Analysis of the Priirtysh Sedimentary Basin for the Presence of Aquifers Suitable for CO_2 Storage

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ABSTRACT

This scientific study presents a comprehensive assessment of the Priirtysh sedimentary basin, focusing on identifying potential reservoirs for carbon dioxide (CO_2) storage. The methodology includes 2D seismic data interpretation, well log analysis, and the construction of a 3D geological model using Petrel software. Seismic surveys conducted between 1992 and 1997, along with data from more than 4,000 hydrogeological wells, were utilized to develop a structural and lithological model of the basin. Kazakhstan currently lacks dedicated infrastructure for CO_2 capture and storage. Notably, potential CO_2 storage formations in the Pavlodar region, which accounts for the highest greenhouse gas emissions in the country, have yet to be systematically evaluated. Thus, investigating the CO_2 storage potential of regional aquifers is of both scientific and strategic importance. By combining geophysical (seismic interpretation) and petrophysical (porosity, permeability, and reservoir quality) analyses with 3D geological modeling, this study offers new insights into the subsurface architecture of the basin. The integration of seismic and well log data significantly enhances the model's accuracy and enables the identification of structural complexities. Key findings indicate the presence of several promising aquifers at depths between 500 and 2,000 m,

particularly within the Upper Jurassic–Cenozoic formations. The study estimates the CO_2 storage capacity of these aquifers and assesses their suitability for long-term containment, laying the groundwork for future hydrodynamic simulations and injection feasibility studies. Ultimately, the identification of viable storage formations in the Pavlodar region aligns with Kazakhstan's strategic goal of achieving carbon neutrality by 2060.

Keywords-geology; geophysics; petrophysics; seismic; stratigraphy; seal; reservoir; well

I. INTRODUCTION

Greenhouse gases, such as carbon dioxide (CO_2), methane, and nitrous oxide, accumulate in the atmosphere, trapping heat and contributing to global warming. This phenomenon drives climate change, resulting in extreme weather events, rising sea levels, and ecosystem degradation [1, 2]. In Kazakhstan, the majority of CO_2 emissions originate from the combustion of fossil fuels for energy production and from industrial activities, such as cement manufacturing. In 2023, Kazakhstan's CO_2 emissions reached 255.16 million tons, underscoring the environmental impact of its energy and industrial sectors [3]. Authors in [2] present an interactive breakdown of annual CO_2 emissions by major sources, including coal, oil, and natural gas combustion, as well as cement production and gas flaring. The current volume of emissions underscores the urgency of deploying low-carbon technologies and enhancing resource efficiency to combat climate change. To this end, the President of Kazakhstan has established a strategic objective to have achieved carbon neutrality by 2060 [4], a move expected to prevent over 9 billion tons of CO_2 from entering the atmosphere [5]. A key component of carbon neutrality is industrial CO_2 utilization, particularly by manufacturing plants, power stations, and other large-scale industrial enterprises. Of Kazakhstan's total emissions, coal-fired thermal power plants contribute the largest share—146.57 million tons. Accordingly, this study focuses on emissions from coal combustion as a primary target for mitigation. According to the national CO_2 emissions map, the Pavlodar region records over 5 million tons of CO_2 emissions annually [6]. This is primarily attributed to the significant concentration of industrial enterprises, including manufacturing facilities and thermal power plants, within this region.

The CO_2 utilization process encompasses two fundamental stages: CO_2 capture and storage. The first stage is relatively well-developed, with oil service companies employing proprietary CO_2 capture technologies. However, the second stage necessitates the presence of suitable geological formations, specifically, underground CO_2 reservoirs, that meet a set of stringent geophysical and geochemical criteria [7], while also meeting both technical feasibility and economic viability criteria for long-term CO_2 storage.

The majority of CO_2 reservoirs worldwide are represented by aquifers [8–10]. It is crucial to establish a set of criteria for selecting suitable aquifers based on the proximity to industrial facilities, the depth of the formation, and other key parameters. This approach will enable a more selective collection of geological data, focusing on the most relevant information [11]. Previous studies [12, 13] have introduced tools for estimating CO_2 storage capacity, including enhanced oil recovery through CO_2 injection, an approach widely used to improve oil production [14].

A review of the literature and data from oil and gas operators [15, 16] has identified six potential CO_2 storage basins in Kazakhstan: Caspian, Mangyshlak, Ustyurt-Bozashinsky, South Turgai, Shu-Sarysu, and Zaisan. However, these studies have several limitations:

- The Priirtysh sedimentary basin, which includes the Pavlodar region—Kazakhstan's largest CO_2 emitter—was not examined. Storing CO_2 in distant basins (over 1000 km away) would be economically unfeasible due to high transportation costs.
- Basin-scale assessments were conducted without identifying specific geological horizons suitable for CO_2 injection.
- No geological or hydrodynamic modeling was performed, and no feasibility studies were carried out—an essential step in planning CO_2 disposal.

Currently, no comprehensive research in Kazakhstan has examined CO_2 storage from both technical and economic perspectives—particularly in the Priirtysh sedimentary basin, where CO_2 utilization is most justified. Globally, large-scale CO_2 storage projects, such as Sleipner in Norway and Gorgon in Australia, have demonstrated the feasibility of geological sequestration as part of climate mitigation strategies [17].

This study is the first to investigate the technical and economic feasibility of CO_2 storage in the Priirtysh sedimentary basin—Kazakhstan's most carbon-intensive region. By identifying suitable aquifers and developing a geological model for CO_2 injection, the research aims to fill a critical knowledge gap in national decarbonization strategies. The findings aim to support industrial stakeholders with data necessary for implementing long-term storage solutions, ultimately contributing to significant reductions in greenhouse gas emissions.

II. METHODOLOGY

This study adopts an integrated geological and geophysical approach to assess the potential of the Priirtysh sedimentary basin for CO_2 storage. The methodology includes seismic data analysis, well log interpretation, and 3D geological modeling using Petrel software.

A. Geological and Geophysical Analysis

The structural framework of the basin was constructed using 2D seismic data acquired between 1992 and 1997, covering a total length of 4,235.68 km. These seismic lines were digitized and interpreted to identify key reflecting horizons. The seismic data were integrated with geological information from over 4,000 hydrogeological wells, with drilling depths reaching up to 1,300 meters. The stratigraphic model was reconstructed through the correlation of lithological columns and geophysical well logs.

B. Well Log Interpretation

A comprehensive analysis of geophysical well logs was performed to characterize lithology and estimate the petrophysical properties of the reservoir rocks. The following well log types were utilized:

- Gamma-ray logs, for lithological identification.
- Neutron porosity logs, for porosity estimation.
- Density logs, for bulk density and porosity estimation.
- Resistivity logs, for fluid saturation analysis.
- Sonic logs, which, when they were available, were used for seismic calibration.

These datasets were quality-checked, depth-matched, and integrated into the geological model.

C. Structural and Lithological Modeling

A regional structural model was developed using interpreted seismic horizons, including markers I (Paleogene base), IIp (Pokur Formation), IIk (Kiyalinsky Formation), IIt (Tara Formation), III (Jurassic top), A (Paleozoic top), and B (Paleozoic base). Lithological and facies models were generated using Sequential Indicator Simulation (SIS), while Gaussian Random Function Simulation (GRFS) was applied to model petrophysical properties, such as porosity. These methods enabled the spatial prediction of reservoir heterogeneity and the identification of potential CO_2 storage intervals.

D. 3D Geological Model Development

A 3D geological model of the basin was developed in Petrel, initially at a grid resolution of 500 × 500 m for the entire basin. For the target area with the highest emission levels, the resolution was refined to 200 × 200 m. Well data were upscaled to match the model resolution, ensuring accurate spatial distribution of lithological and petrophysical parameters. The model served as the basis for dynamic simulations of CO_2 injection behavior. The key modeling parameters are summarized in Table 1.

TABLE I. MAIN PARAMETERS OF THE GEOLOGICAL MODEL

Parameter	**Value / Description**
Seismic data type	2D (total length: 4,235.68 km)
Number of wells	> 4,000
Max well depth	1,300 m
Grid resolution (basin)	500 × 500 m
Grid resolution (target area)	200 × 200 m
Modeling software	Petrel (Schlumberger)
Lithological modeling	SIS
Porosity modeling	GRFS
Input logs	Gamma Ray (GR), Neutron Porosity (NPHI), Bulk Density (RHOB), Resistivity (RT), Sonic

The final model serves as a basis for hydrodynamic simulations to evaluate CO_2 injection feasibility. Hydrodynamic simulation allows assessing the possibility of fluid leakage into the surrounding geological formations or the ground surface [18].

III. GEOLOGICAL AND GEOPHYSICAL KNOWLEDGE

Field seismic studies were conducted in 1992–1996, with aeromagnetic surveys interrupted in 1994–1996 due to funding issues but resumed in 1996–1997. A total of 4,235.68 km of seismic profiles were processed. No deep drilling for oil and gas assessment was conducted; Mesozoic data rely on geological and hydrogeological wells, exceeding 4,000 in number, with depths up to 1,300 m. Very few wells have penetrated the Paleozoic, with only one exceeding 1,200 m in depth. Interpretations of deeper stratigraphic sections remain uncertain due to the limited availability of deep borehole data. The Priirtysh sedimentary basin comprises three structural levels: i) a folded basement, ii) an Upper Paleozoic–Lower Mesozoic intermediate stage, and iii) a subhorizontal Upper Jurassic–Cenozoic platform cover.

The basement includes Hercynian, Caledonian, and Salairian fold systems, influencing the overlying structures. The intermediate stage reflects a transition between geosynclinal and platform evolution, combining basement folding and quasi-platform characteristics. The Mesozoic–Cenozoic cover, composed mainly of terrigenous rocks, shows gradual thickness variations and gentle platform-type structures inherited from basement movements [19].

IV. LITHOLOGICAL AND STRATIGRAPHIC CHARACTERISTICS OF THE PRIIRTYSH SEDIMENTARY BASIN

The lithological and stratigraphic characteristics of the Priirtysh sedimentary basin were examined based on existing geological reports [20, 21].

A. Tectonic Structure of the Priirtysh Sedimentary Basin

The Priirtysh sedimentary basin, located within the North Kazakhstan monocline, forms the southern periphery of the West Siberian Basin. Positioned in the junction zone of the Caledonian and Hercynian folded regions, it exhibits a heterogeneous Paleozoic structure. The southern boundary follows Caledonian outcrops of the Kazakhstan folded massif.

A study of the platform cover identified faults affecting aquifers at depths of 800–1,000 m. The sedimentary basin includes key reflecting horizons: I, IIp, IIk, IIt, III, A, and B. Jurassic deposits (III) dip northward, reaching depths of 2,200 m, with structures like the Maitan uplift. Cretaceous deposits (IIt and IIk) are distributed mainly in the north, showing monoclinic subsidence from 1,050 to 1,950 m in depth. The Pokur Formation (IIp) covers the entire area, overlaying Paleozoic formations. Structural elements align across horizons, with features such as the Zhelezinsky trough merging with the Suvorovsky trough.

B. Structural Framework and Geophysical Investigations

To develop a structural framework, structural maps of the basin from [16] were digitized.

The Pri-Irtyshskaya-1 (P-1) well, drilled by SAUTS-OIL LLP in 2022, was selected as the reference well for studying lithological characteristics, sedimentation mechanisms, and reservoir properties. A comprehensive logging suite was conducted, including radioactive methods, caliper logging, spontaneous potential, acoustic and density logging, high-resolution induction logging, resistivity logging, and microgradient methods. Additional investigations, such as thermometry and profilometry, were also carried out. Based on these data, a correlation diagram was constructed to subdivide the reservoir section into lithologically distinct intervals (IIt1–IIt4 and A1–A3), as shown in Figure 1. Beyond simple stratigraphic subdivision, Figure 1 reveals variations in lithology and porosity trends with depth, indicating zones of enhanced reservoir quality. These observations guided the identification of target intervals for detailed 3D geological modeling and assessment of potential CO_2 storage capacity.

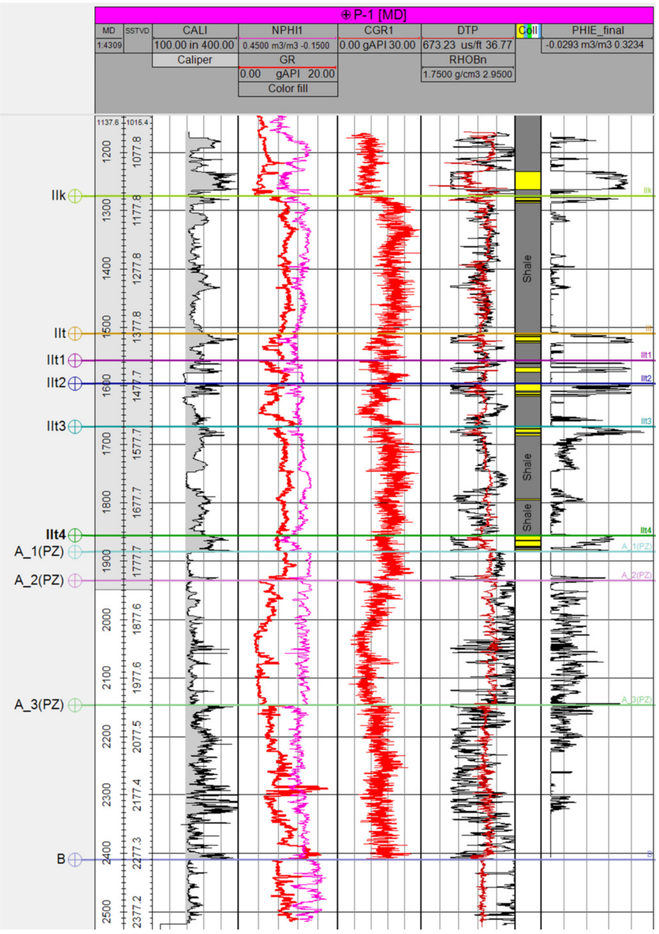

Fig. 1. Correlation diagram showing subdivision of reservoir intervals (IIt1–IIt4 and A1–A3) in well P-1, based on lithological and petrophysical analysis.

Porosity and lithology (reservoir versus non-reservoir) interpretations were also carried out. A core sample was collected from the 1,200.4–2,415.6 m interval, with a total recovery of 44.8 m. Based on these samples, the filtration and reservoir properties of the rocks were analyzed using standard specialized studies.

V. CONSTRUCTION OF A 3D GEOLOGICAL MODEL

The construction of the 3D geological model of the field followed a standard sequence of stages: i) structural modeling, ii) upscaling well data to the geological grid, iii) facies modeling, and iv) petrophysical modeling. A fundamental stage in modeling is the creation of a 3D grid, which consists of a framework of cells containing digital geological data.

The structural framework of the Priirtysh sedimentary basin includes horizons I, IIp, IIk, IIt, A_1, A_2, A_3 (PZ), and B, with a lateral grid size of 500 × 500 meters applied across the entire basin, as shown in Figure 2. The model comprises a total of 9.5 million cells, with a vertical resolution of 10 meters in reservoir intervals.

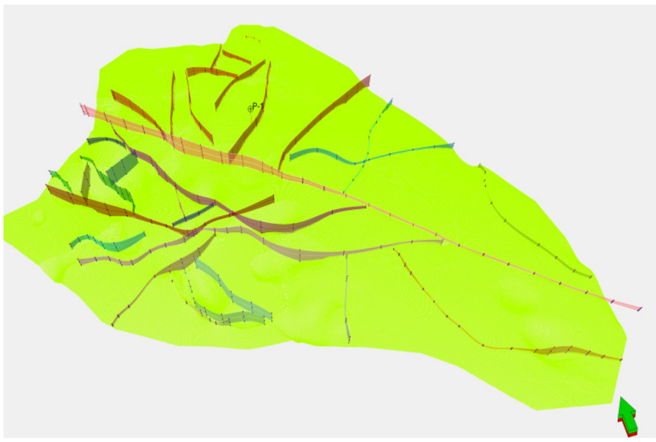

Fig. 2. Structural framework of the Priirtysh sedimentary basin.

A. Upscaling Well Data to the Geological Grid

During the construction of the 3D geological model, well data were upscaled to 3D grid cells intersected by the well trajectory. The grid cells penetrated by the wellbore were automatically identified using well trajectory data and the geometry of the 3D grid. Lithology and porosity log curves were then assigned to the corresponding cells to characterize reservoir properties.

B. Facies and Petrophysical Modeling

Lithology is the primary property in a 3D geological model, as it determines the presence or absence of a reservoir. Each grid cell is assigned to a discrete value, representing either a reservoir (1) or a non-reservoir (0). The lithology model was generated based on processed well log data and regional geological characteristics of the basin. To distribute the discrete lithology property, the stochastic SIS method available in Petrel was applied. Porosity modeling was performed using the stochastic GRFS method across the entire IIt reservoir (Figure 3).

Porosity is a key parameter in evaluating underground reservoirs for CO_2 storage, as it determines the volume of pore space available for gas injection. Suitable porosity values depend on specific geological conditions; however, in most cases, the effective porosity should be at least 10–20% to ensure sufficient storage capacity. While total porosity may be higher, it is important to note that a portion of the pore space may be isolated and not contribute to CO_2 containment. According to Figure 3, the effective porosity within the selected area of the reservoir is approximately 18%, which falls within the acceptable range for CO_2 storage. This indicates that the reservoir possesses sufficient pore volume for injection and long-term containment, making it a promising candidate for further evaluation. Additionally, adequate permeability—typically not less than 10 millidarcies—is essential to ensure efficient CO_2 injection and uniform distribution within the reservoir [22].

Figure 4 shows the spatial configuration of the target CO_2 storage zone near well P-1, located at a depth of approximately 1500 m and selected based on favorable lithological continuity and structural confinement, where a more detailed grid with lateral dimensions of 200 × 200 m was subsequently constructed. The total number of cells is 1.77 million, with a vertical resolution of 0.5 m. Lithology and porosity logs were upscaled onto this grid, and porosity and lithology distributions were reconstructed using the same stochastic methods (Figure 5). Permeability was modeled based on the laboratory analyses' porosity–permeability relationship. The main reservoir properties are summarized in Table II.

TABLE II. RESERVOIR PROPERTIES SELECTED FOR POTENTIAL CO_2 STORAGE

Reservoir properties	Value / Description
Depth, m	1550
Thickness, m	20
Porosity, %	22
Permeability, mD	0.5
Caprock integrity	The caprock consists of clay-rich formations, exhibits moderate structural integrity, and reaches a thickness of up to 500 m

As part of the basin assessment, geological modeling, and site selection for CO_2 storage, particular attention was given to the risk of CO_2 leakage—a critical factor in evaluating storage security, especially near fault zones and caprock formations. Faults may serve as preferential pathways for upward CO_2 migration, especially if they are hydraulically conductive or prone to reactivation under increased pore pressure during injection. Likewise, the effectiveness of the caprock as a sealing formation depends on its low permeability, mechanical stability, and resistance to geochemical alteration. Compromised caprock integrity—whether due to natural fracturing, diagenetic changes, or stress-induced damage—can significantly reduce storage security. Moreover, interactions between CO_2, brine, and caprock minerals may alter sealing properties over time, further contributing to leakage risks. Therefore, comprehensive site characterization—including detailed fault mapping, stress field analysis, and geochemical evaluation of sealing formations—is essential to ensure long-term containment.

In this study, the structural configuration of the Priirtysh sedimentary basin was examined to identify fault systems and evaluate caprock properties. Areas exhibiting minimal fault development and favorable sealing characteristics were selected as the most promising candidates for secure and effective CO_2 storage.

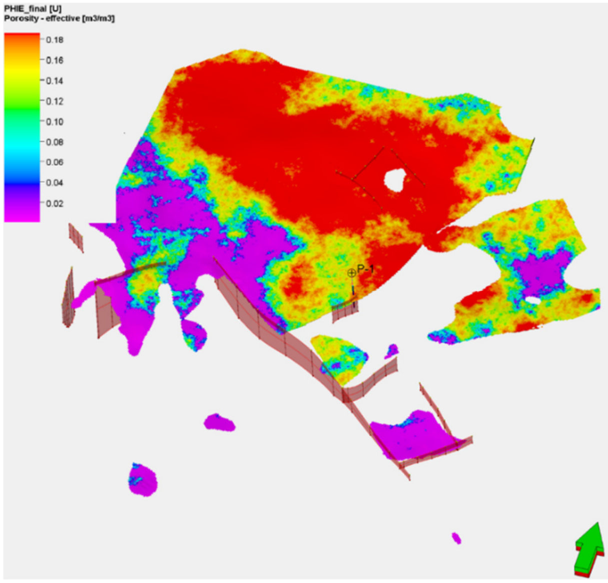

Fig. 3. Porosity model in the IIt reservoir in the P-1 well.

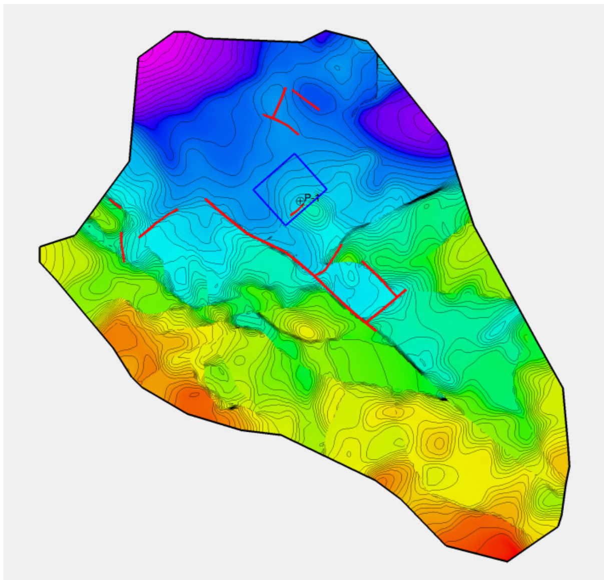

Fig. 4. Location of the prospective CO_2 storage zone near P-1 well, derived from the 3D geological model.

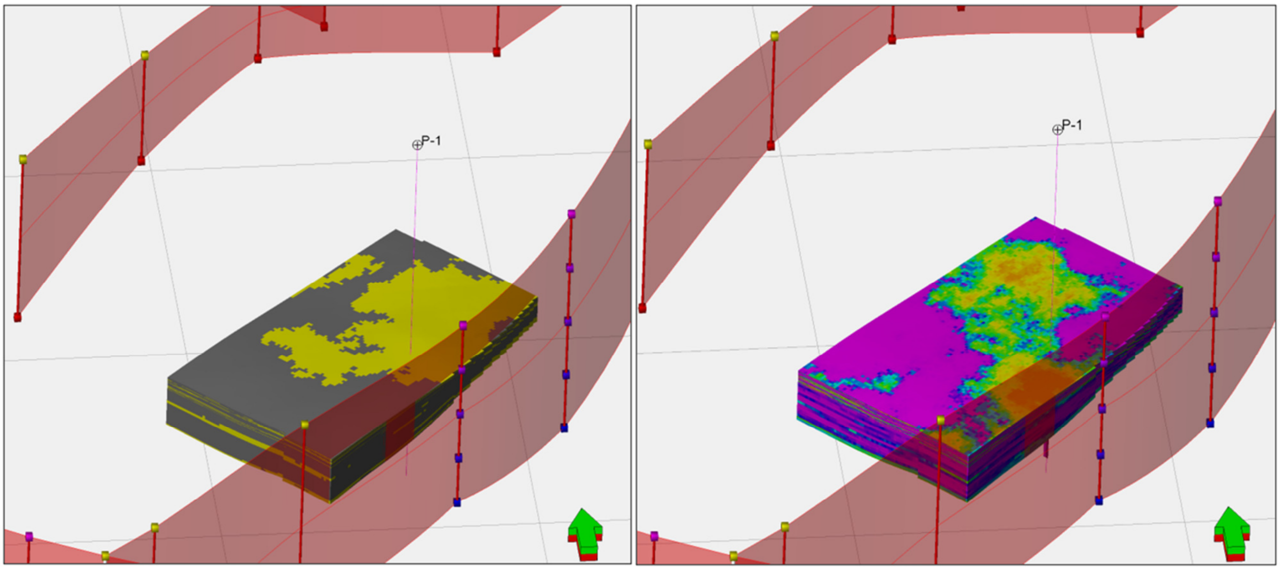

Fig. 5. 3D distribution of lithology and porosity in the target reservoir zone.

VI. CONCLUSION

To mitigate the carbon dioxide (CO_2) emissions in Kazakhstan's Pavlodar region—the country's largest CO_2 emitting area—this study investigates the potential of aquifers within the Priirtysh sedimentary basin as long-term geological storage sites for CO_2. The assessment involved detailed geological and geophysical analyses, structural and lithological modeling, and the construction of a high-resolution 3D geological model using the Petrel software.

The key findings of this work include:

- Stratigraphic Structure: The geological section of the Pavlodar Priirtysh region consists of three structural levels: the folded basement, the intermediate Upper Paleozoic–Lower Mesozoic stage, and the subhorizontal Upper Jurassic–Cenozoic platform. The last two, situated at depths of 500-2,000 m, are especially promising for CO_2 storage, as they provide the required capacity and conditions for supercritical CO_2 storage.
- Reservoir Characterization: The study area is predominantly situated within the Caledonian region. Lithological analysis revealed both regional sealing formations and potential reservoir zones suitable for CO_2 storage. Well P-1, drilled by SAUTS-OIL LLP in 2022, served as a reference well for examining lithological composition, sedimentation processes, and reservoir properties.
- Structural and Tectonic Framework: Tectonically, the Priirtysh basin lies within the North Kazakhstan monocline at the southern margin of the West Siberian basin. Bounded in the south by Caledonian outcrops, the basin displays marked heterogeneity in its Paleozoic complex. The analysis of the platform cover identified aquifer-controlling faults from depths of 800 m, with a target structure located just below 1,500 m. These findings were used to construct regional structural maps and to develop 3D porosity, lithology, and permeability models.

This study represents the initial phase in exploring the potential for CO_2 storage in the Priirtysh sedimentary basin. The findings indicate that the region has significant potential for CO_2 storage in geological formations that offer the necessary conditions for safe and effective storage. Specifically, promising geological structures suitable for CO_2 injection have been identified, and a 3D geological model of the basin has been developed, which will serve as the basis for future hydrodynamic studies and evaluation of the project's technical and economic feasibility.

Future research directions include conducting pilot CO_2 injection tests, developing hydrodynamic models, and performing economic feasibility studies to assess the viability of implementing the technology in the region. These efforts will not only validate the findings of the current study but will also inform the development of strategies for safe and effective CO_2 storage.

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