitic and ultramafic rocks, representing fragments of oceanic crust and upper mantle, provide a favorable natural source for CO₂ fixation through mineral trapping.



Figure 2. Location map of the study area in western Kazakhstan within the Pre-Caspian Basin. The map presents the digital elevation model together with major hydrological features and principal cities. Sampling locations are marked by red dots and include the Kempirsay Massif ultramafic rocks, the Triassic outcrop at the Ilel locality, and core samples from the Condor Oil Field

1.6 Ultramafic Rock Fragments in Sedimentary Record

Ultramafic rock minerals are known for being very unstable as they chemically dissolve by weathering and in rock-fluid interactions in the subsurface (Nesbitt & Bricker, 1978). In addition to being poorly preserved in the rock record, their potential preservation in the sedimentary record is not of common interest either for petroleum and mineral exploration. Thus, ultramafic fragments are commonly grouped and presented on ternary diagrams with other minerals as rock fragments, versus more commonly found quartz and feldspar minerals. Several exceptions include:

- The Devonian Solund basin conglomerates from outcrop exposures in southwest Norway record a substantial content of ultramafic material, with peridotite clasts comprising locally up to 20 vol % of the sedimentary fill (Beinlich et al., 2010). These clasts typically occur as isolated pebbles to boulders ranging from centimeters to meters, and although they average about 1 % of the total clast volume, stratigraphic intervals as thick as 50 m can contain up to 20 vol % ultramafic fragments that extend for several kilometres across the basin (Beinlich et al., 2010). Texturally, the individual fragments, display a concentric zoning with green cores, gray intermediate

zones and red rims, reflecting a progressive alteration from partly serpentinized peridotite to carbonate-rich ophicarbonates. Geochemical analyses show a dramatic loss of MgO (from ≈ 40 wt % to < 3 wt %) and a concurrent increase in CaO (up to ≈ 35 wt %) within the clasts, indicating extensive Mg-mobilization during near-surface weathering under tropical Devonian conditions (Beinlich et al., 2010). Sr-isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7124\text{--}0.7139$) match Devonian basinal fluids rather than mantle signatures, demonstrating that the alteration and carbonate precipitation occurred after deposition, in the subsurface of the sedimentary basin). The thickness of the Solund basin across the southeast dipping strata between La^ogøyfjorden and the Solund fault in the central parts of the basin is more than 6 km (top not seen) (Indrevaer and Steel, 1975). It is estimated that Devonian sediments were buried to ca. 13 km and that the temperatures during burial reached 230–320 °C. Because weathered peridotite develops secondary porosity and readily carbonatizes, the Solund basin exemplifies how sedimentary basins enriched in ultramafic fragments can act as natural low-temperature CO₂ sequestration sites

- One more case is the lower Miocene Bric Palouch Conglomerate (BPC) in the Torino Hill, NW Italy, where fresh peridotite clasts were preserved within marine conglomerates despite post-depositional alteration (Barale et al., 2022). The conglomerates consist predominantly of ultramafic and ophiolitic material, with approximately 95% of clasts composed of meta-ultrabasites, including serpentinite, serpentine-schist, and peridotite (Barale et al., 2022). The ultramafic clasts contain preserved lherzolite cores surrounded by serpentinized rims composed mainly of lizardite, indicating that alteration occurred during early diagenesis after deposition rather than during transport. Burial depths reached approximately 1400–1500 m, while maximum burial temperatures remained relatively low at 50–60 °C, allowing preservation of primary ultramafic minerals (Barale et al., 2022).

1.7 Objectives

The main objective of this study is to evaluate the potential of ultramafic rock-fragment-bearing sedimentary reservoirs for long-term CO₂ mineral storage. This approach represents a novel concept in Kazakhstan, as the potential of ultramafic-derived sedimentary successions for in situ CO₂ mineral trapping has not yet been investigated in the regional scientific literature or implemented in CCS practice. The hypothesis is based on coupling evidence of ultramafic rock fragment preservation in paleo-drainage systems with their residual carbonation potential, suggesting that such sediments may retain long-term geochemical reactivity despite burial. This concept has significant potential to advance CO₂ mineral storage strategies, as sedimentary reservoirs typically offer higher porosity and permeability, enabling efficient CO₂ injection, in contrast to relatively low-permeability ultramafic ophiolite complexes. To achieve this goal, the following steps are undertaken:

- Identification of ultramafic fragments in the Condor Oil Field through macroscopic and microscopic examination of subsurface core material and outcrop samples.
- Textural and compositional analyses of ultramafic fragments to constrain provenance, alteration state, and mineralogical composition.
- Burial history reconstruction using burial chart analysis to estimate the risk of temperature-driven dissolution and diagenetic modification through geological time.
- Experimental batch reactor studies on concentrated ultramafic fragments to evaluate chemical reactivity with injected CO₂; however, this experimental component was not

conducted due to instrument scheduling constraints. Instead, reactivity is assessed by comparison with previously published experimental results on ultramafic material from the Kempirsai Massif, which serves as the primary source area for the studied fragments.

2. Geological settings

2.1 Kempirsay Ophiolite Massif (Sediment Source)

2.1.1 Locality

The Kempirsay Ophiolite Massif located in western Kazakhstan (Figs. 1 and 3), is southernmost part of the Ural Mountains (Fig. 3). This mid-Paleozoic over 2500 km long orogenic belt is a product of the collision between the European Plate to the west and the Siberian Plate to the east (Savelieva & Nesbitt, 1996). The Kempirsay massif itself covers an area of approximately 2000 km², and is characterized by an elongated shape stretching 90 km north-south and up to 32 km wide in an east-west direction (Fig. 3; Melcher et al., 1997, as cited in Pavlov et al., 1968; Segalovich, 1973). A prominent north-south trending shear zone, which is associated with the Main Ural Fault system (Melcher et al., 1997, as cited in Lennykh et al., 1995) separates the massif into two distinct parts (Fig. 3).

The southeastern part of the Kempirsay Massif, known as the Main Ore Field (MOF), hosts some of the largest podiform chromitite deposits globally, with reserves exceeding 300 Mt of high-grade ore (Melcher et al., 1997; Pavlov et al., 1968). This zone is composed mainly of depleted harzburgite and dunite, intruded by pyroxenite veins and cut by east-west faults (Segalovich, 1973). Chromitite bodies are lens- to tabular-shaped, enclosed by dunite envelopes, and structurally aligned with a NNE-SSW-trending anticline (Melcher et al., 1997; Kravchenko and Grigoryeva, 1986). The chromites are Cr-rich (Cr# 78-85) and Mg-rich (Mg# 63-85), indicating crystallization from high-Mg hydrous melts in a supra-subduction zone setting (Melcher et al., 1997). The presence of amphibole, PGMs, and fluid inclusions suggests significant metasomatism by slab-derived fluids during chromitite formation (Melcher et al., 1997; Thälhammer, 1996a).

The northwestern part of the Kempirsay Massif, including the Batamshinsk and Stepninsk areas, is composed of dunites and harzburgites overlain by mafic-ultramafic cumulates, representing a more fertile mantle section (Melcher et al., 1997; Segalovich, 1973). Chromitite bodies here are smaller, Al-rich, and Cr-poor, with variable Cr-number (38-60) and Mg-number (50-88), suggesting formation from MORB-type melts in an extensional tectonic setting (Melcher et al., 1997). These chromites often display zoning and include Ti- and Mn-rich phases, chlorite, hydrogarnet, and sphene, pointing to later-stage, lower-temperature alteration processes (Melcher et al., 1997; Pavlov and Grigoryeva, 1977). The absence of large orebodies and the diverse inclusion assemblages distinguish this zone from the MOF.

2.1.2 Geological / Tectonic History

The formation of the Ural Mountains, which began with the closure of Uralian paleo-ocean between the European and Siberian plates, likely started in the Late Silurian and culminated in the Devonian, with deformation continuing into the Late Permian to (Nesbitt,

1996). The collision resulted in the uplift of over 150 ophiolitic massifs comprised of remnants of ancient oceanic lithosphere composed of harzburgitic and lherzolitic restites (Savelieva & Nesbitt, 1996). These ophiolites are preserved within volcano-sedimentary sequences and mélanges, forming tectonic slices and allochthonous blocks as a result of prolonged interplay of subduction, accretion, and obduction processes (Pirajno et al., 2020).

The Kempirsay Ophiolite Massif was emplaced through obduction, wherein fragments of oceanic lithosphere were thrust onto the continental margin. This event was part of a broader tectonic evolution involving the simultaneous development of new oceanic crust in the east while older oceanic crust was progressively obducted onto the European Plate margin (Savelieva & Nesbitt, 1996). The massif also exhibits evidence of intrusive activity that is step-like in shape, including pyroxenites, hornblende gabbros, and gabbro-norites, which are interpreted as off-axis intrusions emplaced along brittle shear zones (Pirajno et al., 2020). Similar intrusive features have been described in the Lizard Complex of southwest England (Pirajno et al., 2020, as cited in Bromley et al., 1979).

2.1.3 Lithotypes / Stratigraphy

The Kempirsay Ophiolite Massif contains a well-developed ophiolitic sequence (Fig. 3C). Composed of ultramafic tectonites, cumulate gabbros, and mafic intrusions (Pirajno et al., 2020). The ultramafic section is predominantly harzburgitic, with a thinner basal unit of lherzolite. One of the most significant features of the massif is the transition from relatively undepleted tectonites to more depleted, refractory rocks, which is particularly evident in the mineral chemistry of spinel and orthopyroxene (Pirajno et al., 2020). This transition is closely associated with the formation of podiform chromite deposits, which represent an economically significant resource (Savelieva & Nesbitt, 1996).

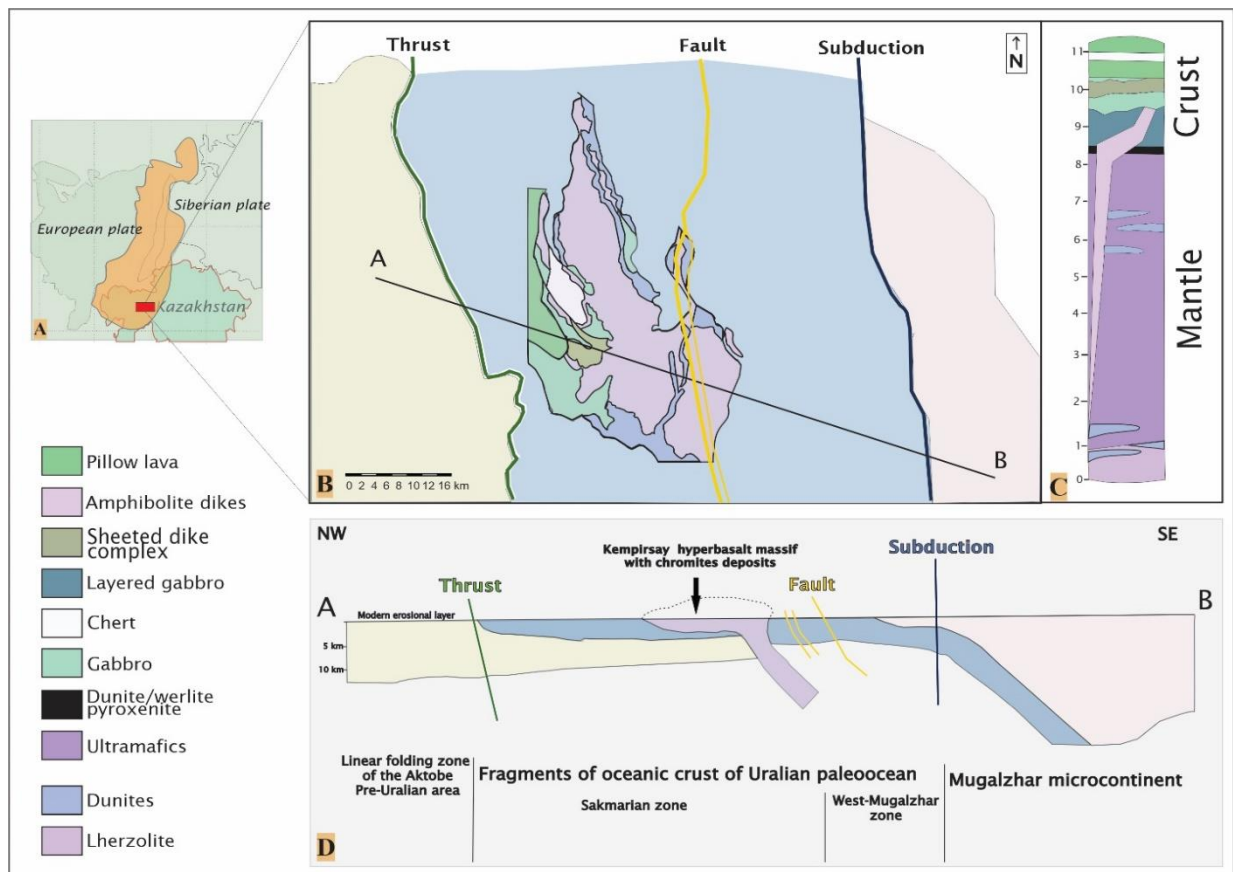


Figure 3. Tectonic setting and internal structure of the Kempirsay ultramafic massif (Kazakhstan). (A) Location between the European and Siberian plates and within Ural Mountain Belt; (B) Simplified geological map showing distribution of ophiolitic units (pillow lavas, sheeted dikes, gabbros, and ultramafics) and major structures (thrust, Ural fault, and subduction zone). Line A-B indicates cross-section location; (C) Idealized vertical lithological profile representing a typical ophiolite sequence, illustrating the transition from ultramafic mantle rocks (dunites, lherzolite, and pyroxenites) to mafic crustal components (layered gabbros, sheeted dikes, and volcanic rocks), modified after Pirajno (2010); (D) Schematic, NW-SE cross-section (A-B) across the massif illustrating its structural setting within the linear folding zone of the Aktobe Pre-Urals, showing fragments of oceanic crust of the Uralian paleo-ocean, the Sakmarian and West-Mugalzhar zones, and their relationship to the Mugalzhar microcontinent. The section also indicates major thrusts, faults, and the inferred subduction zone. Adapted from Yurish, V.(2016).

The stratigraphy of the massif includes a complete ophiolite sequence, comprising fertile mantle peridotites, harzburgite tectonites, cumulates, a sheeted dyke complex, lava flows, and ocean-floor sediments (Savelieva & Nesbitt, 1996). The southeastern part, known as the Main Ore Field (MOF), contains the primary chromite deposits, hosted within dunite, harzburgite, and lherzolite layers reaching a total thickness of 16 km (Merchel, et al., 1997; Segalovich, 1973). Podiform chromitites occur on both sides of a NNE-SSW trending anticline, forming vein-like, pencil-shaped bodies that are often enveloped by dunite shells of variable thickness (Melcher et al., 1997, as cited in Kravchenko & Grigoryeva, 1986). The largest chromite deposits in the western part of the syncline include Millionnoe, Diamond, Pearl, and 20 Years of Kazakh SSR, dipping 5-50° to the west (Melcher et al., 1997, as cited in Pavlov et al., 1968). The eastern part contains smaller deposits such as Sputnik and larger deposits such as Mir, Voskhod-Karagash,

and 40 Years of Kazakh SSR-Molodezhnoe, with orebodies dipping 15-75° to the east (Melcher et al., 1997).

Ophiolite sequences in the Kempirsay Massif, as in other Uralian ophiolites, are dominated by mantle peridotites and associated cumulate ultramafic and gabbroic sequences. While sheeted dyke complexes are common, the basaltic component of the ophiolite spectrum is rarely found in stratigraphic continuity. Instead, basalts are usually observed within associated mélanges and olistostromes, particularly in the southern part of the massif (Savelieva & Nesbitt, 1996). The massif's chromite deposits constitute a major economic resource, with total reserves estimated at 310 million tons of chromite ore, averaging 50% Cr₂O₃, of which approximately 30 million tons have been mined (Melcher et al., 1997, as cited in G. Elpashev, 1993). The largest orebodies, such as Molodezhnoe and Diamond Pearl, extend up to 1800 meters in length and 230 meters in thickness (Melcher et al., 1997).

2.2 Sink Area (Ultramafic fragments in rocks)

2.2.1 Locality

In Kazakhstan, Condor Petroleum holds the Zharkamys West 1 license in the Pre-Caspian Basin and has drilled approximately 24 wells targeting Pre-Salt, Primary Basin, and Post-Salt plays. Of these, 19 were drilled using reverse circulation (RC) methods, producing drill cuttings, while 5 were drilled as diamond cores, providing continuous core material. This difference in drilling methods explains why this study uses both cuttings and core samples.

The Triassic and Jurassic intervals from Ebeity (**EB-1**) and Kiyaktysai North East (**KNE-1**) cores in the Pre-Caspian Basin (Fig. 2) are investigated.

The geological framework, well data, and analytical results presented in Section 2.2 are primarily based on materials provided by Condor Energies and the Aktobe Research Institute of Geology and Oil Exploration (ANGRI). These organizations conducted the main geological and geochemical analyses, forming the basis for the interpretation used in this study.

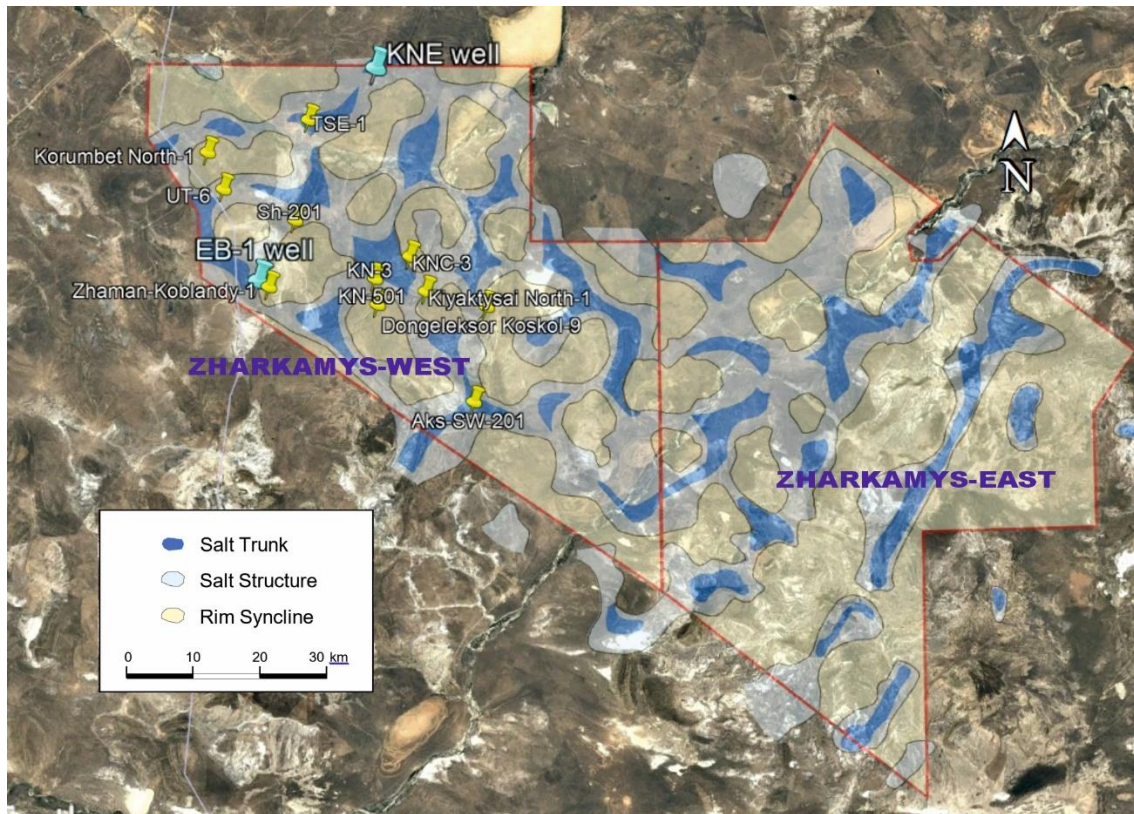


Figure 4A. Locations of studied wells (EB-1 and KNE-1) in broader geological context. Structural map of the Zharkamys license area in the Pre-Caspian Basin, Kazakhstan, showing the distribution of salt-related features including salt trunks, salt structures, and rim synclines. The map distinguishes the Zharkamys West and Zharkamys East blocks, highlighting the structural complexity associated with salt tectonics that controls hydrocarbon prospectivity in the region. Data provided by Condor Energies.

2.2.2 Geological / Tectonic History

The structural evolution of the supra-salt complex was analyzed using regional seismic profiles across both the West and East Zharkamys blocks (Fig. 4A). The corresponding geological cross-section is shown in Fig. 4B.

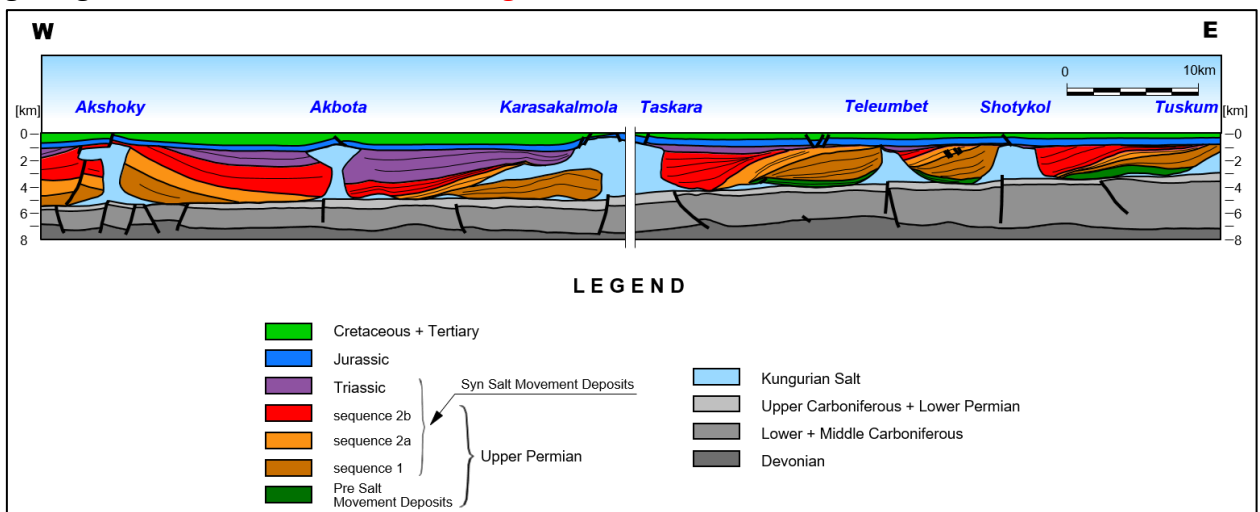


Fig. 4B. Regional W-E geological cross-section across the Zharkamys area showing the

distribution of Kungurian salt and overlying Late Permian sedimentary sequences (Cycles 1 and 2). The section illustrates salt-related deformation, wedge-shaped depositional geometries, and the influence of faulting and subsidence on basin evolution and stratigraphic architecture. Data provided by Condor Energies.

As shown in **Figure 4B**, the Kungurian salt deposits were likely accumulated at the base of a basin with a gentle westward dip, forming a laterally continuous evaporitic layer with an estimated original thickness of approximately 1.5 km prior to deformation. The geometry of this salt layer provides the structural foundation for subsequent sedimentation and deformation patterns observed in the section.

During the Late Permian, continued basin subsidence led to the development of wedge-shaped sedimentary sequences (Cycle 1), particularly evident in the East Zharkamys block, where these deposits thicken basinward. As illustrated in **Figure 4B**, the progressive filling of accommodation space resulted in tilting of Cycle 1 deposits, creating an inclined surface that controlled the deposition of overlying Cycle 2 sediments (Tatarian stage).

The transition between Cycles 1 and 2 varies spatially across the basin. In the eastern marginal zone, this boundary is expressed as an unconformity, whereas within the East Zharkamys block it appears as a detachment surface associated with salt-related deformation. Sub-cycle 2a is characterized by subparallel layering, indicating an intermediate stage of tilting, while Sub-cycle 2b forms wedge-shaped bodies prograding in the opposite direction to Cycle 1, as clearly visible in the cross-section.

Furthermore, **Figure 4B** shows that continued subsidence during the Late Permian was accompanied by active normal faulting in the eastern margin of the Pre-Caspian Basin, with fault activity progressively migrating westward. This structural evolution exerted a strong control on sedimentation patterns, influencing facies distribution, thickness variations, and ultimately the development of reservoir units within the Zharkamys area.

3. Materials and method

3.1 Outcrop and Core Description (Facies Analysis) and Macroscopic Identification of Ultramafic Grains

Triassic and Jurassic strata exposed at localities **Ilek area** and **Quarry outcrop** near Aktobe (**Figs. 2 and 3**) as well as Ebeity (**EB-1**) and Kiyaktysai North East (**KNE-1**) cores were visually described and logged. Grain size information was coupled by identification of sedimentary structures and outcrop scaled sketches to deduce paleo-depositional environment and distances from the sediment source (Kempirsay massif).

3.2 Experimental procedure

Powdered whole rock sample (5 g) was suspended in 100 ml of deionized water. A mixture of 0.64 M NaHCO₃ +1 M NaCl was added into the suspension which was stirred at room temperature prior to adding a universal pH indicator. The addition of NaHCO₃ and NaCl enhances the reactivity of ultramafic mineral phases through retarding the formation of Si-rich layer around the reacted and non-reacted grains . The suspension was moved into a closed PARR batch reactor vessel, and the CO₂ -water-rock batch experiments were conducted at pressure of 60 bars and a fixed temperature of 40 °C for 14 days (**Fig. 8**). The PARR reactor was equipped with a window

to monitor the color changes of the added pH indicator which recorded chemical changes in the aqueous solution. The experiment was stopped multiple times to sample the aqueous solution (5 mL). The sampled solutions were analyzed for major cations using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) System - iCAP 6300 (Thermo Scientific) at core facilities department of Nazarbayev University, Kazakhstan. All major cations were measured with an analytical error of $\pm 0.1\%$.

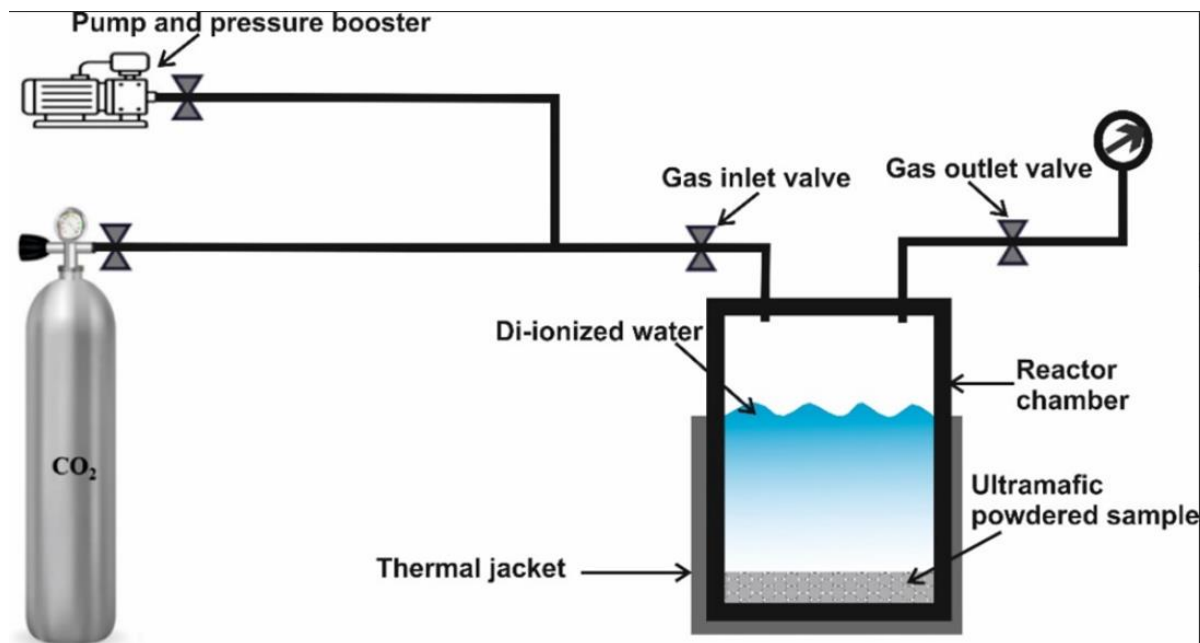


Figure. 8. A sketch shows the experimental setup for aqueous CO₂ reaction with powdered ultramafic rock. Modified after [Leila et al. \(2025\)](#).

3.2 Chemistry of the aqueous solution

The pH of the aqueous solution increased progressively from slightly acidic to neutral, alkaline and towards the end of the experiment hyperalkaline (**Fig. 9a-d**). Rapid increase of concentration of the dissolved Mg over the other cations (e.g. Fe, Si, Na, and K; **Fig. 10**) presents strong corroborative evidence of increasing alkalinity. A progressive increase in the concentration of all cations after 3 days of the experiment is observed; however, the concentration of dissolved Mg was 10 times greater than other cations (**Fig. 10**). Changes in the chemistry of the aqueous solution may be divided into three distinct phases.

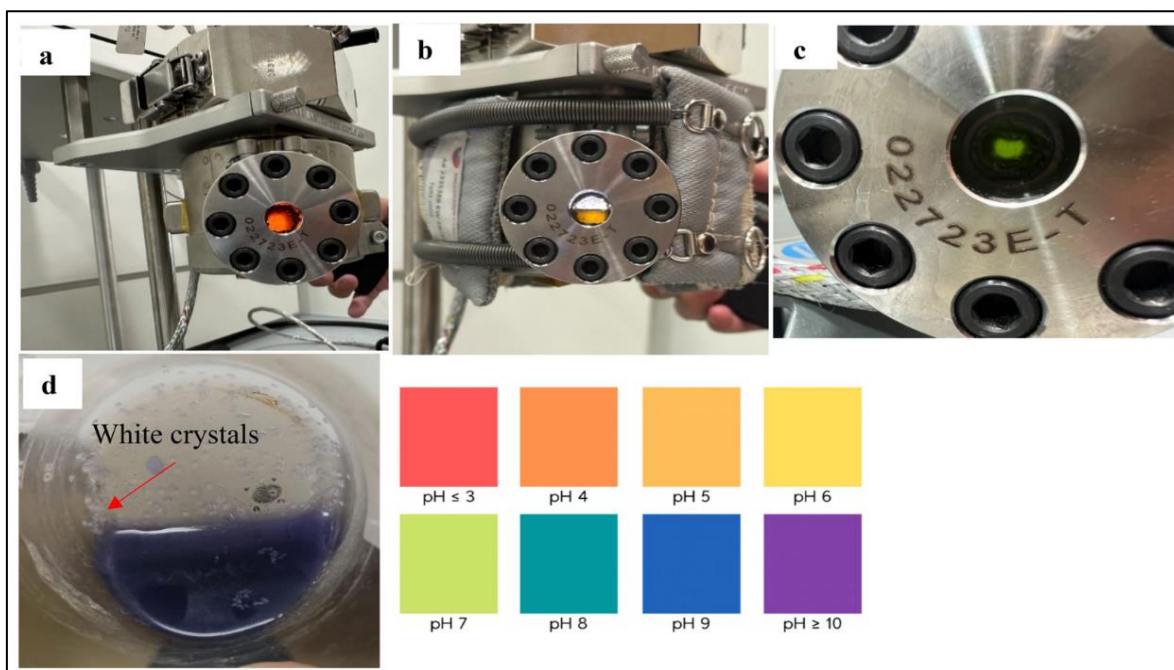


Figure 9. Photographs of batch reactor showing the pH changes throughout the experiment from acidic at the beginning (a), to slightly acidic after 3 days (b), to alkaline after 7 days (c), and to hyper-alkaline after 14 days (d). Precipitation of white crystals at the end of the experiment. Modified after Leila et al. (2025).

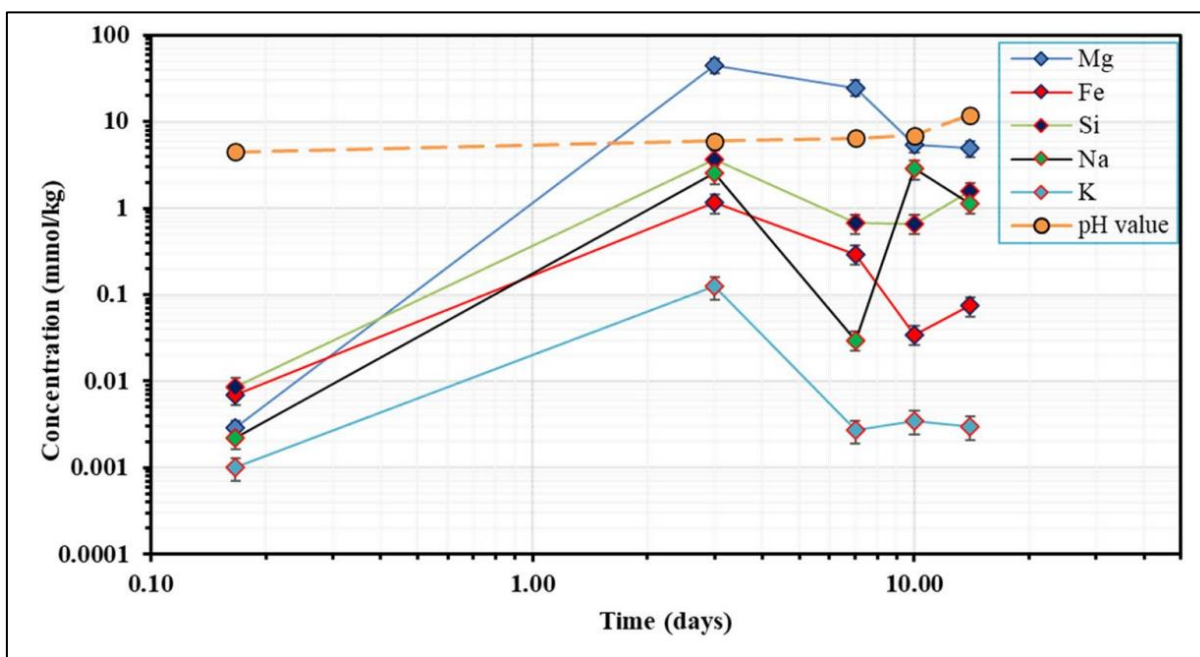


Figure 10. A cross-plot illustrates the variation in chemistry of the aqueous solution throughout the experiment. Modified after Leila et al. (2025).

The first phase (0-3 days) was characterized by pH and cation concentrations increase with time. During the second phase (3-7 days) all cations displayed a progressive decrease as pH swung from acidic/neutral to alkaline. In the third phase (7-14 days), Mg slightly decreased, whereas Fe, and Si showed a slight increase at the end of the experiment. Notably, Na displayed a complex trend during the third phase with a sharp increase and decrease in the dissolved Na content with increasing pH.

4. Results

4.1.1 Macroscopic Evidence of Ultramafic Fragments - Ilek area

Triassic and Jurassic strata exposed in the Ilek area and Quarry outcrop near Aktobe (Fig. 11 and 12) consist of coarse-grained, poorly sorted deposits containing an abundance of ultramafic fragments. The satellite image (Fig. 11A) illustrates the spatial distribution of sampled locations, while close-up images (Figs. 11B-11E) reveal the presence of dark clasts interpreted as ultramafics within a polymictic gravel matrix. The angular to sub-rounded shape and centimeter-scale size of these fragments suggest relatively short transport distances and a proximal source area.

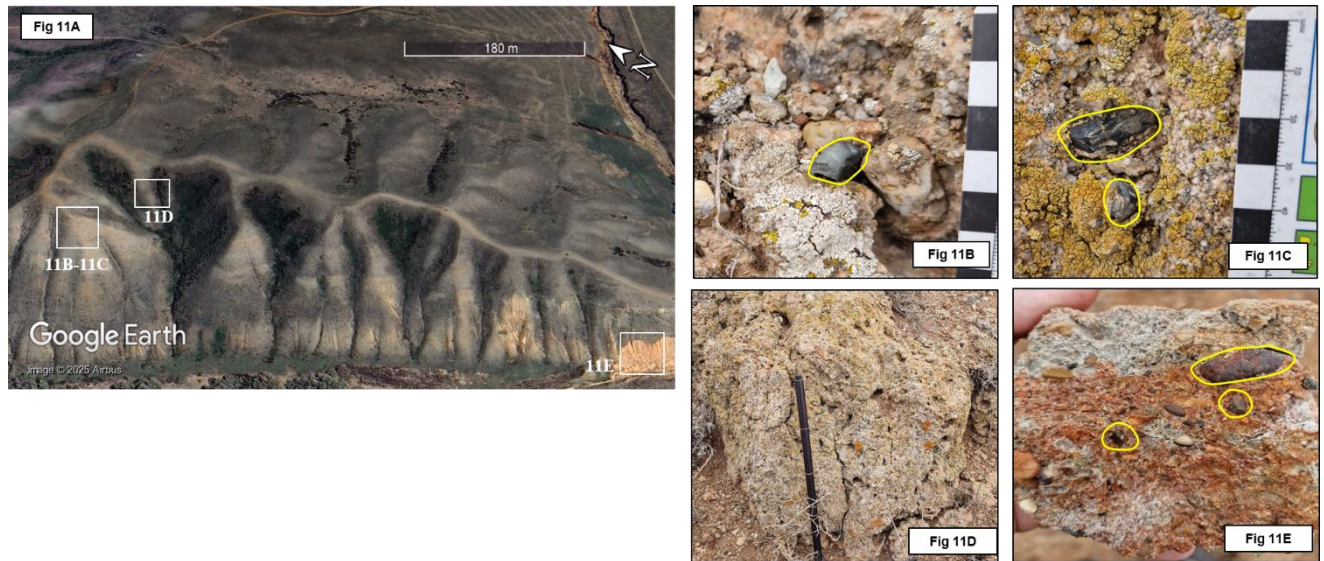


Figure 11. Ultramafic fragments in Middle Triassic outcrops, Ilek area (near Aktobe; 57°13'55"E, 50°19'66"N).

Fig 11A - Satellite image from Google Earth Pro showing the sample location.

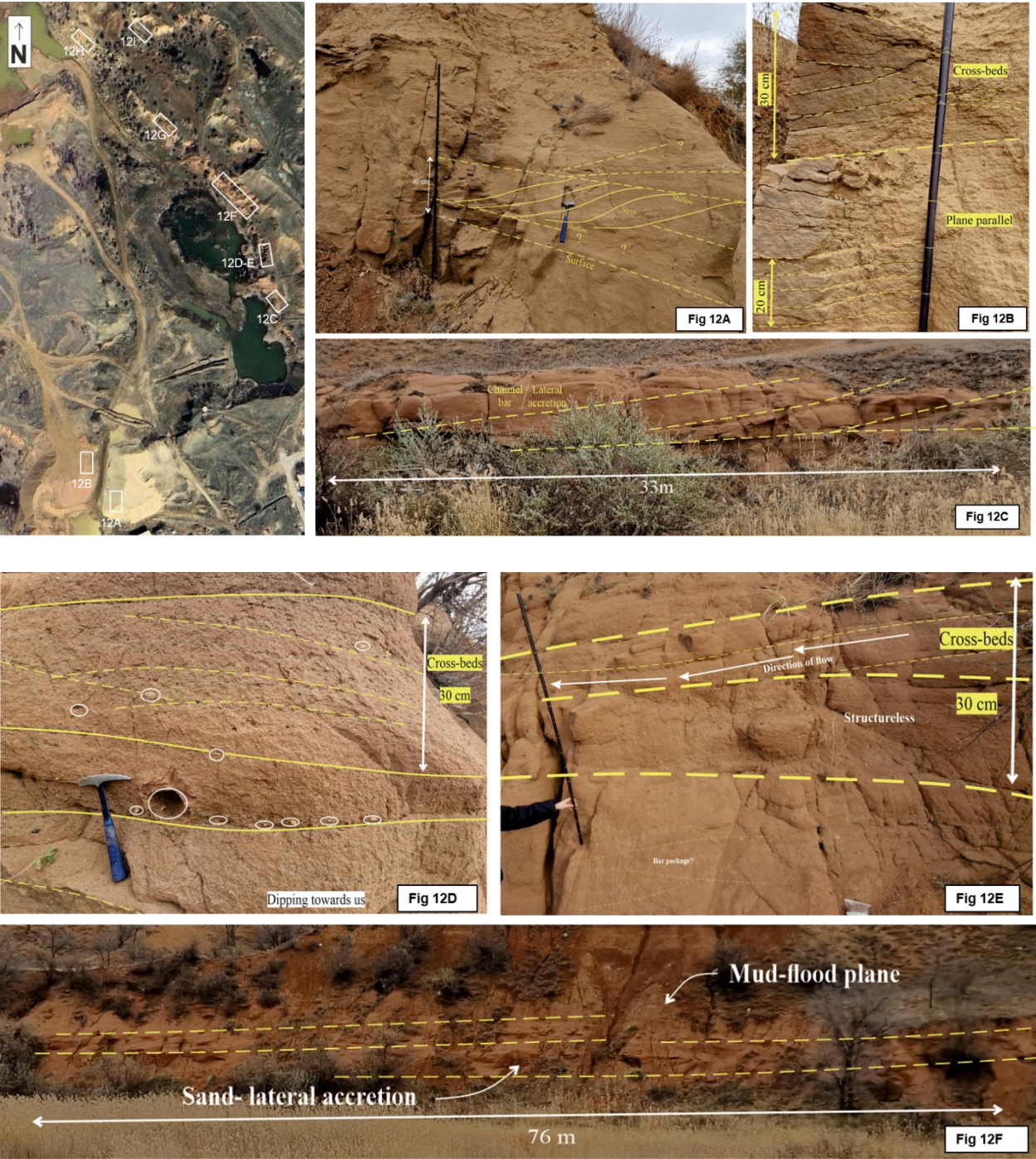
Fig 11B-C - Close-up of ultramafic fragments (~2 cm)

Fig 11D - Highly polymictic gravel deposit with abundant dark, cm-scale clasts. Thickness unclear due to weathering and vegetation.

Fig 11E - Close-up of ultramafic fragment (~7 cm).

The overall texture, clast composition, and poor sorting observed in Figure 11 indicate deposition in a high-energy environment, likely related to alluvial or proximal fluvial systems associated with erosion of the nearby Kempirsay ultramafic massif (Fig. 2).

4.1.2 Macroscopic Evidence of Ultramafic Fragments - Quarry - 1



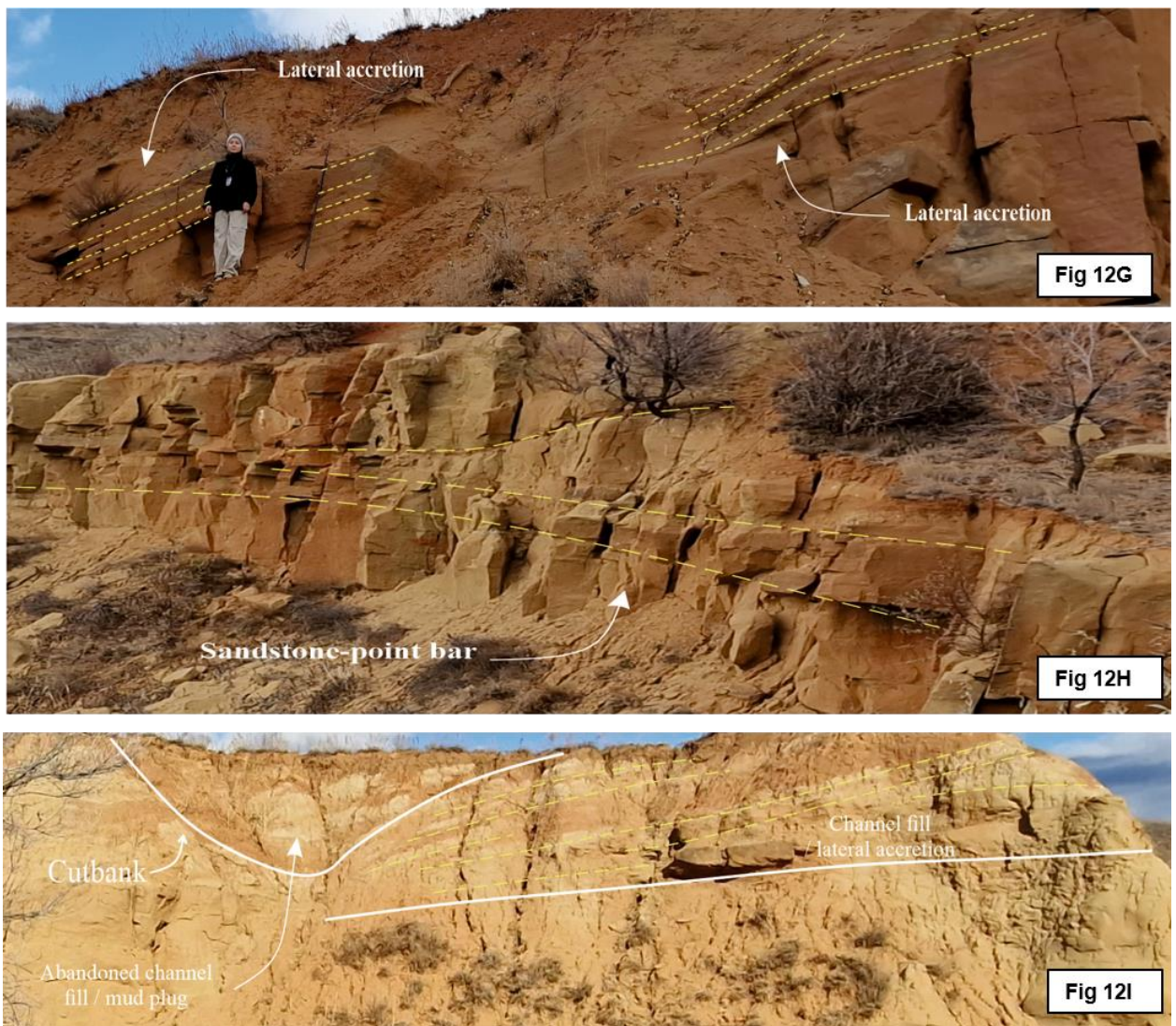


Figure 12. Sedimentary structures observed in the Ileq quarry outcrops. (A) ~40 cm thick cross-bedded unit showing a shallow-to-steep-to-shallow internal geometry. (B) Vertical succession of ~30 cm thick cross-bedded sandstones overlying ~20 cm thick plane-parallel laminated sandstones; (C) ~33 m long channel-scale deposit displaying well-developed lateral accretion surfaces; (D) Cross-bedded sandstones dipping toward the observer (~30 cm thick sets); (E) Cross-bedded unit overlying a structureless to weakly laminated interval, indicating changes in flow conditions and possible bar deposition; (F) ~76 m long exposure showing sand lateral accretion overlain by mud floodplain deposits; (G) Inclined heterolithic stratification showing lateral accretion surfaces; (H) Sandstone point-bar deposits with internal layering; (I) Channel morphology with cutbank, abandoned channel fill (mud plug), and channel-fill deposits associated with lateral accretion.

The studied section corresponds to an outcrop exposed in a clay quarry located on the right bank of the Ileq River, east of Aktobe. The lower part of the section is represented by poorly cemented, rare-pebble conglomerates that alternate upward with sandstones, commonly displaying cross-bedding structures (Fig. 12).

As shown in Figures 12B and 12C, the sandstones exhibit well-developed cross-stratification and plane-parallel lamination, indicating deposition under dynamic flow conditions. The variability in grain size and sorting reflects changes in flow energy and sediment supply within the system, which together with observed architecture suggest the evolution from a

braided river fluvial at the base to a meandering fluvial towards the top, implying that system is becoming more distal.

The conglomerate-sandstone interval exceeds 5 m in thickness and is characterized by coarse clastic material, suggesting high-energy depositional conditions. This coarse-grained unit is conformably overlain by variegated clay deposits, indicative of a paleosol development.

In the eastern wall of the quarry, a coarse clastic unit composed mainly of sandstones ranging from fine- to coarse-grained with minimal gravel content, and a notable lateral accretion (right to left; Fig. 12C), further supports fluvial depositional environment.

Upsection, alternating layers of variegated clays and sandstones are observed, with thicknesses ranging from 1.5-2.0 m to over 5 m. The identified sedimentary structures, including cross-bedding and lateral accretion surfaces, as well as mud-dominated paleosols indicative of floodplain indicate deposition within a channelized fluvial system, and tectonic subsidence allowing for their vertical stacking

Within these coarse-grained horizons, ultramafic fragments are locally present, providing macroscopic evidence of sediment input from nearby ultramafic sources (Figs. 12A and 12D). Their coarse to clast size suggests relatively short transport and a proximal sediment source.

Figure 12 (D-I) illustrates a range of sedimentary structures that collectively reflect the evolution of the depositional system and changing flow conditions within the studied outcrops. Cross-bedded sandstones observed in Fig. 12D, with sets approximately 30 cm thick, indicate deposition under relatively strong, unidirectional flow conditions, typical of high-energy channel environments capable of transporting coarse material. In Fig. 12E, cross-bedded units overlie structureless to weakly laminated intervals, suggesting fluctuations in flow regime and the development of bar-related deposits, where periods of rapid sediment accumulation are followed by renewed current activity.

Further along the succession, Fig. 12F shows a laterally extensive (~76 m) exposure characterized by sandy lateral accretion surfaces overlain by mud-rich floodplain deposits. This transition reflects a reduction in flow energy and the onset of overbank sedimentation. Inclined heterolithic stratification observed in Fig. 12G represents alternating deposition of sand and finer-grained material along migrating point bars, indicating more organized and less turbulent flow conditions. Similarly, the sandstone point-bar deposits shown in Fig. 12H, with well-developed internal layering, further confirm deposition within a meandering fluvial system characterized by relatively stable flow.

Finally, Fig. 12I displays channel morphology including a cutbank, abandoned channel fill (mud plug), and channel-fill deposits associated with lateral accretion. These features indicate channel migration, cutoff processes, and sediment accumulation under low-energy conditions

Overall, the succession shown in Figure 12 reflects a clear depositional evolution from high-energy to lower-energy environments. Cross-bedded sandstones (A, B, D) indicate strong flow conditions typical of high-energy channels and possibly braided bar systems. These deposits transition into bar-related and channel-scale features (C, E), representing intermediate-energy conditions with active sediment transport and bar formation. Further development of

lateral accretion surfaces and point-bar deposits (F-H) indicates a shift toward meandering fluvial systems. Finally, the presence of floodplain deposits and abandoned channel fills (F, I) reflects low-energy conditions associated with overbank sedimentation.

This vertical and lateral facies transition—from cross-beds to braided bars, followed by lateral accretion and floodplain deposits—demonstrates a progressive decrease in flow energy and increasing stability of the depositional system.

4.2 Microscopic and Analytical Evidence of Ultramafic Fragments

Macroscopic examination of drill cores and cuttings reveals a pronounced lithological heterogeneity, with several very dark, rock fragment–rich intervals that are interpreted as zones enriched in mafic–ultramafic detritus and more strongly affected by diagenetic alteration compared to the lighter, more matrix-supported sections. These darker intervals are also reflected in the cuttings, which contain abundant altered lithic fragments, suggesting enhanced post-depositional modification. Thin section analysis of representative drill cuttings (see figures below) confirms this interpretation, showing that many ultramafic-derived fragments are variably to completely replaced by serpentine-group minerals exhibiting mesh- and fibrous textures indicative of low-temperature diagenetic serpentinization, consistent with fluid–rock interaction during burial. Locally, carbonate cement is also observed within the matrix, further supporting late-stage diagenetic overprinting. Overall, both macroscopic and microscopic observations indicate that the dark, fragment-rich intervals correspond to the most intensely altered parts of the succession (see figures below).

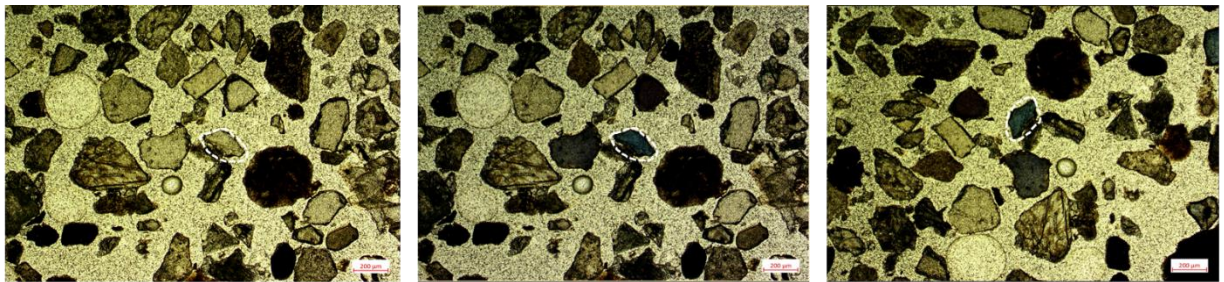


Figure 13. Photomicrographs of sandstone matrix from the Triassic Ilel outcrop (Fig 11D). The sandstone is medium-to coarse-grained, subangular to subrounded, and polymictic. Preserved ultramafic grains (serpentinized peridotite/pyroxenite fragments) are visible, indicating proximal derivation from an ophiolitic source (e.g., Kempirsay Massif). Magnification 5×. Left: plane-polarized light (PPL); middle: cross-polarized light (XPL); right: XPL rotated by 90° to for figure enhance birefringence contrast in serpentine and phyllosilicate minerals. Cement includes clay and secondary silica; porosity is low to moderate.

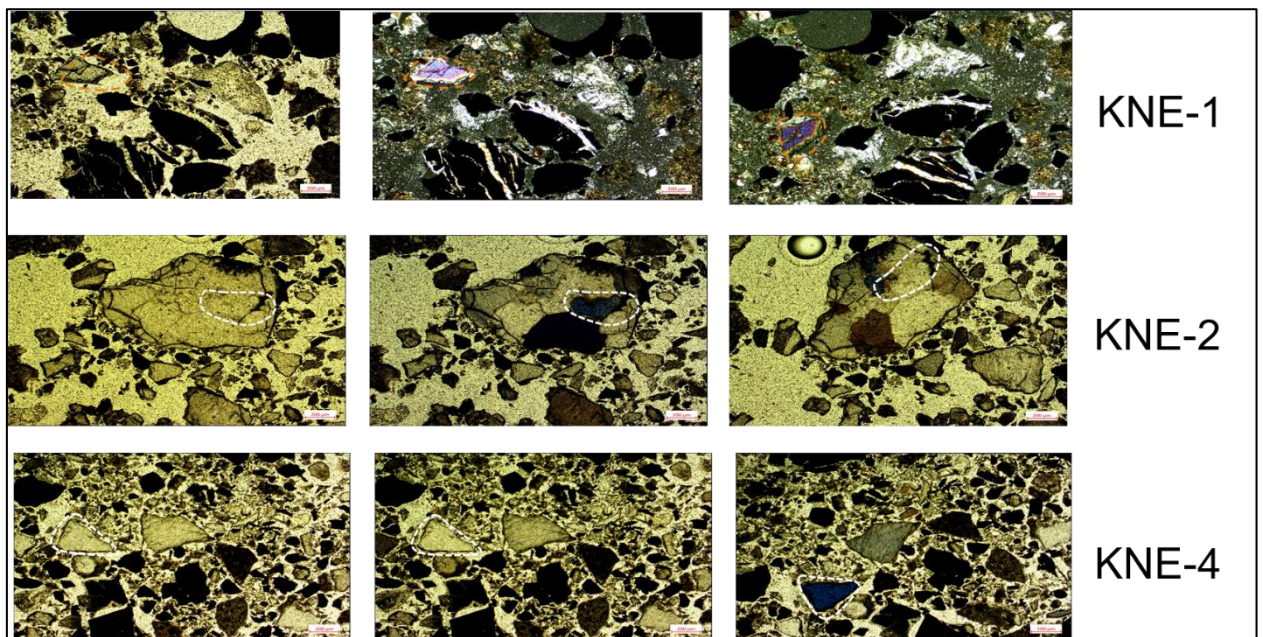


Figure 14. Petrographic images of sandstone samples KNE-1, KNE-2, KNE-4 containing ultramafic-derived grains

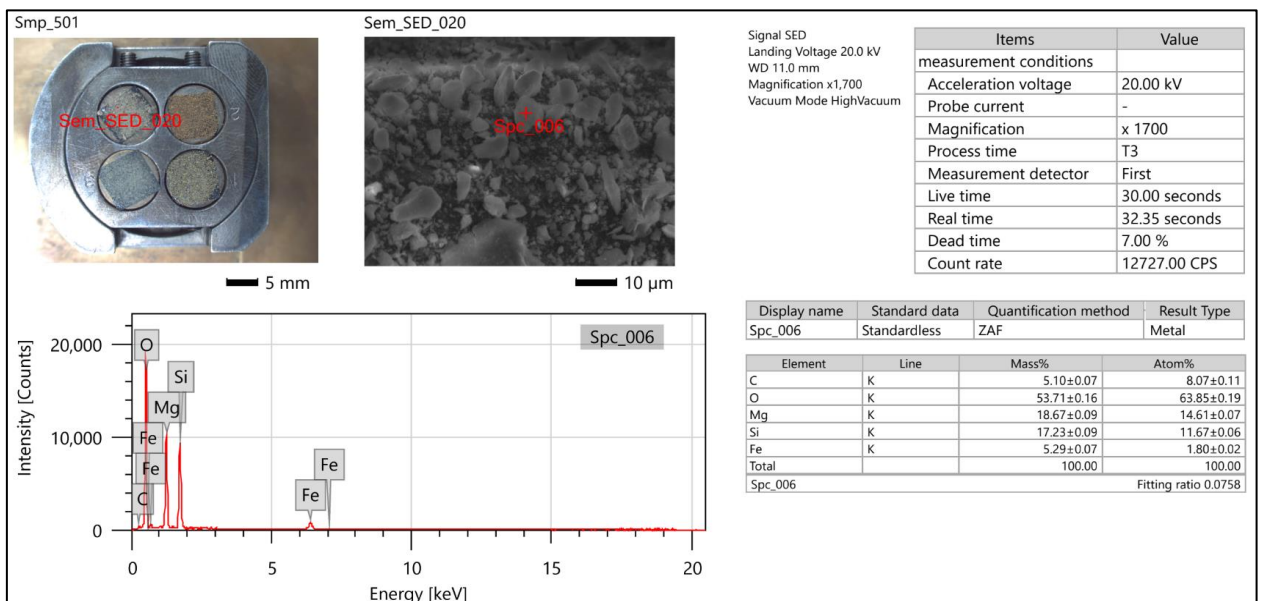


Figure 14A. SEM results of sandstone sample KNE-1 containing ultramafic-derived grains

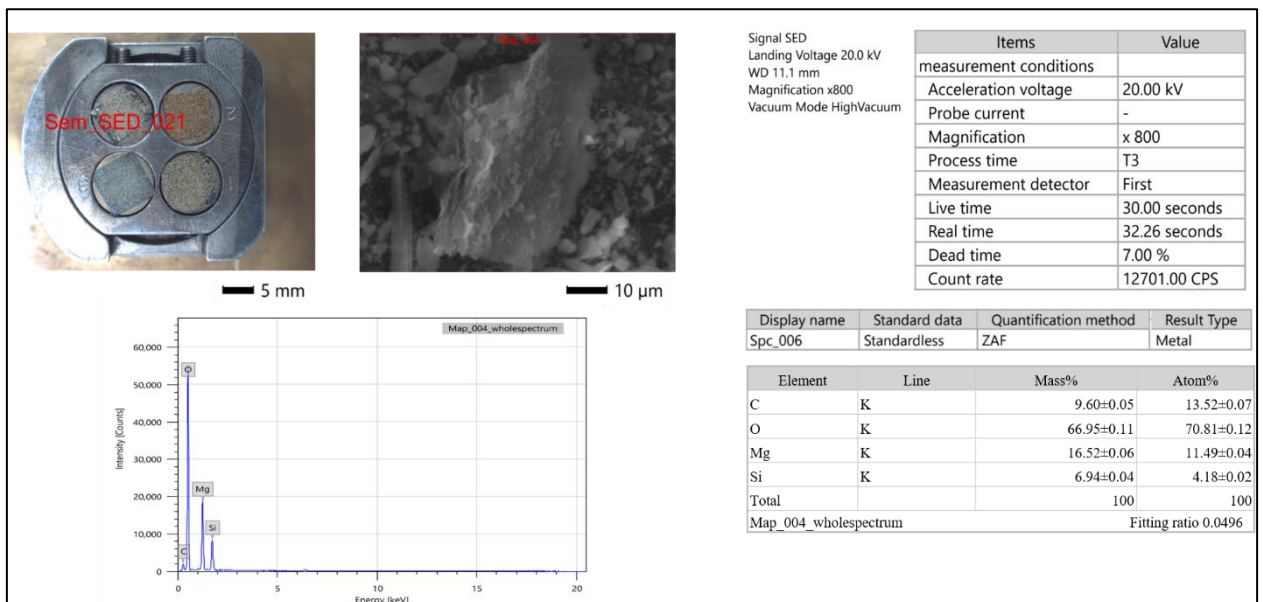


Figure 14B. SEM results of sandstone sample KNE-2 containing ultramafic-derived grains

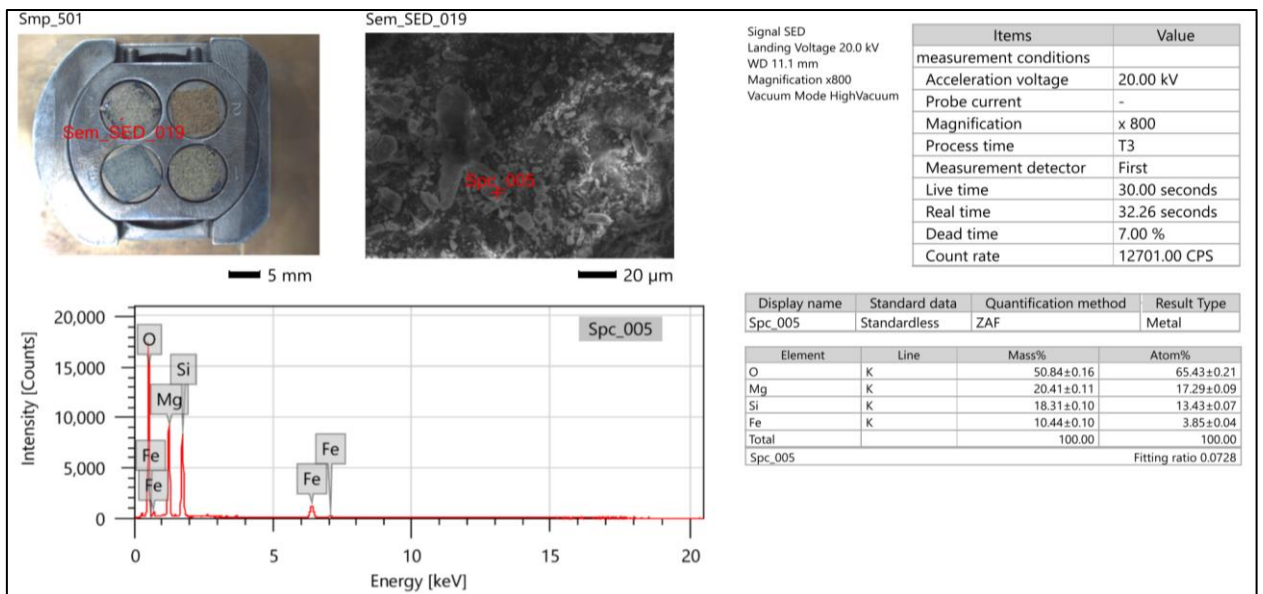


Figure 14C. SEM results of sandstone sample KNE-2 containing ultramafic-derived grains

Figure 14. Petrographic and SEM images of sandstone samples containing ultramafic-derived grains. Highlighted grains show irregular morphology and distinct optical properties under plane- and cross-polarized light. SEM analysis confirms the presence of preserved ultramafic remnants, represented by Fe- and Mg-rich particles within the sandstone matrix.

As shown in **Figure 14**, the studied samples are composed predominantly of sandstone with embedded grains interpreted as ultramafic-derived material. These grains are distinguished by their darker appearance, irregular shapes, and contrast with the surrounding quartz-rich matrix.

SEM analysis (**Fig. 14A, 14B and 14C**) revealed that these particles contain Fe- and Mg-rich components, which are interpreted as preserved ultramafic remnants within the sediment. This suggests that, despite transport and possible alteration, signatures of ultramafic source material can still be identified at the microscopic scale.

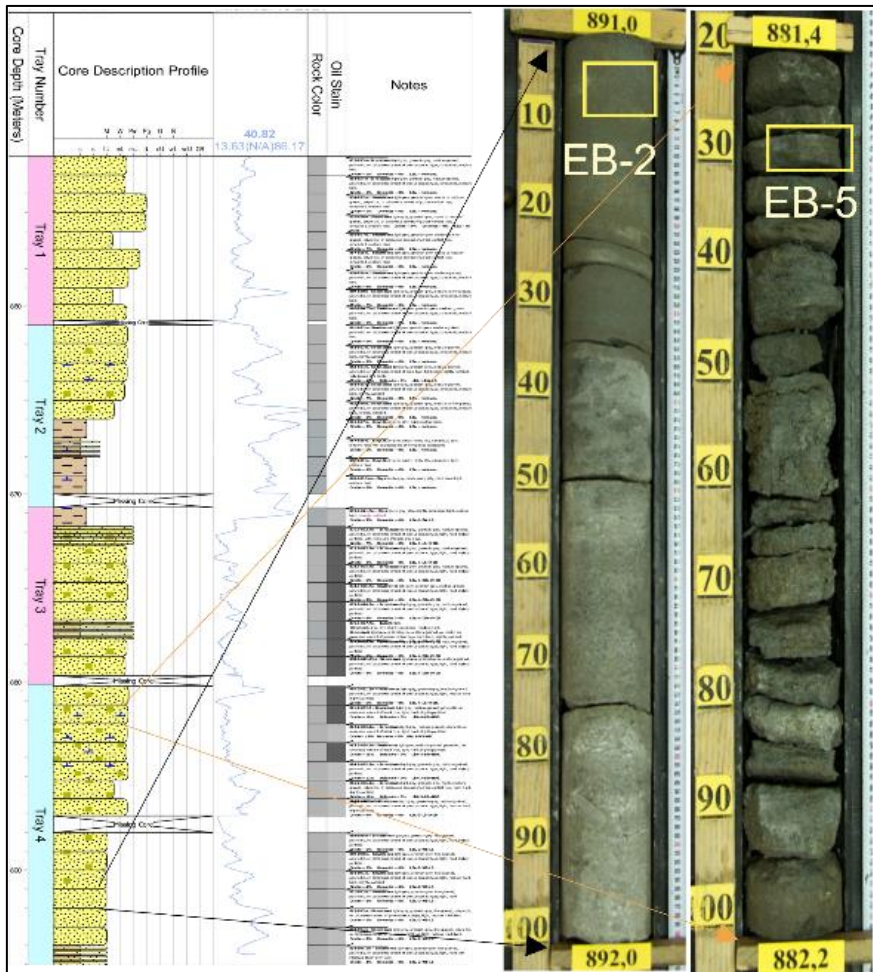


Figure 15A. Core description profile and core photographs from the EB-1 well, illustrating lithological variations and selected intervals. The photographed samples correspond to intervals **EB-2** (at a depth of 891 m) and **EB-5** (at a depth of 881.4 m). Data provided by Condor Energies.

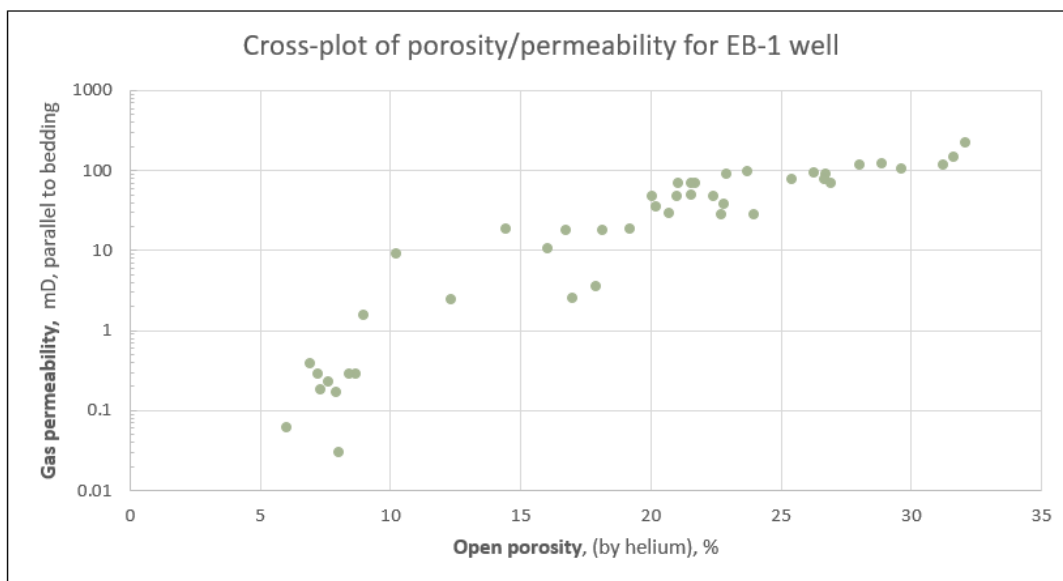


Figure 15B. Cross-plot of open porosity (%) versus gas permeability (mD) for the EB-1 well, showing the relationship between porosity and permeability.

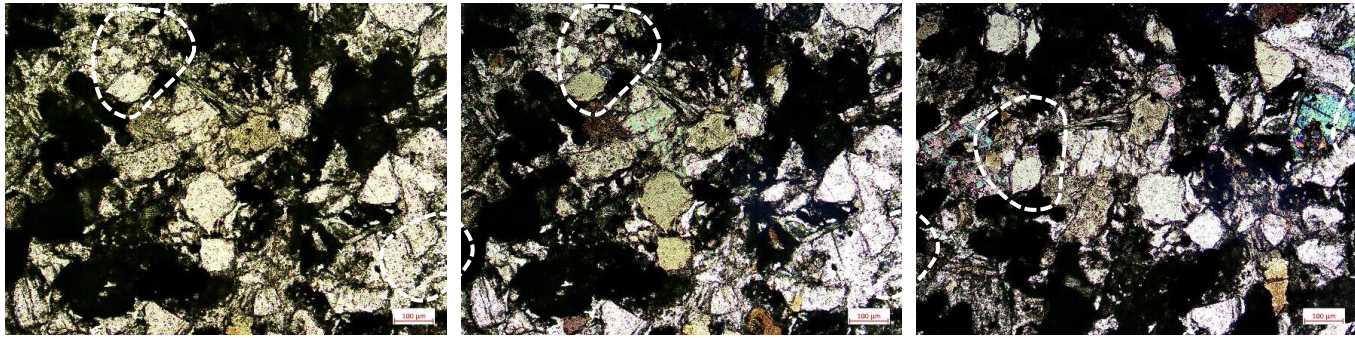


Figure 16A. Photomicrographs of the **EB-2** sandstone sample at $5\times$ magnification. Left-PPL; Middle-XPL; Right-XPL rotated 90° to enhance visibility of birefringence.

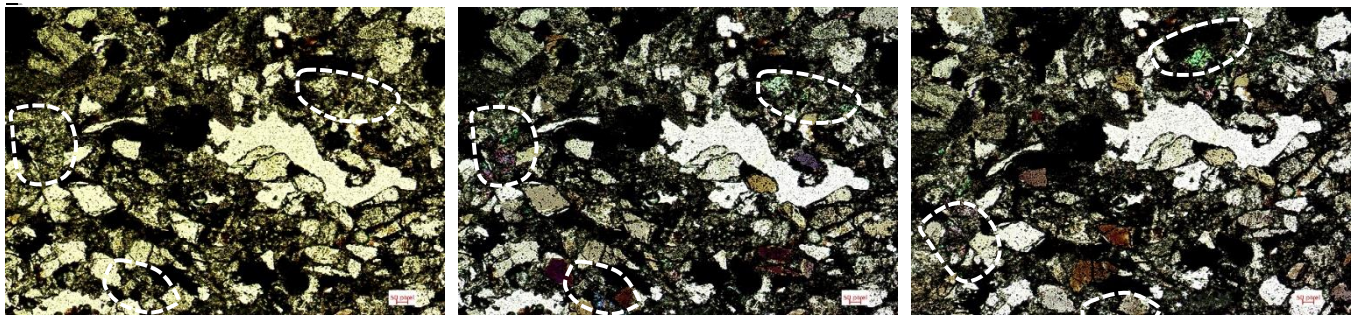


Figure 16B. Photomicrographs of the **EB-5** sandstone sample at $5\times$ magnification. Left-PPL; Middle-XPL; Right-XPL rotated 90° to enhance visibility of birefringence.

Figure 16A. Integrated analysis of the EB-1 well, including core description, core photographs, thin section petrography, and porosity-permeability cross-plot. The figure combines macroscopic observations (core logging and visual inspection) with microscopic (SEM/petrography) and petrophysical data to evaluate reservoir characteristics and mineral composition.

The EB-1 well was selected for detailed analysis because it includes both core samples and drill cuttings, allowing for a more comprehensive comparison between macroscopic observations and microscopic results. Initial visual interpretation of the core and cuttings suggested the presence of ultramafic fragments based on dark-colored grains and their apparent textural characteristics.

However, further investigation using SEM and petrographic analysis revealed that no true ultramafic minerals were present. Instead, the dark grains initially interpreted as ultramafic fragments were identified as remnants of kaolinite alteration, along with molybdenum-bearing phases and various sulfide minerals. This indicates that visual identification alone can be misleading, especially in altered or diagenetically modified sediments.

The porosity-permeability cross-plot for the EB-1 well shows a clear positive correlation, with porosity values ranging approximately from 5% to over 30% and permeability spanning several orders of magnitude. This suggests that reservoir quality is primarily controlled by pore structure rather than mineral composition, and that diagenetic processes, including clay formation and sulfide precipitation, may influence reservoir properties.

Overall, this figure demonstrates the importance of integrating macroscopic, microscopic, and petrophysical analyses, as initial interpretations of ultramafic input were not supported by detailed mineralogical evidence.

4.3 Paleogeographic evolution and basin development

This section presents the paleogeographic and basin evolution of the study area from the Permian to the Jurassic, based on regional reconstructions and cross-sectional interpretations (Figures 17–18). It outlines the major shifts in depositional environments, sediment supply, and basin architecture through time, highlighting the transition from marine to more continental-dominated conditions and the progressive infill and structural reorganization of the basin.

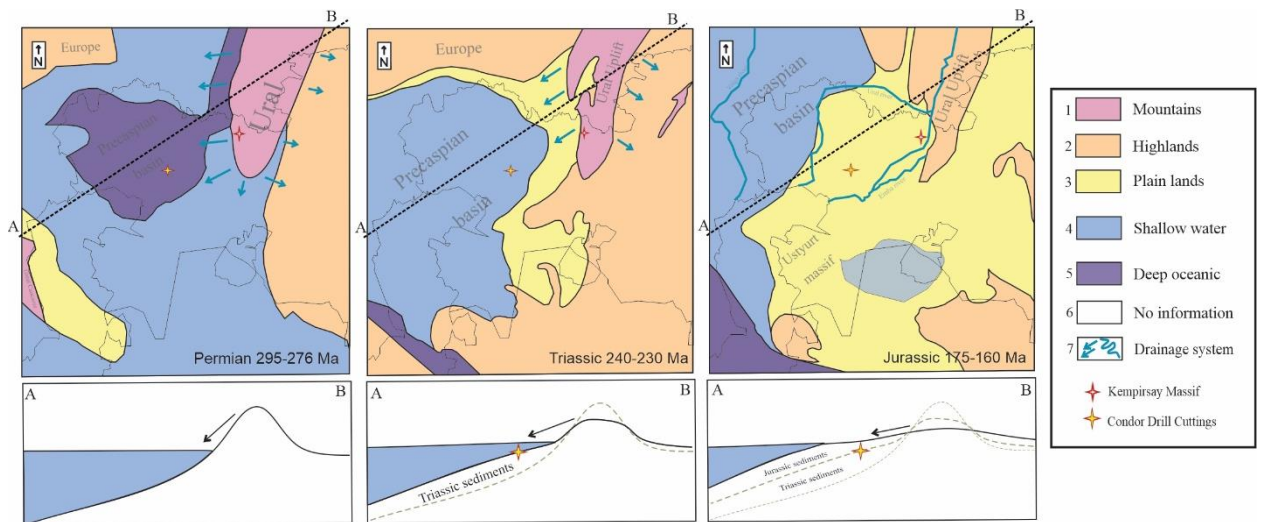


Figure 17. Paleogeographic evolution and basin development from the Permian to Jurassic. Top panels show regional maps for the Permian (295-276 Ma), Triassic (240-230 Ma), and Jurassic (175-160 Ma), illustrating progressive changes in depositional environments, shoreline positions, and distribution of lithological units. The A-B lines indicate the location of corresponding cross-sections. Stars mark Kempirsay Massif and Condor wells points. Bottom panels present schematic cross-sections along A-B, highlighting basin architecture, uplifted source areas, and sediment infill. Progressive accumulation of Triassic and Jurassic sediments records basin subsidence and lateral facies migration through time (Compiled after the *Atlas of Lithological-Paleogeographic, Structural, Palinspastic and Geocological Maps of Central Eurasia*, 2002)

As illustrated in **Figure 17**, the paleogeographic evolution of the study area reflects a transition from predominantly marine conditions in the **Permian** to more continental environments in the Triassic and Jurassic. In the Permian stage (left panel), the basin is characterized by deeper marine settings, indicating relatively lower-energy depositional conditions across most of the area.

During the **Triassic** (middle panel), **Figure 17** shows increased sediment input from uplifted source regions, particularly the Kempirsay Massif. This stage represents higher-energy depositional conditions, with active sediment transport and progradation of clinoform systems toward the basin. The corresponding cross-section highlights the development of inclined depositional surfaces and basin infill.

By the **Jurassic** (right panel), the system evolves into more stable, laterally extensive continental and shallow depositional environments. As shown in **Figure 17**, this reflects a shift

toward relatively lower-energy conditions compared to the Triassic, with more uniform sediment distribution and reduced influence of strong transport processes.

Overall, **Figure 17** demonstrates a general transition from higher-energy depositional conditions associated with active sediment supply and basin infill toward lower-energy environments as the basin became progressively filled and sedimentation stabilized. This evolution also supports the interpretation of decreasing transport intensity and more distal depositional settings over time.

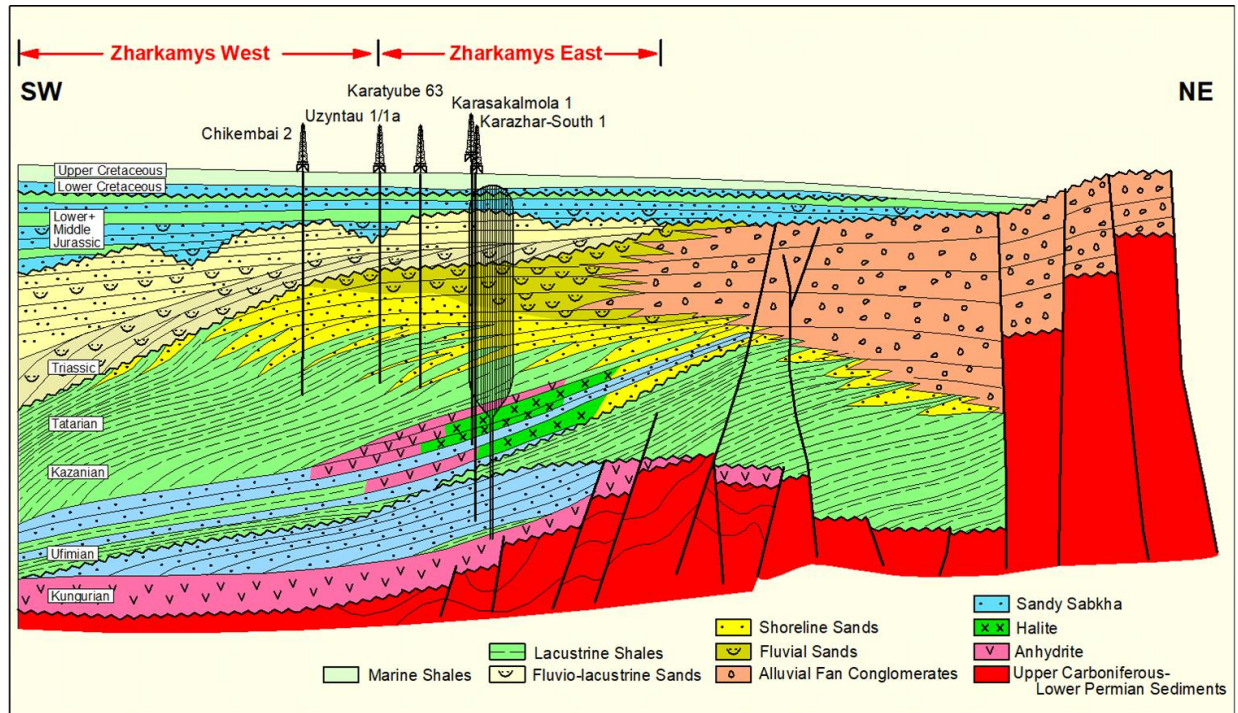


Figure 18. SW-NE geological cross-section of the Zharkamys area (Pre-Caspian Basin) illustrating the stratigraphic architecture and facies distribution controlled by salt tectonics. The section shows the transition from Zharkamys West to Zharkamys East, with well locations indicated. Major lithofacies include marine and lacustrine shales, fluvio-lacustrine and shoreline sands, alluvial fan conglomerates, and evaporites (halite and anhydrite). The geometry of Kungurian salt bodies and overlying Late Permian-Mesozoic deposits demonstrates the strong influence of salt movement on basin evolution and sediment distribution. Source: Data provided by Condor Energies.

According to the facies model of the eastern margin of the Pre-Caspian Basin (Fig. 18), sedimentation during the Late Permian can be fully interpreted as a westward (basinward) progressing alluvial clinoform system formed in response to the uplift of the Ural Mountains.

Late Permian deposits had a strong influence on the movement and structural development of the Kungurian salt. These sediments were deposited over salt ridges, forming so-called “turtle shell” structures, or initially ring-shaped synclines. As a result, the maximum thickness of the Late Permian deposits in the East Zharkamys area exceeds 3 km, which is significantly greater than the subsidence level.

The geometry of salt structures and their surface expression influenced subsequent depositional conditions. The caprock salt of salt domes was often dissolved and redeposited along the flanks of synclinal structures. In addition, salt glaciers reflect sedimentation processes active during the Late Permian

4.3.1 Stratigraphic Implications

Overall, the Zharkamys stratigraphic succession records repeated cycles of continental to shallow-marine sedimentation, which are strongly influenced by salt tectonics, regional uplift, and basin tilting. These processes controlled both the distribution and heterogeneity of sedimentary units across the basin. As illustrated in **Figure 19**, the stratigraphic framework highlights key seismic markers, salt activity phases, and lithological variations that define the basin evolution.

Reservoir-quality sandstones are restricted to suprasalt units and are most consistently developed within the Triassic, Jurassic, and Lower Cretaceous intervals, as shown in the figure by laterally continuous sandstone packages. In contrast, Upper Permian sandstones, although thick, display significant heterogeneity due to syn-depositional tectonic activity and variable sediment supply.

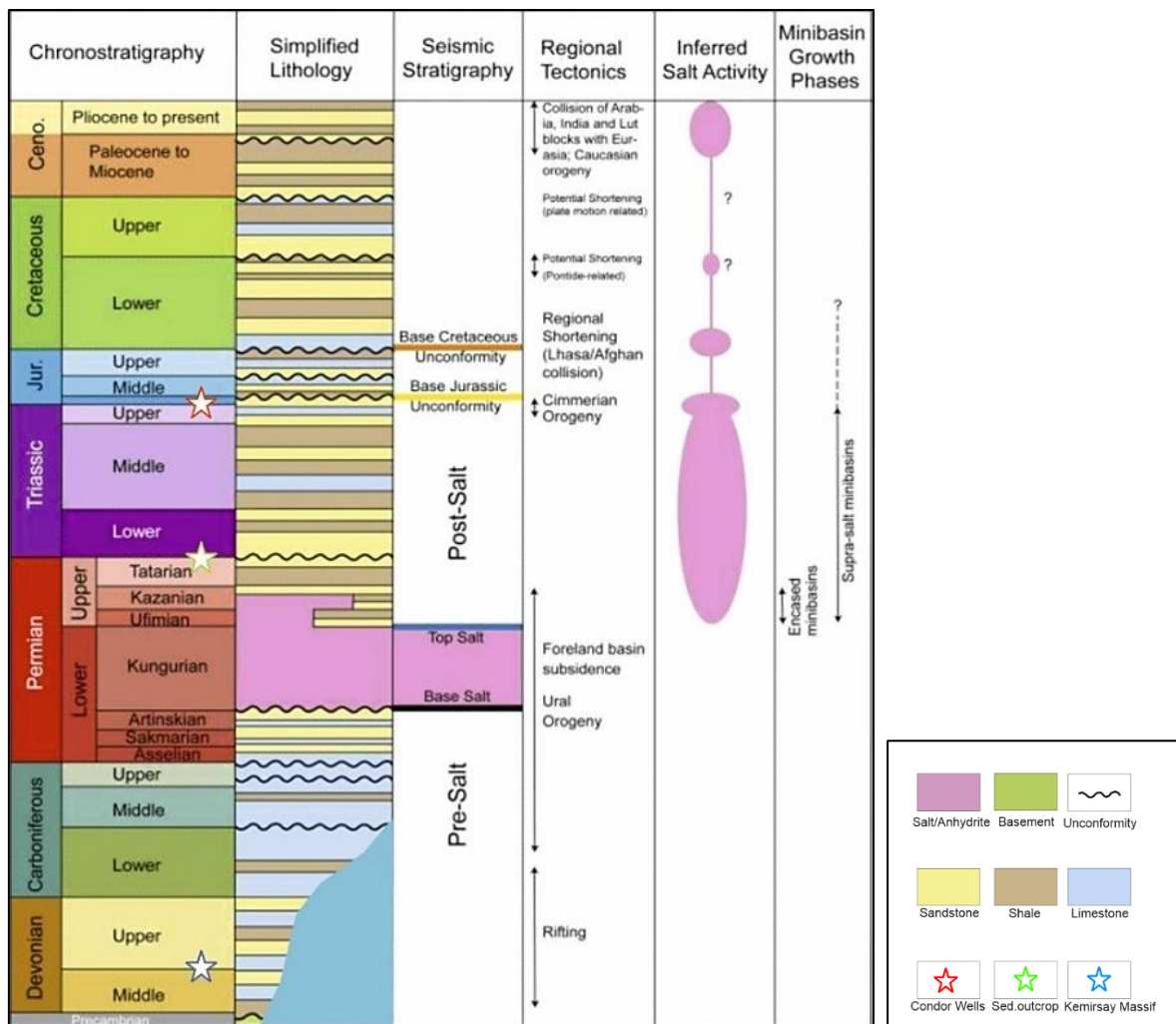


Figure. 19. Stratigraphic framework and representative lithologies of key units in Eastern Precaspian Basin, after Barde et al. (2002b). Key seismic stratigraphic markers colour coded and continued throughout the article. Key tectonic events and phases of inferred salt mobilisation also shown.

The integration of stratigraphy and tectonic evolution presented in Figure 19 demonstrates how salt mobilization and basin dynamics influenced sediment distribution, burial conditions, and preservation potential. This framework also suggests favorable conditions for the accumulation and reactivity of ultramafic-derived detrital material, which is important for CO₂ mineral trapping processes.

5. Discussion

5.1 Ultramafic grains provenance, transport, burial, and preservation

The provenance of ultramafic (UM) grains in this study is interpreted with caution and is primarily linked to a nearby source consistent with the Kempirsai Massif, a major ophiolitic complex containing Mg-rich lithologies such as harzburgite and dunite. Petrographic observations confirm the presence of olivine- and serpentine-bearing lithic fragments within the studied samples; however, this interpretation is based on mineral assemblages and textures rather than detailed mineral chemical analysis. Sedimentological evidence indicates that the host sandstones were deposited in a generally low-energy environment, whereas the ultramafic fragments commonly occur as sub-angular grains. This textural contrast suggests limited transport distance and relatively rapid sediment delivery from the source area into the basin, rather than extensive reworking or long fluvial transport. As such, the data support a proximal sediment source, although the exact degree of transport cannot be fully constrained with the available dataset. It should also be noted that a definitive classification of these grains as ultramafic-derived remains tentative in the absence of mineral chemistry or compositional fingerprinting. Future work involving geochemical or microprobe analyses would be required to confirm their ultramafic affinity with higher confidence. Comparable occurrences of ultramafic detritus have been reported in ophiolite-influenced basins worldwide, including the Solund Basin (Beinlich et al., 2010), where relatively immature transport and rapid burial have been shown to preserve reactive Mg-silicate phases in clastic systems. The interpretation remains limited by the lack of mineral chemical data and heavy mineral analyses, which does not allow for a fully robust confirmation of ultramafic provenance.

Transport of UM grains from the source to the depocenter (Triassic Ilek and quarry outcrops) implies mechanical durability of these minerals despite weathering and insitu alteration processes. The preservation of olivine and serpentine indicates limited chemical alteration during transport and long burial history (since Triassic and Jurassic), which is critical for maintaining their reactivity. A key control on preservation is temperature: ultramafic minerals are stable and retain their reactivity at low temperatures (<50 °C). Burial history reconstruction (Fig. 21) for the study area shows that temperatures did not exceed ~25 °C, well below the threshold for significant thermal alteration or dissolution. This is consistent with the preservation of primary mineral phases and supports the interpretation that ultramafic grains remained chemically intact from source to sink. Consequently, the Pre-Caspian Basin, including the EB-1 and KNE-1,

represents a suitable sink where ultramafic grains are preserved under favorable thermal conditions for subsequent CO₂ mineralization.

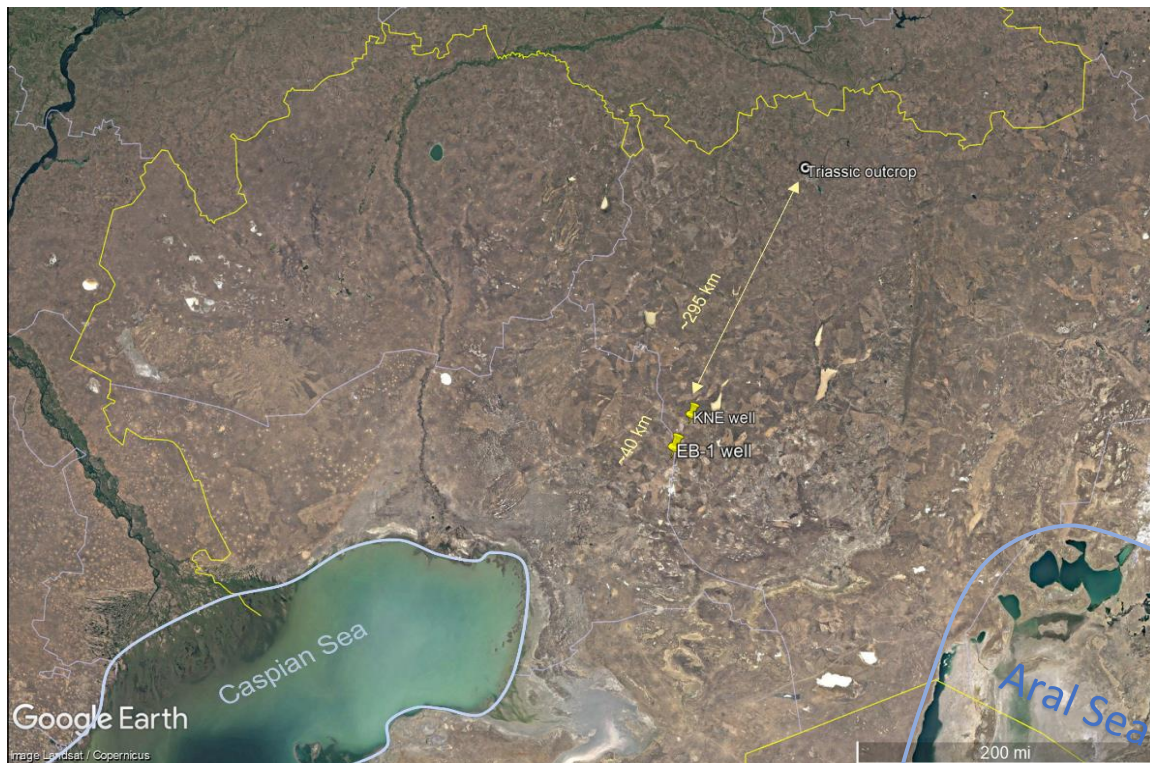


Figure 20. Regional map showing the Triassic outcrop and the locations of the KNE and EB-1 wells. The Triassic outcrop is interpreted as the main sediment source for both wells. Because the KNE well is located closer to this source area, it is more likely to contain less transported and less altered material, including ultramafic grains. In contrast, the EB-1 well lies at a greater distance from the source, meaning that sediments have undergone longer transport. This increased transport distance may explain the higher degree of reworking and alteration observed in EB-1, which also makes the preservation of fragile ultramafic particles less likely and therefore difficult to identify in these sections.

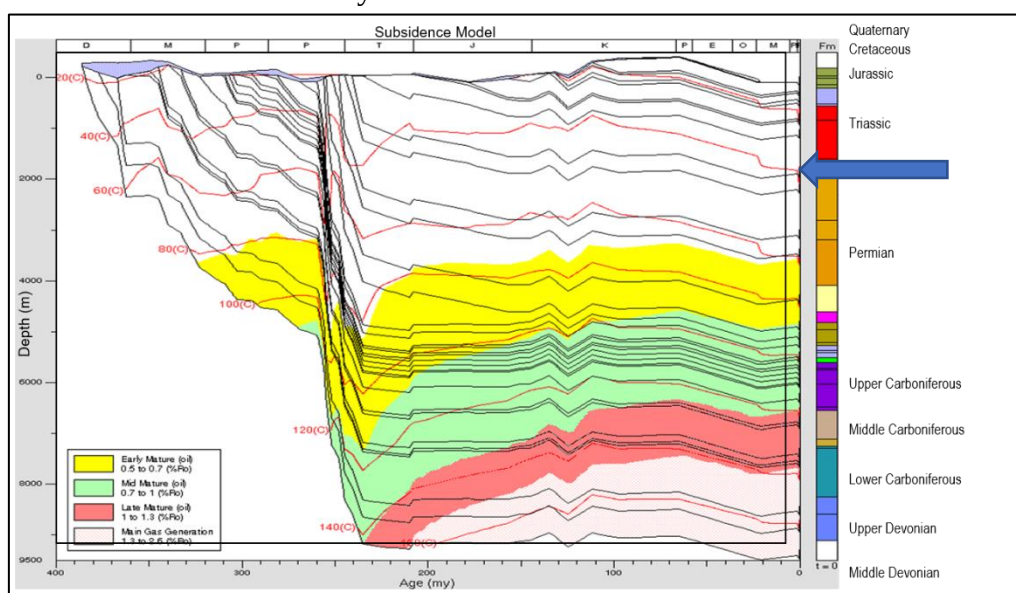


Figure 21. Burial and thermal maturity model (KNE well). Courtesy of Condor Petroleum.

Burial history diagram showing stratigraphic subsidence through time versus depth. Black lines: stratigraphic layers; red lines: temperature isotherms (20-140 °C). Colored zones indicate hydrocarbon maturity stages based on vitrinite reflectance (%Ro).

The burial chart shows Devonian to Lower Carboniferous formations reached the main gas generation window, while Middle to Upper Carboniferous strata are in late to mid-mature oil windows. Triassic and Jurassic samples (this study) are too shallow (~2000 m) to enter the oil window. Triassic formation exhibits 20-40 °C isotherms.

For carbon capture and storage (CCS) purposes, achieving a supercritical state for CO₂ (minimum 31.1 °C) is essential for injection efficiency, with optimal conditions between 31.1 °C and 60 °C (ideally near 45 °C; e.g., [Bachu, 2003*](#)). The thermal profile suggests that the lower half of the Triassic section offers the most favorable conditions for carbon storage, which coincides with the interval where ultramafic minerals are identified in the samples. Overall, the burial and thermal history indicates that temperatures did not fall below ~40 °C, confirming consistently suitable conditions for CCS processes across the studied intervals.

5.2 Chemical reactivity of ultramafic grains

Ultramafic grain-bearing reservoirs demonstrate high potential for CO₂ storage due to their favorable petrophysical and geochemical properties. The presence of excellent porosity ensures high storage capacity and efficient injectivity, allowing CO₂-rich fluids to penetrate the reservoir effectively. In addition, interconnected pore networks enhance fluid circulation and maximize fluid-rock interaction, which is a critical requirement for mineral carbonation reactions.

Laboratory experiments by [Leila et al. \(2025\)](#) provide direct evidence of the high reactivity of ultramafic materials. Under controlled conditions, powdered ultramafic rocks reacted with CO₂-rich fluids produced approximately 70% carbonate minerals within 14 days, demonstrating rapid and efficient carbonation. These results highlight that the key controlling factor is the availability of sufficient fluid-rock contact, which governs the dissolution of Mg-silicates and subsequent precipitation of carbonate phases.

Importantly, natural reservoirs are expected to exhibit better-developed porosity and permeability compared to laboratory systems using powdered samples. This suggests that, under subsurface conditions such as those in the Pre-Caspian Basin, fluid flow pathways are likely to be more extensive, enabling more effective fluid-rock interaction. As a result, in situ carbonation processes may proceed more efficiently than those observed experimentally. Overall, the combination of high porosity, interconnected pore networks, and reactive mineralogy creates favorable conditions for in situ CO₂ mineral trapping, supporting the feasibility of ultramafic grain-bearing reservoirs as long-term carbon storage systems.

However, the abundance of ultramafic (UM) grains in the studied samples is limited, which may reduce the overall reactive surface area available for carbonation. In addition, significant mineral trapping under natural conditions is likely to develop over extended timescales.

6. Conclusion

This study demonstrates the strong potential of integrating ultramafic source regions and sedimentary sink systems into a unified source-to-sink framework for long-term CO₂ mineral storage. By linking the Kempirsai Ophiolite Massif with subsurface reservoirs of the Pre-Caspian

Basin, the research confirms that ultramafic-derived sediments can be effectively transported, deposited, and preserved within sedimentary environments while maintaining their chemical reactivity.

Field observations, core descriptions, and petrographic evidence confirm the presence of ultramafic fragments within the sedimentary record, supporting the hypothesis of transport through paleo-drainage systems. These findings are consistent with the proposed geological model and indicate that such fragments can survive burial processes without losing their mineralogical character. Experimental results further demonstrate that these materials remain reactive under elevated CO₂ conditions, as shown by rapid Mg release, progressive alkalization, and favorable conditions for carbonate precipitation.

Importantly, burial depths of approximately 1000 m are identified as optimal for CO₂ mineral trapping, where pressure–temperature conditions enhance water–rock interaction and promote stable carbonate formation. This confirms that sedimentary reservoirs containing ultramafic detritus can act as efficient and scalable sites for in situ carbon mineralization, overcoming limitations associated with direct injection into low-permeability ultramafic rocks.

The Pre-Caspian Basin contains deep subsurface reservoirs with strong potential for geological CO₂ storage. One of the promising injection sites within the basin is the Condor Oil Field, which links the ultramafic source region of the southern Ural Mountain Belt to a potential sink for subsurface CO₂ storage. This source-to-sink relationship highlights an important decarbonization opportunity in Kazakhstan, where reactive ultramafic material and suitable sedimentary basin storage systems occur within the same broader regional framework.

Overall, this research provides a novel perspective on carbon storage by demonstrating that sedimentary systems enriched with ultramafic material represent a viable and previously underexplored pathway for permanent CO₂ sequestration. The results highlight Kazakhstan's significant geological potential for developing large-scale carbon capture and storage strategies, contributing to global decarbonization efforts and advancing the practical implementation of mineral trapping technologies.

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