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Sara Amanzholovna Istekova [1], Alexandr Valerievich Logvinenko [1,*], Daniyar Sadykovich Kairov [2], Yernar Nurzhanovich Narimanov [3], Nurbek Nurlanovich Shamiyev [4], Raushan Galimzhanovna Temirkhanova [1] and Nurastana Kairatuly Slambek [1]

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Abstract

This paper presents the results of research aimed at identifying deep-seated natural sealed reservoirs for the isolation of chemically active gases, including CO_2. A comprehensive analysis of geological, geophysical, and hydrogeological data was conducted to identify potential structures within the aquifers of Almaty and the Almaty region (Southern Kazakhstan) capable of capturing and storing carbon dioxide under geographically favorable and economically viable conditions. The study utilizes seismic survey results and drilling data from the eastern part of the Ili Basin, demonstrating the efficacy of seismic exploration in identifying stratigraphic horizons and their structural-tectonic settings. Based on an integrated analysis of available geo-physic information, the lithological and stratigraphic characteristics of the sedimentary cover in the Ili Basin are substantiated. Key caprock sequences and reservoir units for potential storage sites are identified, and recommendations for further geological exploration are provided. Five reflecting horizons were identified within the geological section of the troughs. It was established that the Miocene-Paleogene and Jurassic horizons contain sandstone reservoirs with a thickness exceeding 10 m and enhanced filtration properties. Clay complexes are prevalent in the Upper Jurassic deposits, which can serve as a caprock for these reservoir rocks. Furthermore, the Upper Cretaceous clay sequence may act as a fluid seal for the Neogene-Paleogene sandy horizons. Such conditions meet the requirements for sealed reservoirs for the isolation of chemically active gases, including CO_2. According to hydrogeological studies, seven aquifer complexes are distinguished: Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene and Quaternary. The novelty and practical significance of this research lie in obtaining new information on the geological structure of deep horizons in poorly studied areas of the Ili Basin and establishing favorable geological factors for identifying potential sites suitable for carbon dioxide sequestration.

Keywords: carbon capture; utilization; and storage (CCUS); Ili Basin; geological setting; underground reservoirs; reservoir rocks; caprock; seismic exploration; drilling; hydrogeology; carbon dioxide

1. Introduction

CO_2 sequestration is an integral part of the comprehensive Carbon Capture, Utilization, and Storage (CCUS) technology. It represents a crucial stage in reducing carbon dioxide emissions into the atmosphere, thereby contributing to the mitigation of the greenhouse effect and ensuring the environmental safety of human activities [1–6].

CCUS technologies encompass:

- Carbon dioxide capture during industrial technological processes;
- Transportation of the captured carbon dioxide;
- Utilization of CO_2 as a resource for creating valuable products or services;
- Permanent storage in the deep horizons of geological complexes [7–9].

A dominant component of CCUS is the identification and preparation of underground reservoirs for CO_2 injection into rock formations capable of absorption and long-term safe storage [10–12]. Global experience demonstrates that various geologically favorable conditions exist for the subsurface sequestration of carbon dioxide. The primary options include depleted hydrocarbon reservoirs and saline aquifers. Additionally, practices exist for storing carbon dioxide in unmineable coal seams, as well as in salt and basalt formations [13–18].

The most favorable sites for these purposes are geological complexes formed within ancient sedimentary basins, which are widespread across all continents. Numerous oil and gas provinces containing the world's major hydrocarbon reserves are associated with these basins. Within these regions, natural reservoirs suitable for the injection and storage of natural gas and the sequestration of carbon dioxide have been identified through geological structural studies [19–20].

Natural reservoirs for carbon dioxide storage must meet specific requirements to ensure long-term safe sequestration. Primarily, this includes the presence of a natural trap and an effective caprock, which facilitate gas preservation over long geological periods. Secondly, high porosity and permeability (reservoir properties) of the reservoir beds are essential to ensure the natural accumulation and storage of both indigenous and artificially injected gases. During the development of oil and gas fields, after the depletion of hydrocarbon reserves, it is possible to carry out effective CO_2 injection into the depleted productive horizons. Such depleted hydrocarbon reservoirs are considered the most favorable sites for long-term safe CO_2 storage. Furthermore, significant volumes of detailed information regarding geological structure, reservoir properties, and caprock integrity have been accumulated during the exploration and development of hydrocarbon fields in every petroliferous sedimentary basin. Leveraging historical data and experience from hydrocarbon production, coupled with ongoing assessment and monitoring of the fields, significantly reduces uncertainty in reservoir selection and the monitoring of injected CO_2 within the formation [21–23].

The primary requirements for selecting a natural reservoir for carbon dioxide injection and storage are based on the following criteria [24–27]:

1. Presence of structural or stratigraphic fluid traps (oil, gas, water) within sedimentary complexes. Carbon dioxide injected into the reservoir rock of a trap remains stationary and is unable to migrate beyond its boundaries due to the presence of impermeable caprocks, sealing faults, etc.
2. Presence of a reservoir rock containing voids (pores, caverns, or fracture systems) capable of containing and transmitting fluids. The vast majority of reservoir rocks are of sedimentary origin. The most common reservoirs are sandstones, characterized by high values of porosity and permeability coefficients.
3. Presence of faults and fractures. In rock formations, these create a risk of CO_2 leakage, although certain faults can act as barriers (seals).
4. Presence of aquifers within reservoir beds with high porosity values (at least 10–20%).
5. Hydrodynamic connectivity to ensure gas retention via capillary forces within the pore space of the reservoir rock.
6. Solubility trapping, where CO_2 dissolves in formation waters, thereby neutralizing the aggressive properties of the injected gas.
7. Prediction of chemical interactions between CO_2 and the host rocks and fluids, leading to the formation of solid precipitates or aqueous solutions (mineral trapping). As a result, the carbon dioxide is completely transformed and ceases to exist in its original composition.

Incomplete data regarding these characteristics can lead to inaccurate calculations of reservoir capacity and significant risks during CO_2 storage [28–29].

Currently, the Republic of Kazakhstan faces an urgent challenge in improving the environmental safety of populations living near major cities and industrial centers. CO_2 emissions are primarily generated by the electric power and heat supply sectors, transportation, and metallurgy, as shown in **Figure 1**.

Figure 1. Map of CO_2 emissions across the territory of the Republic of Kazakhstan [29].

In Kazakhstan, the storage potential in saline aquifers (approximately 403 Gt) has been evaluated only for Western Kazakhstan. Reservoirs were studied within oil and gas-bearing regions, specifically on carbonate platforms in subsalt and postsalt complexes formed by clastic rocks and sealed by salt domes [30]. Within the framework of the National Low-Carbon Development Program for 2022–2031, and considering the large number of active oil and gas fields in the region, JSC NC "KazMunayGas" has developed a CCUS technology project adapted to Kazakhstan's conditions. The Low-Carbon Development Department of JSC NC "KazMunayGas," with expert support from "KMG Engineering" LLP, prepared a CCUS pilot project to determine the CO_2 injection potential for Enhanced Oil Recovery (EOR) in depleted oil reservoirs.

Geological surveys were conducted at fields within the Caspian, Ustyurt-Buzachi, and Mangyshlak oil and gas basins. Researchers performed searches for potential CO_2 sequestration traps in close proximity to emission sources. Consequently, a screening of all active CO_2 emission sources across all three basins was carried out, identifying their type, volume, and location. Preliminary analysis results regarding the selection of suitable fields for CO_2 injection and the search for potential traps indicated that the most promising prospects for CO_2 storage are found in the Lower and Middle Cretaceous terrigenous deposits of the Mangyshlak sedimentary basin, and to a limited extent in the western part of the Ustyurt-Buzachi basin. Late Cretaceous marls and local intraformational clays will serve as regional and local caprocks, respectively. Information regarding the methodology for evaluating potential traps remains limited, and the authors consider this assessment to be preliminary.

High levels of annual carbon dioxide emissions, exceeding 2 million tons, are recorded in the largest region of the country's south of Almaty and the Almaty region. This phenomenon is attributed to the high concentration of numerous industrial enterprises, factories, combined heat and power (CHP) plants, and other production facilities in the area [31–32].

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At present, there are no active facilities for CO_2 utilization in Kazakhstan. Furthermore, issues regarding the location, presence of traps, and required actual capacities of potential reservoirs for carbon dioxide storage remain practically unstudied in the republic.

To advance projects for subsurface CO_2 utilization and sequestration in the Republic of Kazakhstan, it is first necessary to conduct purposeful studies of the geological environment to identify favorable storage conditions. Additionally, uniform requirements for the geological parameters of underground CO_2 storage sites must be developed at the legislative level. Given the country's vast mineral wealth and diverse geological conditions, the potential for natural CO_2 utilization and sequestration in its subsurface is very high. This requires additional study of existing geological, geophysical, and hydrogeological data to determine the structure and composition of underground formations in regions favorable for identifying carbon dioxide traps. Addressing these issues will allow for an assessment of the total sequestration potential in the republic and the formulation of a national CCUS development strategy.

The authors of this publication have collected, summarized, and analyzed accumulated geological information for the territory of Southern Kazakhstan to identify potential geological structures capable of capturing and storing CO_2 emitted by industrial facilities in Almaty and the Almaty region. While the region lacks active oil and gas fields, it features extensive sedimentary complexes with widely distributed deep saline aquifers. The research is focused on the analysis of geological, geophysical, and hydrogeological data to identify potential geological structures within the aquifers of Southern Kazakhstan capable of CO_2 retention and storage under geographically favorable and economically viable conditions. The identification and evaluation of the target reservoir potential were carried out considering the scientific, economic, and technical prospects for the underground storage of carbon dioxide emissions for the entire territory of Kazakhstan.

2. Materials and Methods

2.1. Materials

For Kazakhstan, storage in porous geological media, both in general and specifically within sedimentary basins, is considered the most viable option for CO_2 sequestration [33–35]. As previously noted, the most effective potential storage sites include depleted hydrocarbon reservoirs and deep saline aquifers. According to numerous researchers, saline aquifers possess the highest global potential for CO_2 storage [36].

The south of Kazakhstan is characterized by the widespread occurrence of saline aquifers, which can be considered as CO_2 storage sites if they meet the following fundamental requirements [37–39]:

• Sufficient porosity and permeability of the formation to ensure carbon dioxide absorption;

• Presence of an overlying fluid-resistant rock (caprock) capable of preventing carbon dioxide leakage;

• Significant thickness and lateral extent of the host formation to store large volumes of CO_2;

• Sufficient burial depth (greater than 800 m) to ensure safe storage. At such depths, under elevated pressure and temperature conditions, carbon dioxide transitions into a liquid or supercritical state with a relatively high density.

The selection of the storage site location, as well as the ability to evaluate its filtration characteristics, is of paramount importance for successful geological CO_2 sequestration. Before selecting a reservoir site, information regarding the geological conditions must be obtained: whether a sufficiently voluminous and permeable formation exists; whether the overlying rock will provide effective sealing; and whether the integrity of the seal is compromised by abandoned or active wells. To address these challenges, international practice employs traditional methodologies developed for oil and gas exploration, the identification of reservoirs for underground gas storage, and sites for liquid waste disposal [40–41].

For the Almaty region, the Ili Sedimentary Basin is considered the most promising, technologically effective, and economically viable option for CO_2 sequestration [42]. Administratively, it is located within the Almaty region, in close proximity to the city of Almaty. Geographically, the Ili Basin is an intermountain depression situated between the Ketmen and Trans-Ili Alatau mountain ranges to the south, and the spurs of the Dzungarian Alatau and the Altyn-Emel

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range to the north. The basin is an elongated east-west graben structure extending up to 450 km, with a total area of approximately 40,000 km². To the east, the basin extends into the territory of China, with the state border of the Republic of Kazakhstan serving as its eastern limit, as shown in **Figure 2**. The western boundary runs along the Kendyktas range and the Chu-Ili mountains. Within the depression, two significant troughs have formed: the East Ili (Zharkent) trough to the east and the Almaty (West Ili) trough to the west, separated by the Boguty saddle [43].

The Ili Basin is characterized by structural, formational, and tectonic similarities to the Central Asian Fergana and Dzungarian basins and is predicted to be oil and gas-bearing. The hydrocarbon potential of the basin is inferred from previously identified oil shows observed in springs and deep well sections. Within the basin, the East Ili trough has been identified as the primary and most promising area for oil and gas potential. Due to several geological features, this trough is analogous to the oil and gas-bearing regions of the Dzungarian Basin located in the adjacent territory of China [44–47]. It represents a complex graben-synclinal zone filled with Mesozoic-Cenozoic sediments. Within the northern and southern flanks of the trough, Lower and Middle Jurassic deposits with high organic content are widely developed in the geological section. Within this area, the Penjim graben-syncline and the eponymous anticlinal structure are considered the most promising for gas-bearing deposits [48–49], as shown in **Figure 3**.

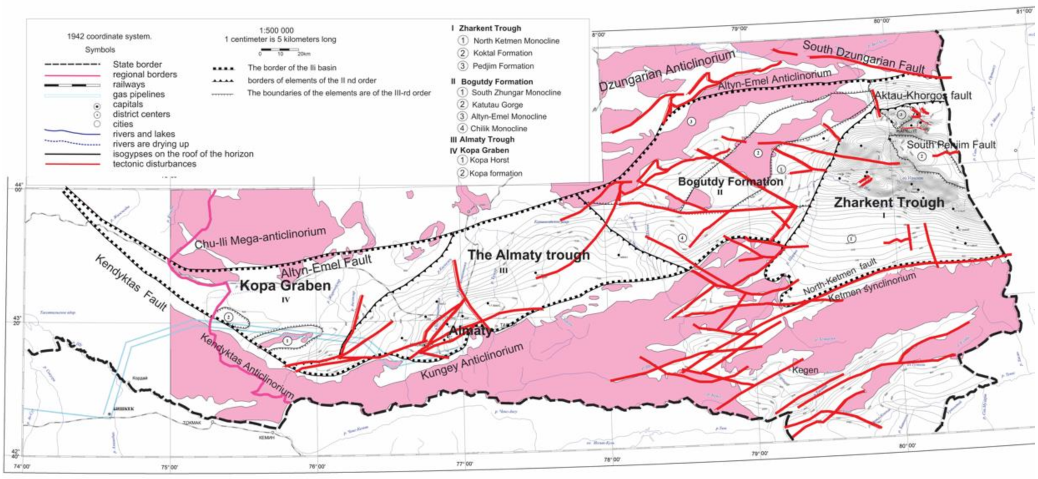

Figure 2. The Ili Basin: Tectonic structure and regionalization scheme based on Upper Paleozoic deposits. [50].

Since the 1980s, comprehensive geological and geophysical studies have been systematically conducted across the East Ili trough to identify local areas promising for further oil and gas exploration. These studies include gravity and magnetic surveys, Common Depth Point (CDP) seismic surveys, drilling, well logging (wireline logging), and core sampling. Current operations are carried out at an advanced technical and methodological level, primarily utilizing high-resolution seismic exploration with non-explosive (vibratory) excitation sources.

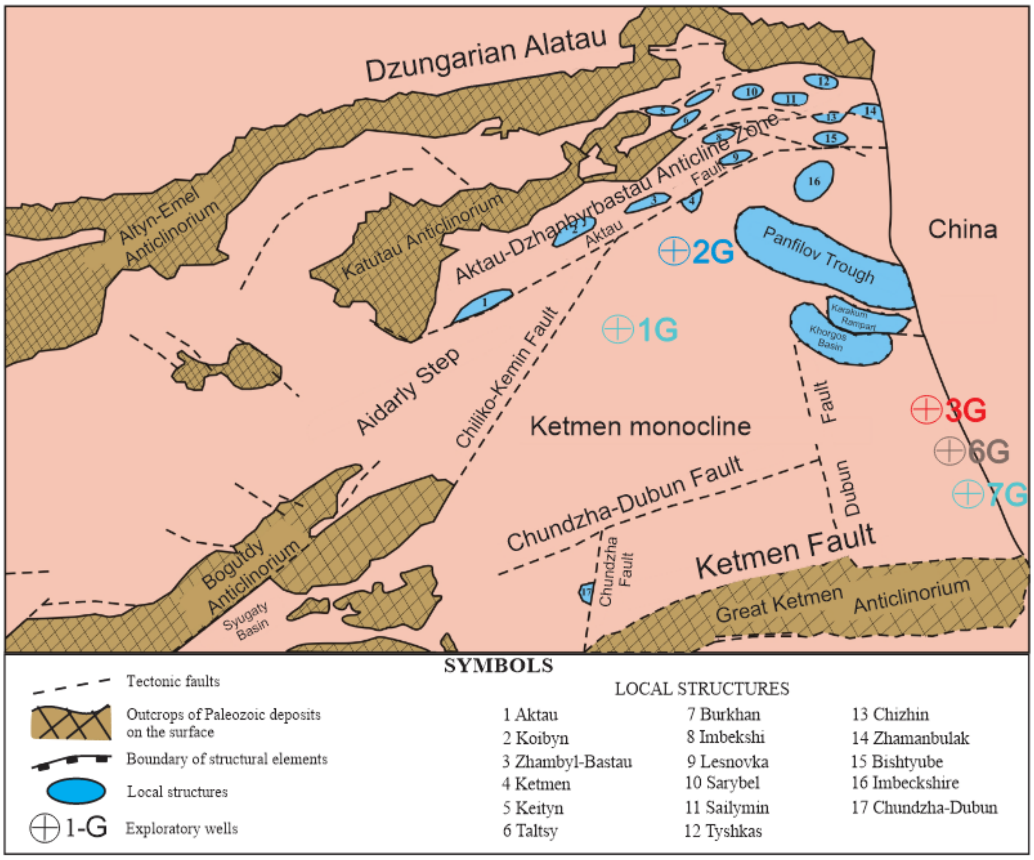

Figure 3. The East Ili trough: Structural and tectonic scheme.

Field 2D CDP seismic surveys were conducted in the area along a network of profiles. The layout of these profiles was designed to account for the pinch-out zone of Upper Permian deposits and was oriented perpendicular to the strike of the primary structures identified as promising for reservoir bed discovery. Reprocessing of previously acquired seismic data was performed by PGC-Services using a standard processing flow, incorporating Pre-stack Depth Migration (PSDM) within modern geophysical information systems. The geological interpretation of the seismic data relied extensively on results from parametric and exploration wells drilled over various periods. A total of 22 wells for various purposes were drilled across the East Ili trough, including 18 wells in the western and southwestern parts of the basin and 4 wells in its central part, as shown in **Figure 4**.

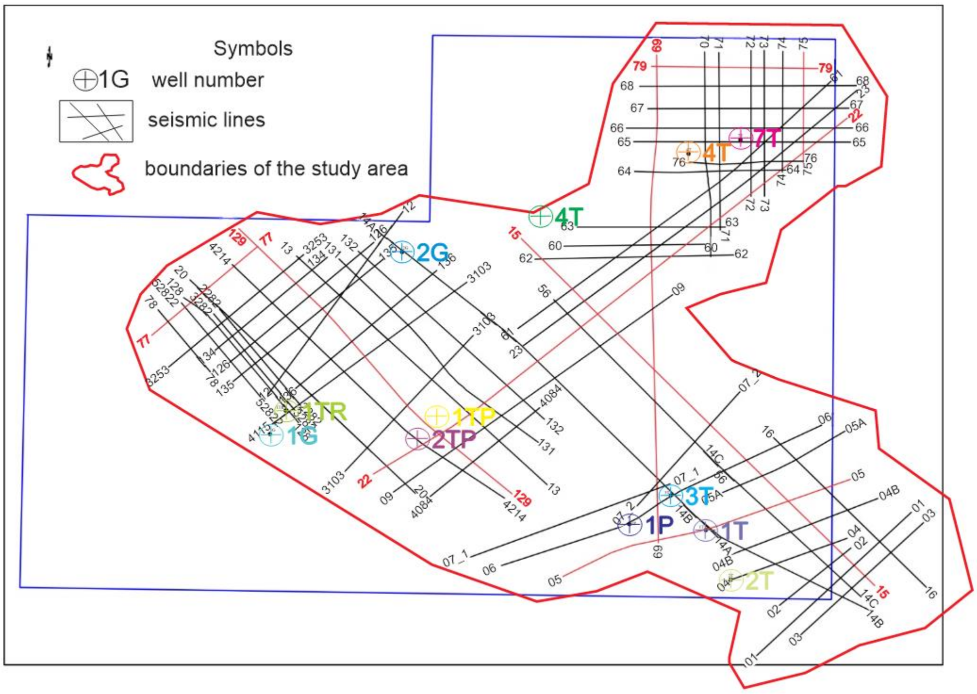

Figure 4. The East Ili trough: Map of geological and geophysical exploration coverage. [50].

To explore thermal waters in the region, a series of deep wells were drilled: 1T (total depth 2,903 m), 2T (total depth 3,157 m), and 3T (total depth 3,281 m). During testing of wells 1T and 3T, commercial inflows of hot water were obtained from Cretaceous deposits. On the northern flank of the East Ili trough, wells 4T, 5T, and 6T were drilled but not tested. As a result of these operations, new data were obtained that refine the structural understanding of the eastern part of the Ili trough.

The drilling of deep parametric well 1P indicated the extensive presence of Permian and Triassic-Jurassic deposits in the geological sequence. Specifically, a thick Jurassic coal-bearing formation was identified as a primary source for gas accumulation. However, an analysis of well logging data, drilling results, and the testing of several reservoir horizons revealed an absence of hydrocarbon-saturated beds in the 1P well section. Instead, all identified reservoir horizons were classified as aquifers [51–53].

2.2. Research Methodology

The primary methodological principle of this scientific research involved the synthesis, analysis, and correlation of geological and geophysical results obtained during the study of the Miocene-Paleogene and Jurassic horizons of the East Ili trough. According to regional data, these horizons contain sandy aquifer reservoirs with thicknesses exceeding 10 m. It is hypothesized that these geological complexes have formed structures that meet the requirements of sealed reservoirs for the isolation of chemically active gases, including CO_2. Data obtained during previous hydrocarbon exploration in the region served as the basis for a detailed study of the geological structure of deep-seated sedimentary complexes and the identification of potential natural reservoirs. The field data included geological, geophysical, hydrogeological, geochemical, geomechanical, and seismic information accumulated over the last 30 years, as well as well data and wireline logging results.

First, the authors analyzed and correlated the results of 2D CDP seismic data interpretations from various years, which were reprocessed and re-interpreted using modern geophysical information systems. Drilling results and well logging data were extensively utilized to reconstruct sedimentation processes and study the geological sequence of Mesozoic-Cenozoic horizons. The correlation and analysis of seismic interpretation results, performed using Open Works (Landmark), Kingdom, and Petrel software, significantly refined—and in several instances, created fundamentally new—structural and tectonic models of the region's sedimentary complex formation.

The research included the following stages:

• Collection and synthesis of raw field and thematic study data;

• Creation of a digital geological and geophysical database;

• Critical analysis of geological and geophysical interpretation results performed by various authors for predictive tasks;

• Analysis of seismic survey results and construction of updated interval velocity maps for the main reflecting horizons;

• Analysis of raw data and construction of a depth-velocity model of the medium;

• Construction of structural and isochrone maps.

The identification of reflecting horizons was based on the construction of a velocity model for the East Ili trough. The velocity section is characterized by a complex model due to the specific nature of intermountain basins. A general analysis of interval velocities for the target horizons showed lateral and vertical velocity variations across the study area, which are associated with the extensive development of disjunctive tectonics and varying periods of sedimentation [50]. The constructed interval velocity maps allowed for the identification of five velocity boundaries (I, II, III, IV, V), from which structural maps for the reflecting horizons were derived. Depths calculated from seismic data were compared with well tops obtained from check-shot surveys and Vertical Seismic Profiling (VSP) data.

The geological interpretation of seismic data was based on drilling results and borehole investigations, including:

• Assessment of the reliability of stratigraphic correlation for the main reflecting horizons and the tracing of tectonic faults;

• Structural-tectonic and facies-sedimentological analysis of the sedimentary complex to identify favorable conditions for the formation of reservoir rocks and potential geological structures within aquifers capable of capturing and storing carbon dioxide.

A network of deep structural-exploration and thermal hydrogeological wells was drilled within the study area and adjacent territories. Most of these wells were accompanied by wireline logging, check-shot surveys, and geological sequence descriptions based on core data. Data from deep wells 1G, 2G, 3G, 5G, 6G, 7G, 1T, 2T, 3T, 4T, 5T, and 6T were utilized; these wells intersected Mesozoic-Cenozoic deposits as well as Paleozoic sedimentary-effusive formations. Based on the analysis of seismic and geological materials, structural mapping was performed for five reflecting horizons across the trough area. It was established that all horizons traced on the seismic time sections coincide with the well tops derived from borehole data with an accuracy of up to 5 ms, as shown in **Figure 5**.

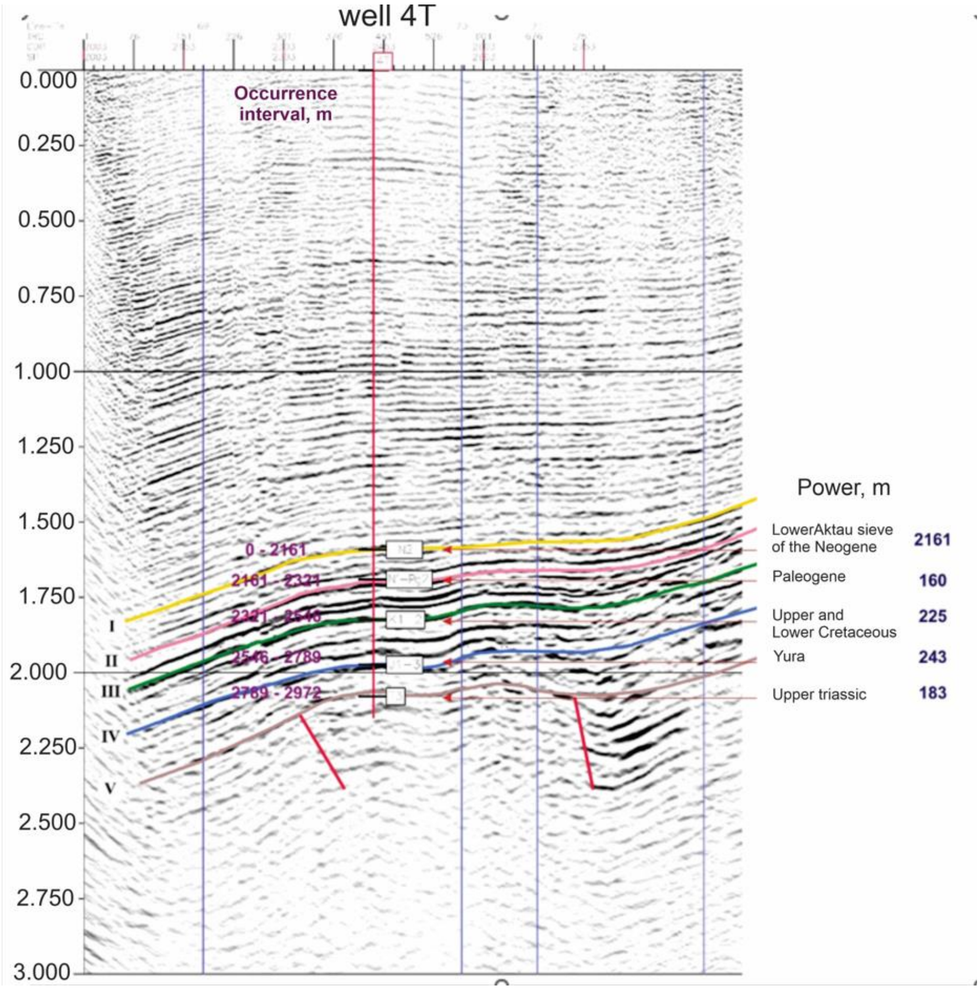

Figure 5. The East Ili trough: Stratigraphic tie based on well 4T. [50].

As shown in **Figure 6**, the stratigraphic correlation of reflecting horizons incorporates extensive seismic data, deep drilling results, and check-shot surveys.

The assessment of the hydrodynamic regime of the East Ili trough was conducted by studying the distribution patterns of subsurface thermal waters within various stratigraphic complexes of the sedimentary cover. This involved analyzing hydrochemical zonality maps of thermal waters, maps showing the distribution of the average geothermal gradient across the depression, and the results of thermal water resource evaluations, as shown in **Figure 7**.

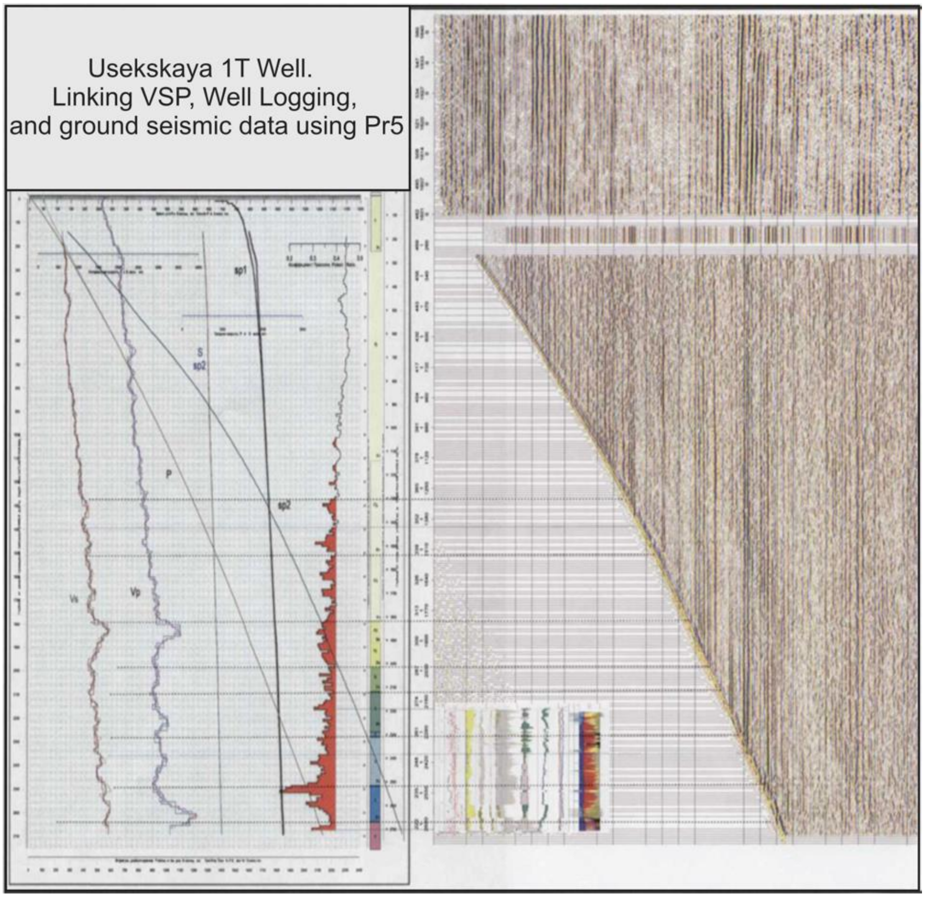

Figure 6. Well Usekskaya 1T: Correlation of VSP (Vertical Seismic Profiling), wireline logging, and surface seismic data along Profile 5. [50].

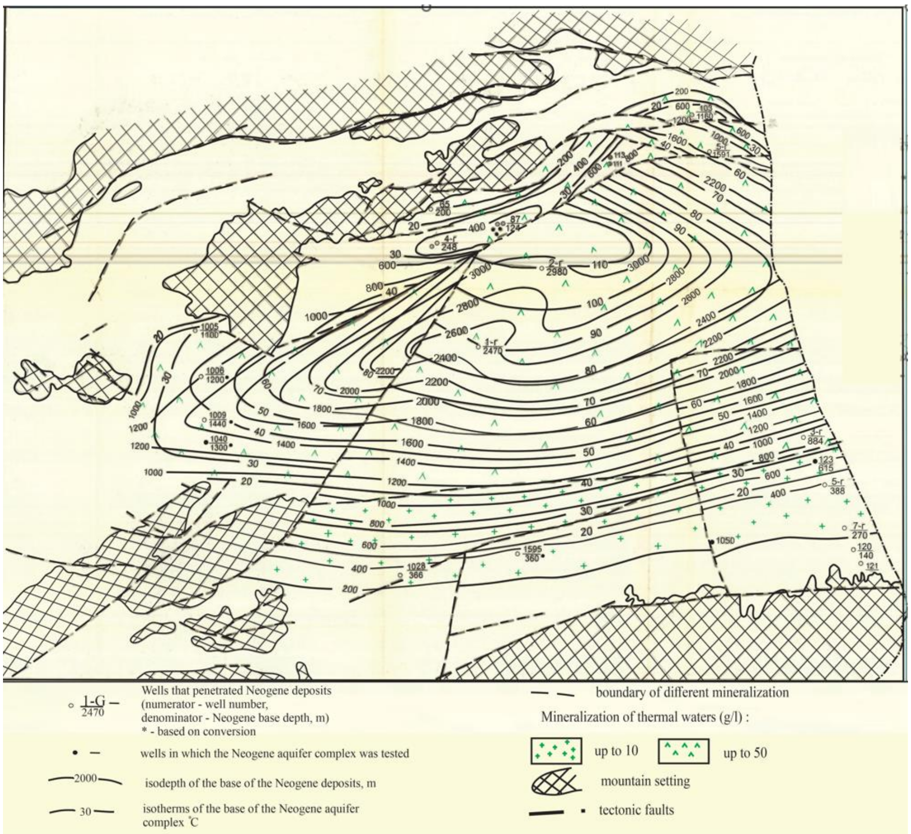

Figure 7. Schematic hydrothermal map of the Neogene aquifer complex in the East Ili trough. [50].

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3. Results

The synthesis and analysis of the acquired geological, geophysical, and hydrogeological data for the East Ili trough have enabled the characterization of the geological conditions necessary for identifying underground CO_2 storage reservoirs. The primary criteria for identifying these sequestration reservoirs included:

Structural and Tectonic Conditions: Presence of local anticlinal structures capable of serving as reliable traps for artificial carbon dioxide deposits.

Favorable Lithostratigraphic Complexes: Presence of reservoir rocks with enhanced filtration properties (porosity and permeability).

Hydrogeological Conditions: Presence of persistent aquifer-reservoirs in the section, overlain by caprock formations.

Structural and Tectonic Conditions for Reservoir Identification

As a result of the seismic data interpretation for the East Ili trough, structural maps were constructed for the target reflecting horizons of the sedimentary sequence:

Reflecting Horizon I – Base of the Pliocene (N_2)

Reflecting Horizon II – Base of the Miocene-Paleogene (N_1-Pg)

Reflecting Horizon III – Base of the Cretaceous deposits (*K*)

Reflecting Horizon IV – Base of the Jurassic deposits (*J*)

Reflecting Horizon V – Top of the Paleozoic basement (*Pz*)

On the structural map for Reflecting Horizon I (identifying the base of Pliocene deposits), a large anticlinal structure, the Penjim structure, is identified in the northeastern part of the trough within the North Ketmen Monocline. To the south lies the Usek monocline, and to the west, the Aidarly uplift. As shown in **Figure 8**, the 3D visualization clearly highlights the geological boundaries and structural features of the Aidarly, Penjim, and Usek uplifts. Tectonic faults, to which these structures are adjacent, are indicated in dark colors. The inherited nature of these structures' development through the Cretaceous, Jurassic, and Permo-Triassic geological systems is clearly evident.

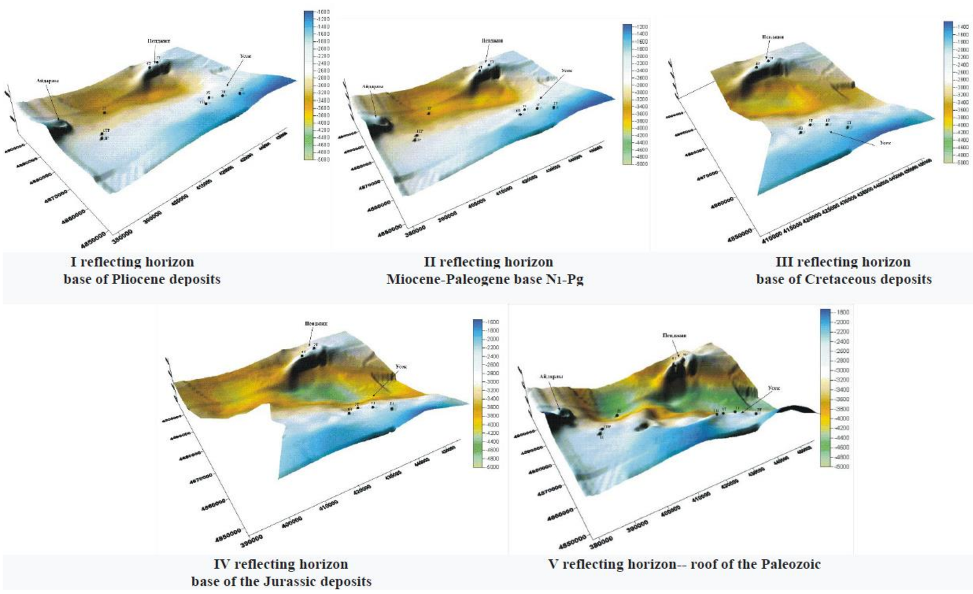

Figure 8. The East Ili trough: Structural maps for the reflecting horizons. [50].

The Penjim anticline, which has a sub-latitudinal strike, is bounded to the west by the -2,500 m isohypse. Its dimensions reach 15 x 5.0 km, with an amplitude of 600 m and an area of 75 km^2. The structure is bisected by a low-amplitude fault with a meridional orientation. In the western periclinal part of the structure, wells 4T and 7T were drilled, intersecting Pliocene deposits at depths of -2,160 m and -2,050 m, respectively. The eastern pericline of the structure extends into the territory of China. South of the Penjim structure, the sedimentary cover subsides into the Panfilov trough (syncline), where Pliocene deposits reach a depth of -3,600 m.

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The Usek monocline has been studied using seismic and well data and is situated within the uplifted area toward the extreme southeast of the sedimentary cover (Ketmen Range). Based on the results from wells 1G, 3T, 1T, and 2T, Pliocene deposits here lie at depths ranging from -1,996 m to -1,413 m, further shallowing to -1,100 m to the south.

The Aidarly structure, investigated by a network of seismic profiles, is fragmented by parallel tectonic faults. Pliocene deposits here are situated at a depth of -1,900 m. Southeast of the Aidarly structure, deep well 1G was drilled, intersecting Pliocene deposits at a depth of -2,460 m. The Aidarly structure is identified only along Horizon V by the -2,450 m isohypse as an oval uplift with an amplitude of 100 m and an area of 6.25 km².

Analysis of the Lithostratigraphic Composition of the Sedimentary Sequence

Based on the available lithological descriptions from the wells, it has been established that the basement of the Ili trough consists of orogenic complex deposits. In most cases, these are represented by effusive formations of the Permian system, which are widely developed on the flanks of the Ketmen Range, Trans-Ili Alatau, and Dzungarian Alatau. Major tectonic movements associated with the orogenic stage led to the emergence of ancient latitudinal faults, along which the subsidence of the Ili trough occurred, marking its formation as a sedimentation area. The initiation of the Ili trough dates back to the Upper Paleozoic; throughout the Mesozoic and Cenozoic, it was involved in subsidence processes that became most active during the Neogene-Quaternary period, as shown in **Figure 9**.

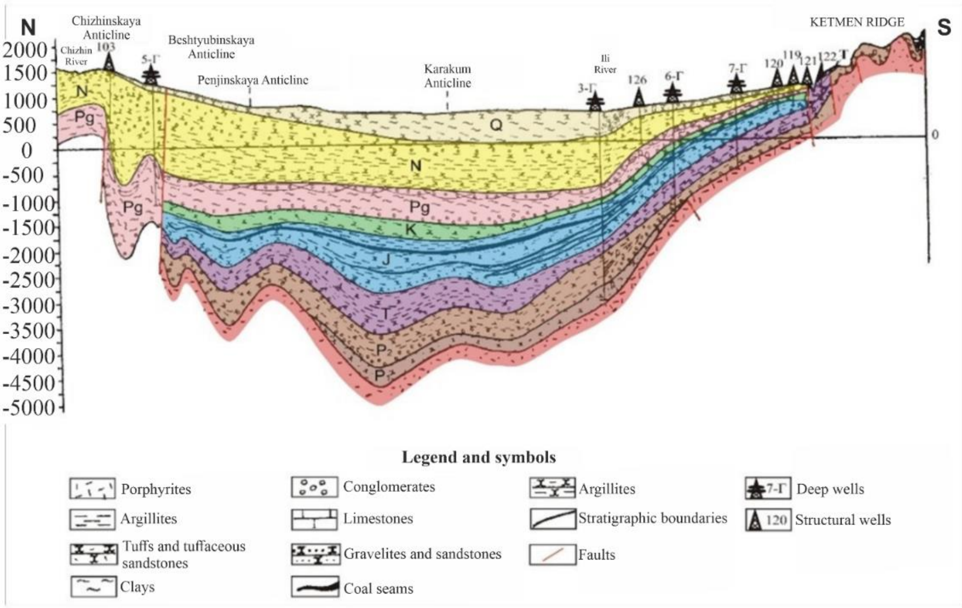

Figure 9. Geological section of the eastern part of the Ili trough. [50].

The depositional environment was studied based on well logging results, including stratigraphic subdivision, lithological columns, generalized lithological descriptions by stage, and well logs [51–52].

According to data from [50], the Permo-Triassic complex is most likely represented by alluvial fan facies (including colluvium and proluvium) with elements of a braided river system. In well 4T, according to the generalized lithological description, the Triassic complex consists of dark-gray siltstones with thin interbeds of gray fine-grained sandstone, dark-gray to black argillaceous shales, and floral remains. These data suggest the potential development of an intermontane alluvial system, as shown in **Figure 10**.

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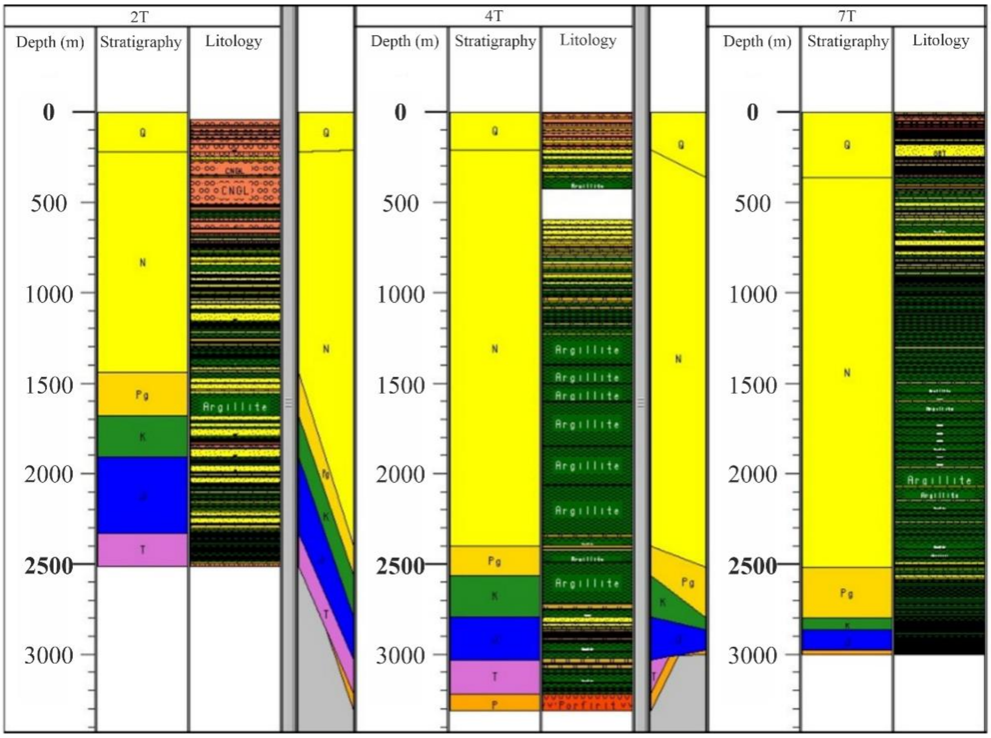

Figure 10. Generalized lithostratigraphic scheme based on wells 2T, 4T, and 7T.

The highest sand content in the Triassic sequence is observed in the area of well 2T, where the development of braided river system facies is likely. Similar conditions are noted in the Jurassic complex deposits, which are characterized by the development of coal seams, dark-gray thin-bedded siltstones, and dark-gray to black clays and shales with floral remains. Presumably, these deposits were formed in marginal-lacustrine or coastal facies environments. The abundant inclusion of organic material allows this sequence to be considered from a source-rock perspective.

The Jurassic deposits in well 2T reflect a specific depositional character, represented here by a more sand-prone sequence. The sandstones range from fine- to coarse-grained, with the presence of light-gray and gray clays. Overall, this indicates a low-energy fluvial environment, possibly involving a meandering river system. The thickness of the Jurassic deposits decreases gradually from south to north, as shown in **Figure 11**. During the Cretaceous period, intense argillization of the sequence occurred in the area of wells 4T and 7T as the transgressive regime continued, as shown in **Figure 12**. The thickness of the sequence decreases toward well 7T, and the deposits consist primarily of clays with interbedded sandstones and siltstones.

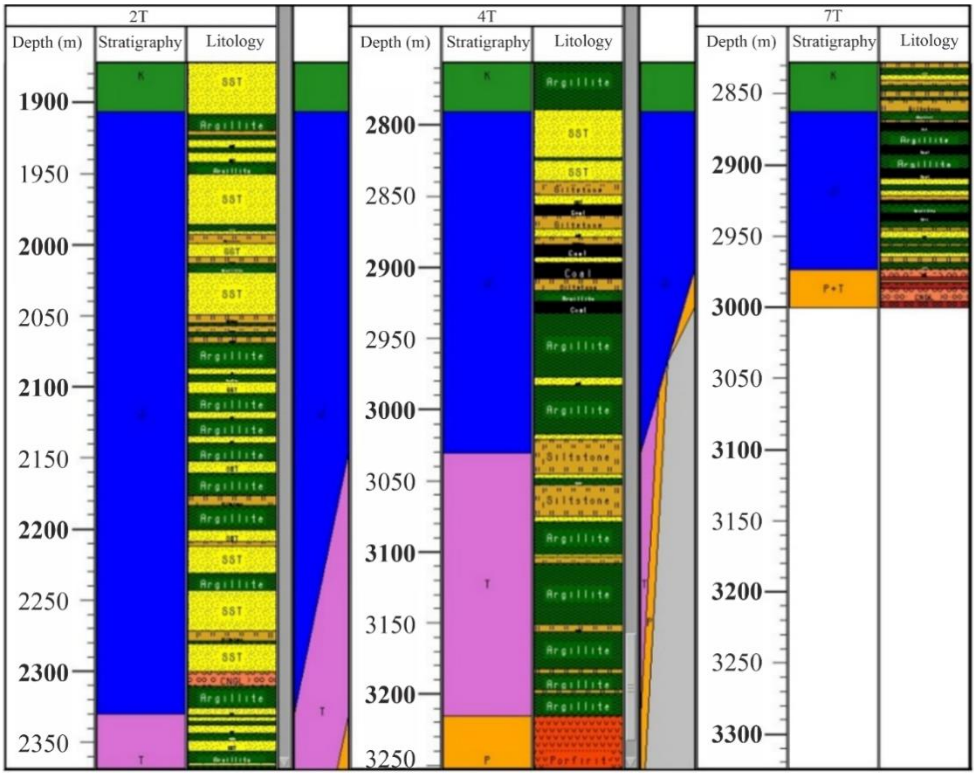

Figure 11. Lithostratigraphic correlation scheme of the Jurassic deposits for wells 2T, 4T, and 7T.

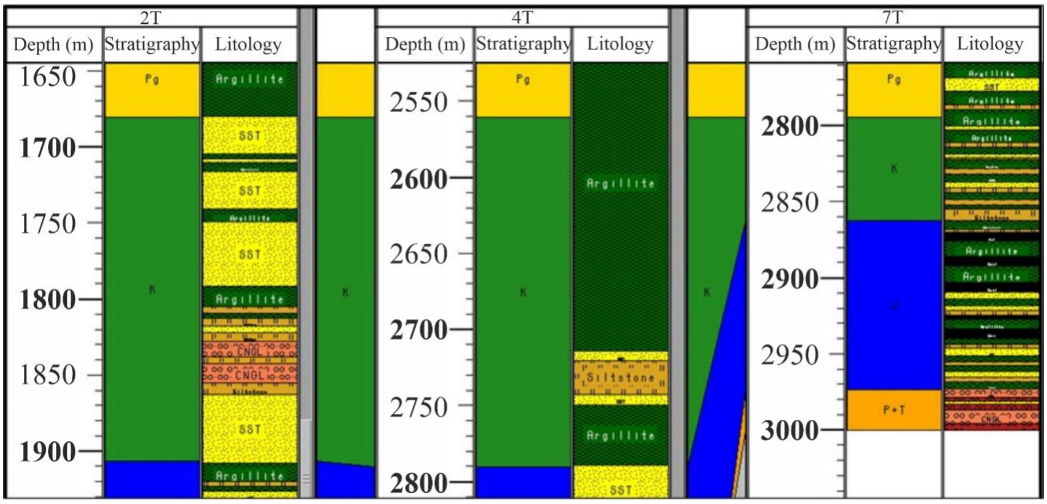

Figure 12. Lithostratigraphic correlation scheme of the Cretaceous deposits for wells 2T, 4T, and 7T.

The continuous Upper Cretaceous clay sequence identified in well 4T, extending into the Paleogene, may serve as a fluid seal, provided it has widespread lateral coverage. In the area of well 2T, a potential activation of the tectonic regime is observed. The low-energy fluvial system is replaced by higher-energy flows; consequently, the section is dominated by conglomerates and sandstones with infrequent interbeds of clay and siltstone. This depositional environment shares similar features with the Lower Triassic conditions, characterized by the development of young braided river systems.

The Cenozoic sequence (Paleogene, Neogene) is represented by continental fluvial and lacustrine systems, predominantly under aerobic conditions. In the vicinity of wells 4T and 7T, the transgressive regime persists. This is primarily a clay-rich sequence with occasional sandy and silty inclusions. These sandy and silty beds can be considered potential reservoirs into which hydrocarbon fluids could have migrated under favorable conditions.

The reservoir properties of the potential reservoir beds across all stratigraphic horizons are characterized as good, according to well data. In the Permian effusive-terrigenous sequence, tuffaceous sandstone beds (wells 4G, 3G) possess relatively high-quality reservoir properties. These reservoir horizons dominate the sequence, with their cumulative thickness potentially reaching several hundred meters. Testing results indicate that reservoir quality improves toward the central zones of the East Ili trough (from well 6G toward well 3G). In the Upper Permian, conglomerates and thin sandstone interbeds exhibit reservoir properties, while the overlying chemogenic-terrigenous sequence acts as a fluid seal. Mesozoic deposits are characterized by high-quality reservoir properties throughout the investigated section.

Hydrogeologically, the Zharkent artesian basin is a relatively large multi-tiered basin, with its recharge areas located in the surrounding mountain ranges at elevations up to 3,500 m. Significant precipitation and extensive glacier development in the region facilitate constant groundwater flow into the depression, leading to the formation of thermal waters. Hydrogeological studies have identified seven aquifer complexes: Permian, Triassic, Jurassic, Cretaceous, Paleogene, Neogene, and Quaternary.

As shown in **Figure 13**, the well correlation scheme illustrates the changes in lithofacies composition and thickness of the Mesozoic thermal aquifer complex from the southeast to the north.

Within the East Ili trough, several hydrothermal complexes are identified, spanning nearly all horizons of the sedimentary sequence. The Permian thermal aquifer complex is intersected in the extreme southeast of the depression and is associated with fractured sedimentary-effusive formations at depths starting from 1,200 m. In the Upper Permian, conglomerates and thin sandstone interbeds possess reservoir properties, while the overlying chemogenic-terrigenous sequence serves as a caprock. The Triassic thermal aquifer complex is intersected at depths starting from 1,080 m and is associated with sandstones and conglomerates isolated by impermeable rocks. Within the Usek area, it is encountered at depths from 2,620 m to 2,990 m.

The Jurassic thermal aquifer complex is associated with multi-grained sandstones and includes two horizons: Lower and Middle Jurassic, which were intersected and tested in the Usek area wells. Reservoir horizons constitute up to 70% of the section. Clays developed in the upper part of the Lower Jurassic and the lower part of the Middle Jurassic, with a total thickness starting from 220 m, act as a regional aquitard (seal) between the Lower and Middle Jurassic thermal aquifer horizons. The reservoirs consist of sandstones characterized by an open porosity of 20–26% and high permeability.

The Cretaceous thermal aquifer complex is intersected in the eastern part of the basin and by wells in the Usek area. It consists of two horizons: Lower and Upper Cretaceous, separated by an aquitard represented by a clay unit at the top of the Lower Cretaceous. Well testing and sampling at depths of 782 m and 2,290 m showed that the waters are ultra-fresh, ranging from sodium-bicarbonate to sodium-chloride types, while in well 2T "Usekskaya" the water exhibits a calcium-chloride composition.

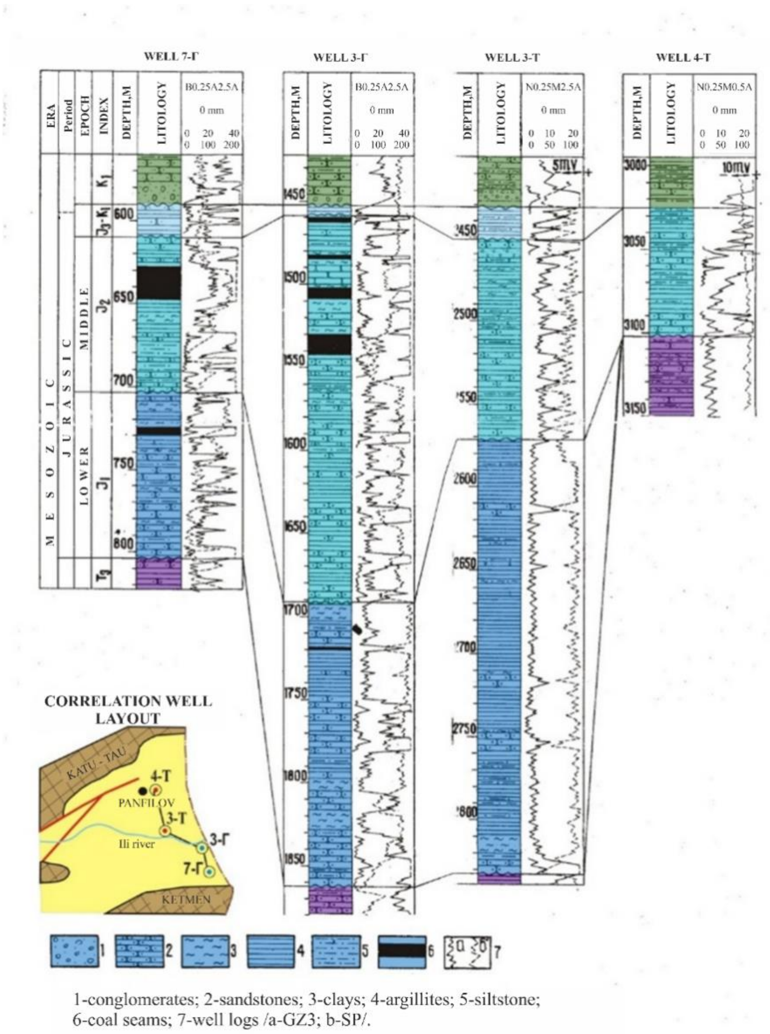

Figure 13. Well correlation scheme for wells 7G, 3G, 3T, and 4T.

In the Paleogene and Neogene complexes, aquifers are locally developed at depths ranging from 50 m to 2,600 m. A regular decrease in rock water yield and an increase in groundwater mineralization are observed as one moves from the south toward the northwest of the basin. The Quaternary thermal aquifer complex is primarily distributed in the piedmont zone of alluvial fans and is associated with coarse-clastic deposits of alluvial-proluvial origin, where all aquifers are hydraulically interconnected.

It should be noted that the waters of the Zharkent Trough trough are thermal. Within the trough, a geothermal zone begins at depths of 2,800–3,600 m, with water temperatures ranging from 75-100 °C and higher (up to 160 °C). Notably, in the southern part of the depression, this zone lies deeper (up to 3,600 m) than in the central part.

4. Discussion

A review and analysis of the accumulated data on the Ili trough indicates that the geological conditions for identifying reservoirs for CO_2 injection and storage are highly favorable. In the western part, specifically the Almaty trough, almost the entire sedimentary cover consists of continental red-bed terrigenous Neogene-Quaternary deposits resting directly on heterogeneous Paleozoic folded formations. Consequently, this structure should be considered non-prospective for identifying favorable natural reservoir conditions.

In the eastern part of the Ili trough, the sequence is more favorable: it includes Triassic-Jurassic terrigenous coal-bearing deposits (potential gas-generating sequences), a predominantly sandy Cretaceous sequence (potential reservoir), and a very thick, primarily clayey sequence of Paleogene-Neogene deposits acting as a regional fluid seal.

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The East Ili trough possesses a thick sedimentary sequence (up to 5,000 m), with Permian, Triassic, and Jurassic deposits reaching a thickness of 1,200 m. In the Lower Triassic sequence, natural reservoirs can account for up to 60% of its volume. In the Cenozoic deposits, reservoir horizons have been identified across all stratigraphic subdivisions, lithologically represented primarily by fine-grained sandstones with an open porosity of 18–23%. In the Jurassic and Cretaceous deposits, natural reservoirs constitute up to 70% of the section, characterized by an open porosity of up to 20–26% and high permeability.

Hydrogeological factors indicate a close hydrodynamic connection between groundwater and the favorable conditions for reservoir formation. Groundwater in the Paleozoic and Mesozoic-Cenozoic deposits of the East Ili trough belongs to the calcium-chloride and sodium-bicarbonate types, containing iodine, bromine, boron, and other trace elements. The high hypsometric position of the basin's rim, which serves as a catchment area, facilitates the formation of large artesian basins; thus, most potential traps in the Ili trough are associated with a water-drive system.

A critical hydrodynamic feature of the Zharkent Trough trough is that the southern part of the basin (between the Ketmen Range foothills and the Ili River) has been almost entirely flushed by fresh pressurized waters throughout the sedimentary sequence. Conversely, the northern part of the region (between the Dzungarian Range foothills and the Ili River) appears hydrodynamically closed, as the trough is separated from the groundwater recharge area by a series of high-amplitude thrust faults. These features are decisive factors in delineating the artificial reservoir area and determining its volumetric characteristics.

5. Conclusions

The study outlines and critically analyzes the primary findings and results from seismic surveys and drilling operations across various sections of the Ili trough. It demonstrates the capabilities of seismic exploration in identifying the morphological and tectonic conditions of reflecting horizons and presents the results of a comprehensive geological and geophysical data interpretation aimed at identifying new potential sites suitable for carbon dioxide sequestration.

It has been established that the natural reservoirs of the East Ili trough offer the most favorable conditions for CO_2 injection. The deep zones of the North Ketmen Monocline and the adjacent areas of the Koktal syncline (trough), which contain three local uplifts—Aidarly, Penjim, and Usek—are considered the most promising sites for CO_2 storage.

Within the geological section of these structures, five key reflecting horizons ranging from the Pliocene to the Paleozoic have been identified. Particular attention is given to the Miocene-Paleogene and Jurassic horizons, which, according to regional data, contain sandy reservoirs exceeding 10 m in thickness with enhanced filtration properties. In the Upper Jurassic Kairgalinskaya suite, clayey deposits formed in lacustrine facies are prevalent; these can serve as a caprock for the Triassic and Jurassic reservoir rocks. Additionally, the Upper Cretaceous clay sequence, extending into the Paleogene, may act as a regional fluid seal for the Neogene-Paleogene horizons, provided it has widespread lateral coverage. Such conditions meet the stringent requirements for airtight reservoirs necessary for the isolation of chemically active gases, including CO_2.

The study area is characterized by extensive fault tectonics, which complicate the morphology and structural features of the sedimentary sequence and potentially lead to a wide distribution of fault-bounded (tectonically screened) traps.

Analysis of the accumulated data reveals that the regional stage of exploration in the area has been insufficient. Further study of the Lower Cretaceous, Triassic-Jurassic, and Permian deposits is required, along with the stratification of reference seismic boundaries and an assessment of hydrocarbon potential. It is recommended to conduct wide-area seismic surveys and structural profile drilling within the southeastern part of the East Ili trough.

To delineate and study the morphology of traps within the potential reservoirs at the Aidarly, Penjim, and Usek sites, and to determine the filtration parameters of the reservoir rocks, detailed 3D seismic surveys are necessary in conjunction with VSP, exploratory drilling with extensive core recovery and well logging. These data will enable the construction of geological and hydrodynamic reservoir models, including facies models and the distribution of reservoirs and seals. This will also allow for the assessment of trap morphology and dimensions in 3D space, evaluation of porosity and permeability parameters, and identification of the hydrodynamic connections essential for the placement and retention of the CO_2 gas phase in underground horizons. Furthermore, numerical simulation of reservoir hydrodynamic parameters is required to model the processes of gas injection and storage.

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Abbreviations

CCUS	Carbon Capture, Utilization, and Storage
CHP	Combined heat and power plants
CDP	Common Depth Point
PSDM	Pre-stack Depth Migration
VSP	Vertical Seismic Profiling

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