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Exploring the Viability of Underground Gas Storage Facilities in Southeastern Kazakhstan: Ensuring a Stable Gas Supply for Almaty, the Nation's Largest Metropolis

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Abstract

The growing energy demand in Almaty, Kazakhstan's largest metropolis, necessitates a reliable gas supply, making underground gas storage (UGS) a strategic solution. This study evaluates the feasibility of developing UGS facilities in southeastern Kazakhstan, specifically within the Pidzhim structure of the Zharkent trough. The geological and geophysical analysis identifies favorable conditions for gas storage, including the presence of anticline structures that meet UGS reservoir requirements. In addition to assessing the region's hydrocarbon potential, the study examines key geotechnical characteristics, caprock integrity, and hydrodynamic properties that support the suitability of the structure for long-term gas storage. The findings highlight the Pidzhim structure's potential as a prime candidate for UGS development, which could significantly enhance Almaty's energy security and regional stability. Future research should focus on reservoir performance modeling and a comprehensive assessment of the environmental and economic aspects of UGS implementation.

Keywords: Underground gas storage; Aquifer; Structure; Depression; Hydrocarbon; Energy security; Reservoir assessment.
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1. Introduction

The need for a reliable and stable gas supply in urban areas has become more urgent due to rapid population growth and economic expansion.[1] Almaty, Kazakhstan's largest city, faces this challenge directly, requiring innovative approaches to maintain its energy security.[2] Underground gas storage (UGS) is a method that involves storing natural gas in geological formations below the Earth's surface.[3] It primarily addresses gas supply fluctuations and demand, which include seasonal shifts, changing consumption patterns, or supply interruptions.[4] UGS ensures a consistent energy supply, stabilizes gas prices, and maximizes infrastructure efficiency.[5] By offering a buffer against these fluctuations, UGS is a promising solution to balance supply and demand, especially during seasonal changes or unforeseen disruptions.[6] UGS systems are classified based on the geological formations used for storage,[7] including depleted gas fields, aquifers, and salt caverns.[8]

The success of underground gas storage relies on certain physical and geological principles to ensure safe and efficient gas containment.[9] Porosity measures how much gas a rock or formation can hold, with higher porosity allowing for greater gas storage capacity.[10] Permeability, on the other hand, indicates how easily gas can move through the rock, with high permeability being crucial for effective gas injection and extraction.[11] A cap rock, an impermeable layer that prevents gas from escaping to the surface, is also essential in the UGS process. Common cap rocks include shale, clay, and salt.[12] Gas is typically injected into storage formations during

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periods of low demand, such as in warmer months, and extracted when demand peaks, particularly in the winter.[13] Managing the injection and extraction processes is vital to maintain the pressure within the reservoir and to prevent damage to the geological structure.[14]

The injection and withdrawal rates at which gas can be injected or withdrawn depend on the reservoir permeability.[15] Salt caverns typically allow injection and withdrawal rates more than aquifers or depleted gas fields.[16] The storage capacity is generally measured in terms of energy content (*e.g.*, terajoules or cubic meters).[17] The capacity of an underground storage facility is influenced by the volume of the geological formation and the pressure it can safely withstand.[18] The frequency and volume of injection and withdrawal over time in the UGS depend on the gas demand and the physical characteristics of the storage formation.[19,20] Continuous monitoring of pressure, temperature, and gas composition is essential to ensure the safe operation of underground gas storage.[21] Technological advancements, such as remote sensing and seismic imaging, allow for better monitoring of the integrity of storage formations.[22]

The global experience of using aquifers for UGS demonstrates their effectiveness and reliability.[23-25] For example, in China, gas storage systems in aquifers are actively developing, especially in the Yangtze River delta region, where the West-East main gas pipeline runs through this region.[26,27] UGS in this area provides about 11% of the annual gas demand for peak balancing.[28] This is a successful example of how aquifers can be used to store gas in regions with no depleted deposits.[29]

In Europe, Germany and France demonstrate a similar experience, where gas storage facilities using aquifers show high efficiency and low construction costs compared to UGS in depleted fields.[30,31] The UK also has successful experience in creating UGS in aquifers with active seismic monitoring.[32] These examples show that aquifers can effectively serve as reservoirs for gas, especially in seismically stable regions.

In assessing the economic feasibility and geological aspects of UGS, it is crucial to consider the current state of Kazakhstan's mining and metallurgical industries, as these sectors are closely linked to the development of storage and transportation infrastructure for natural gas. Notably, Hsu *et al*.[33] and Kunarbekova *et al*.[34] provided an in-depth analysis of Kazakhstan's mining sector, highlighting resource development prospects and engineering solutions applicable to the oil and gas industry. These factors should be considered when developing sustainable UGS strategies in the region.

This research explores the potential for developing UGS facilities in southeastern Kazakhstan, an area with geological characteristics that may be suitable for such initiatives. The Balkhash depression and its surrounding regions are not only strategically located but also contain geological formations that could facilitate effective gas storage. Understanding the geological setting, including sediment composition and structural integrity, is essential for assessing the feasibility and safety of UGS development. Additionally, this study aims to evaluate the economic implications of UGS facilities for the Almaty region. The research provides a comprehensive overview of the benefits and challenges associated with UGS implementation by analyzing potential investment opportunities, operational costs, and regulatory frameworks. Ultimately, the findings of this research are intended to support policymakers, industry stakeholders, and researchers in making informed decisions regarding the development of underground gas storage solutions. By ensuring a stable and reliable gas supply, Kazakhstan can enhance its energy security, promote economic growth, and contribute to the overall sustainability of its energy resources.

2. Geological setting

The Balkhash depression is located south of the Central Kazakhstan Shield and is limited by the folded systems of the Shu-Ili belt and Dzungaria.[35] In the northeast, it is separated from the Alakol depression by the main Dzungar fault.[36,37] The Balkhash depression has been studied quite well from a general geological point of view. Its entire area is covered by geological surveys at a scale of 1:200000, and on part of the territory, surveys at a scale of 1: 50000 and larger were carried out.[38,39] Drilling activities in the oil and gas industry were conducted only in 1958.[40] Six structural wells, with depths ranging from 350 to 580 meters, were drilled along the right bank of the lower reaches of the Ili River. Two revealed Paleozoic deposits, the rest were stopped in Neogene-Paleogene deposits or the Paleozoic weathering crust. A single well 10-K with a depth of 108 m was drilled in the southwestern marginal part of the basin near the Kolshengel spring uncovered Paleozoic deposits. According to these data, further work on the oil and gas industry in the Balkhash depression was stopped due to negative assessments of the prospects for oil and gas content (justification - shallow depths to the foundation and low thickness of the Meso-Cenozoic complex).[41] Aeromagnetic survey at a scale of 1:50000 and gravimetric survey at a scale of 1:200000 have been conducted across the entire territory and with partial surveys conducted at a scale of 1:50000. Between 1950 and 1970, seismic exploration using the reflection wave method (RWM) and the correlation method of refracted waves (CMRW) was conducted in a profile-based approach across isolated areas to investigate the structure of Mesozoic deposits and determine the depth of the Paleozoic basement.[42]

Seismic exploration of seismic sediments in the areal version was carried out by JSC Volkovgeology from 1984 to 1986 in the western part of the depression (in the Lower Ili trough) – within the area of uranium-coal deposits.[43,44] Based on these data, a map of isohypses along the top of Paleozoic deposits was constructed. It has been established that the depths to this surface vary from 200-300 m in the north of the depression near Lake Balkhash to 1000 m in its southern part - at the foot of the Malaysary and Dzungarian Alatau mountains (Fig. 1). The traditional perspective on the Balkhash depression regarding the interface between Meso-Cenozoic and Paleozoic sediments identifies it as the surface of the crystalline basement. The surface of a quasi-platform complex (QPC) includes deposits of the Upper Devonian, Carboniferous, and Permian.[38] The depression is filled mainly with continental Neogene-Quaternary formations. Jurassic deposits fill only erosion-tectonic depressions in the basement surface northwest of the basin. Late Cretaceous and Paleogene deposits are of insignificant thickness and are located in the submerged parts of the depression. The foundation of depression is heterogeneous. In the structure of the sedimentary cover of the depression, the Lower Ili trough is distinguished in the west, and the Lepsi trough with the Sarkand and Shubar troughs in the east.[39] The Lower Ili trough is located in the western part of the depression. It is filled mainly with Cenozoic continental sediments.[45] In the southeastern part, the most submerged part of the trough near the Dzungarian Alatau mountains, the Jurassic deposits of low thickness are possible.[46] The Sarkand and Shubar troughs of the Lepsi trough are pressed against the northern slope of the Dzungarian Alatau ridge. They are also filled with Cenozoic terrigenous sediments with a 900-1000 m thickness. They may contain Jurassic and Cretaceous sediments of low thickness.[47]

2.1 Lithological and stratigraphic characteristics of the depression

The structure of the frame and foundation of the Balkhash depression involves deposits of many structural and formational strata.[48] Under the Mesozoic-Cenozoic cover of the Balkhash depression, formations of Devonian and Late Paleozoic age are widespread. They overlie Lower Paleozoic sediments with a structural unconformity. The foundation of the northwestern part of the depression is best studied, where JSC Volkovgeology investigated the uranium-coal deposit and carried out GDP-200.[49] Based on these data, a diagram of the structure of the foundation of the western part of the Balkhash depression was compiled, in which the boundaries of the development of Paleozoic deposits are highlighted. Most of the area in the diagram is occupied by Upper Paleozoic deposits. In the rest of the territory, ideas about the foundation structure are based on geophysical data and the results of drilling sparse hydrogeological wells and the search for solid minerals.

Formations of the Devonian volcano-plutonic belt (D) form the foundation of the Balkhash depression in its northwestern part on the left bank of the river.[50] Volcanic rocks of basic and felsic composition are separated in the section. They comprise layers and packs of terrigenous rocks, intruded by subvolcanic bodies as well as granodiorite and granite-leucogranite plutons.[39] Fig. 2 is a brief description of

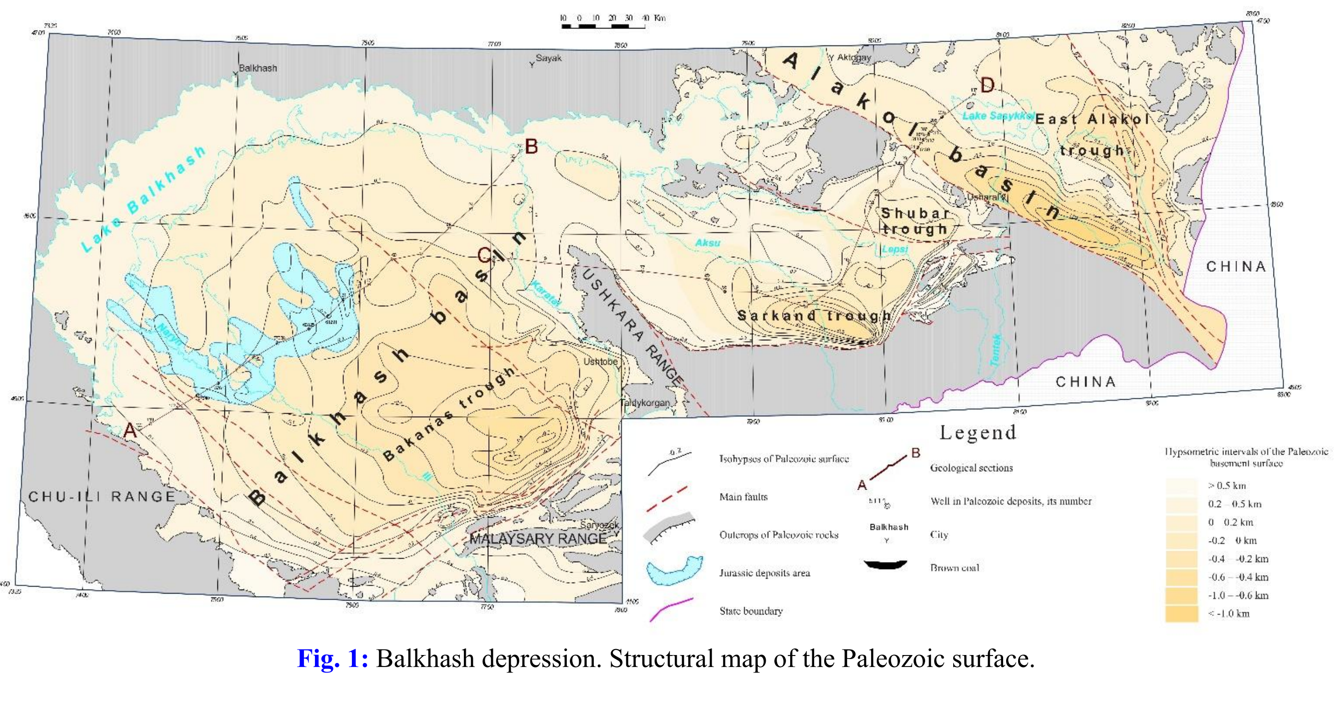


Fig. 1: Balkhash depression. Structural map of the Paleozoic surface.

the erosion surface of Paleozoic deposits at the Paleozoic-Mesozoic interface. Based on drilling data and outcrop observations, the figure illustrates that various formations of the Pre-Jurassic complex have developed on the Paleozoic erosion surface. A linearly elongated zone of Upper Paleozoic deposits, trending northwest and extending up to 300 km in length and 140 km in width, is bounded by faults and may display characteristics indicative of rifting. Devonian marine sediments (D) are exposed in the northern part of the Balkhash depression through sparse wells on the right bank of the river. They are represented mainly by sandstones, siltstones, gravelites, and conglomerates. The Famennian-Lower Carboniferous deposits of the Chuli type (D_3-C_1) along the southwestern side of the Balkhash depression form small, branched synclinal structures. They lie with structural unconformity on Lower Paleozoic and Devonian formations and are represented by sandstones and siltstones. Tuffites and more rarely tuffs are noted in the interlayers. Carboniferous Marine sediments of the Sayak type (C) are exposed in the north. Balkhash is represented by terrigenous rocks (from siltstones to conglomerates) containing layers of tuffs and limestone.[51] They lie conformably on terrigenous marine Devonian and unconformably on Ordovician-Silurian sediments. Late Paleozoic formations are most widespread under the cover of the Balkhash depression. They are represented by Lower Carboniferous - Lower Triassic terrigenous-volcanogenic deposits.

Permian deposits have not been found in the Balkhash depression, but they may be present in its submerged parts.[52] At the base of the orthoplatform sedimentary cover of the Balkhash depression, Triassic-Jurassic weathering crusts are found, which are common in the side parts.[53] It is a structural

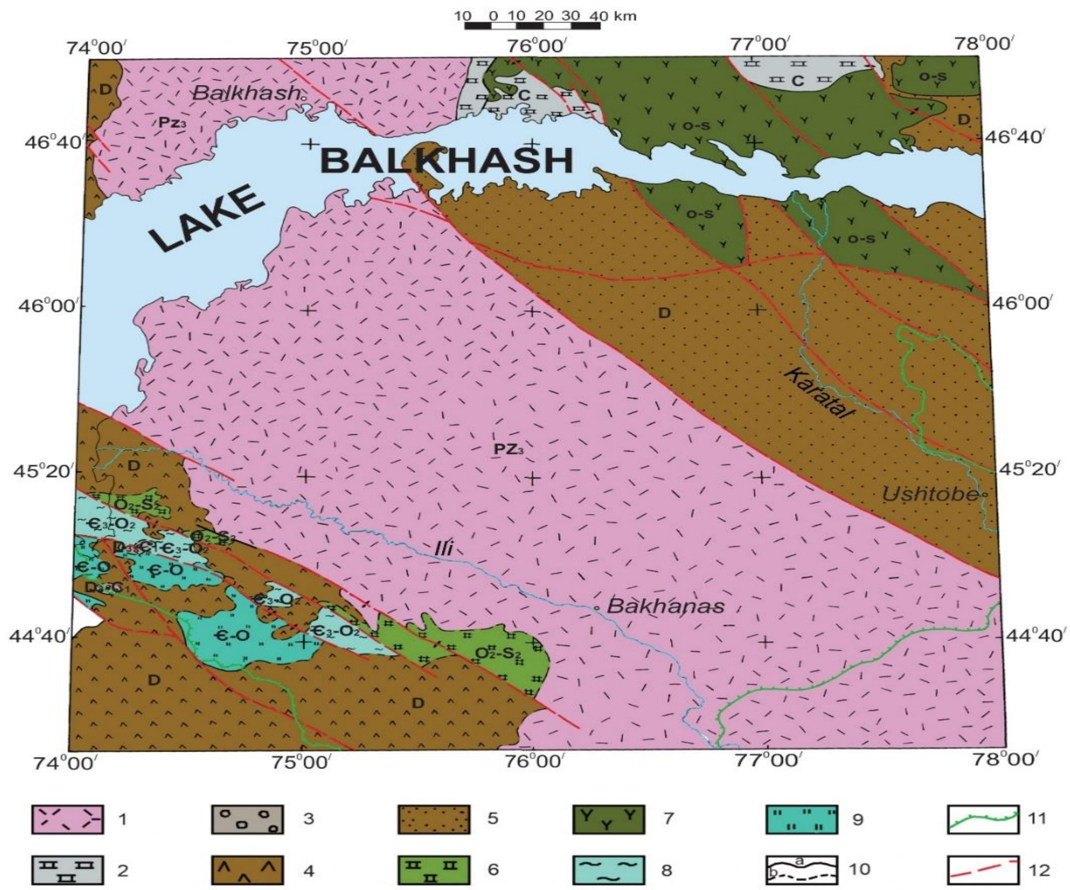


Fig. 2: Scheme of the structure of the foundation of the western part of the Balkhash depression. 1 - Upper Paleozoic. Clastic-volcanogenic formations and intrusive complexes of the Pribalkhash-Ili volcanic-plutonic belt; 2 - Carboniferous. Marine carbonate-clastic deposits of the Sayak type; 3 - Famennian-Lower Carboniferous. Lacustrine and alluvial clastic deposits of the Chu-Ili type; 4 - Devonian. Clastic-volcanogenic formations and intrusive complexes of the Devonian volcanic-plutonic belt; 5 - Devonian. Marine clastic deposits; 6 - Middle Ordovician-Upper Silurian. Marine carbonate-clastic deposits of the Mynaral type; 7 - Ordovician-Silurian. Oceanic volcanogenic-siliceous-clastic deposits and ultramafics of the Itmurundy-Tyulkulam type; 8 - Upper Cambrian-Middle Ordovician. Marine siliceous-clastic deposits of the Buruntau type; 9 - Cambrian-Ordovician. Riftogenic volcanogenic-siliceous-clastic deposits of the Sarytum type; 10 - Boundaries of the identified complexes: a - at the surface, b - beneath the basin cover; 11 - Boundaries of the Balkhash basin (hachures directed inward toward the basin); 12 - Faults.

kaolinite weathering crust developed over volcanic and intrusive rocks in the lower part. Bauxite occurs along the edges of the Pre-Mesozoic basement ledges in the upper part. Triassic deposits are known only in the southwestern part of the Balkhash depression, where they performed a small graben-like plunge in the pre-Mesozoic bed of the Aksuek trough.[54] They are consolidated into the Aksuek formation, dated to the Middle-Upper Triassic period. The upper part of the section is washed out everywhere. The thickness of the formation reaches 120-200 m. At the base of the formation are polymictic sandstones.[55] Higher up, these are substituted by a series of gray and dark gray siltstones and mudstones, with layers and lenses of carbonaceous mudstones, siltstones, brown coal, and oil shale. Jurassic deposits within the Balkhash depression were discovered in 1973 under a cover of Cenozoic deposits during drilling by JSC Volkovgeology.[56] The total area of their distribution is about 5000 km^2. The depth of their roof varies from 100 m near the mouth of the river. In general, the thickness of Jurassic sediments reaches a maximum in this depression, 250-260 m, and in others does not exceed 125-160 m. They are overlapped with significant erosion, angular, and stratigraphic unconformity by Upper Cretaceous and Paleogene deposits. The Jurassic deposits of the Balkhash depression are divided into three formations (from bottom to top): Kairlagan J_1^3 - J_2^1, Zharkent – J_2^2 bt, and Saryozek – J_2^3 cl.[35] The two lower formations are combined into a coal-bearing series, and the upper formation is called the carbon-bearing series. The coal-bearing series has been studied in detail in the Lower Ili trough. Its maximum thickness is 180-200 m. There are four cycles in the series. Sediments of the first three cycles (Kairlagan formation) are distributed only in the central, western, and southwestern parts of the Lower Ili depression, and the Zharkent formation is distributed throughout its entire territory.

Their section is represented by conglomerates, gravelites, and coarse-grained sandstones. In the middle part, sandstones of various grain sizes dominate with a sharply subordinate role of silty sandstones, siltstones, and clays, and in the upper part, siltstones and clays with layers and lenses of brown coal, less often oil shale. The section of the Zharkent suite differs from the underlying deposits in the presence of brown coal in the upper part of the seam, with a thickness of 1-2 to 58.8 m. The area of the seam is about 700 km^2. In the southeastern part, the deposits of the Zharkent formation are represented by carbonaceous silts, clays, and a continuous layer of coal (1-32 m), which, in most cases, lies directly on the weathering crust of Paleozoic rocks. The Saryozek (overlying coal-bearing) formation J_3 cl transgressively overlies the eroded surface of the coal-bearing series. The thickness of the formation ranges from a few meters at the sides to 60-80 m in the axial parts of the depressions. It consists of a consistent sequence of sandstones with varying grain sizes, mixed with gravel material, along with thin layers and lenses of conglomerates and gravelites. Upper Cretaceous–Lower Paleogene deposits, characterized by erosion and angular unconformity, rest on various formations, extending down to the basement. The base comprises whitish gravel and pebbles with a clay-sand-kaolinite matrix and conglomerate lenses. Above are heterogeneous, poorly sorted clayey sands with gravel and clay lenses. Paleogene deposits overlie the lower ones without a visible unconformity. They are represented at the base by a basal unit of limonitized sands with interlayers of gravelites, which are replaced higher up the section by variegated clays with thin layers of sands and siltstones, and lenses of lignites. Above that usually lie cross-bedded medium or different-grained clayey pinkish-red sands, calcareous gypsum-bearing red clays with interlayers of clays and sands. Neogene deposits are represented by interlayers of marls, variegated clays, sands, and siltstones with an admixture of sand and gravel material. Their trough thickness reaches 500-600 m. The depression is filled mainly with continental Neogene-Quaternary formations - continental red-colored molasse.

2.2 Structural and tectonic characteristics of the depression

The Balkhash depression is part of the system of northern intermountain alpine depressions of the Central Asian orogeny. It is located on the southern edge of the Central Kazakhstan arched uplift (shield) on its border with the Dzungar folded mountain structure.[57] The fault system separating these two blocks essentially marks the southeastern boundary of the Balkhash depression.[58] Available information for the region as a whole suggests that these faults are of the type of reverse faults and thrusts. In this regard, the southeastern side of the depression is steep, and the parts of the troughs adjacent to it from the north are the deepest. From the southwest, the depression is limited by the Chu-Ili arch-block uplift.[59] The southwestern and northern flanks of the depression are gentle, while in the northeast, the Balkhash depression borders the Alakol depression along the Main Alakol-Dzungar fault.[60] The depression is divided by the Mulaly swell (the northwestern continuation of the Ushkara Mountains) into two parts: the Lower Ili trough in the west and the Lepsi trough in the east.[61,62] Non-lithified and weakly lithified sediments of the cover of the Balkhash depression lie on the basement with a structural unconformity. It consists of three stages: lower (Triassic-Jurassic), middle (late Cretaceous-Eocene), and upper (late Oligocene-Quaternary). They are separated by stratigraphic breaks with minor angular unconformities. Jurassic deposits fill relatively shallow (from 20 to 260 m) erosion-tectonic depressions elongated in the northwest direction. They were established only in the northern part of the Lower Ili trough. Sediments of the middle, Cretaceous-Eocene structural stage, preserved from erosion, occupy the central and southeastern parts of the Balkhash depression.

Oligocene-Miocene deposits are somewhat more extensive than the Cretaceous-Eocene deposits, with a thickness ranging from several tens to a few hundred meters. Sediments of the Pliocene-Quaternary stage cover the area of the depression in a continuous cloak. An analysis of the thickness of the sedimentary cover and the relief of the basement of the Balkhash depression defines it as an asymmetric depression structure that developed from the beginning of the Oligocene. The accumulation of sediments of the Jurassic and Cretaceous-Eocene stages occurred under conditions of a quiet platform regime. The deposits of the upper structural stage lie subhorizontally. It was at this stage that the Balkhash depression was formed in its modern form, which allows us to consider it as a typical intermountain depression that arose simultaneously with the uplift Dzungar mountain-fold structure.

Materials and maps were compiled on the tectonic zoning of the depression. Magnetic and gravity survey data were used as the main materials. Klimov *et al.*[63] presented a scheme of the deep tectonic structure of the Balkhash segment of the Earth's crust (southern part). Based on the calculated data, an isodepth map of the "main magnetically active surface" was compiled, proposed as the base of the QPC and at the same time as the "roof" of the foundation.[64] Based on this map, the contours of the supposed horst-anticlines and graben-synclines are highlighted.[38]

To verify the reliability of this zoning, it is necessary to carry out seismic exploration using a technique that allows studying the internal structure of the Paleozoic and parametric drilling (Fig. 3). On the area of the depression there are two regional seismic profiles, RWM, deep seismic sounding (DSS) crossing the entire depression. Of these, one is sub-meridional (Sayak South) in Fig. 3 and the second is sub-latitudinal (Turkestan).[65] The Lower Ili trough is assumed to be filled with an effusive-sedimentary complex of sediments, and the Lepsi trough is essentially sedimentary.

A structural diagram of its deep structure was compiled bysummarizing and reinterpreting DSS and ECWM (Earthquake Converted-Wave Method) data for the Balkhash

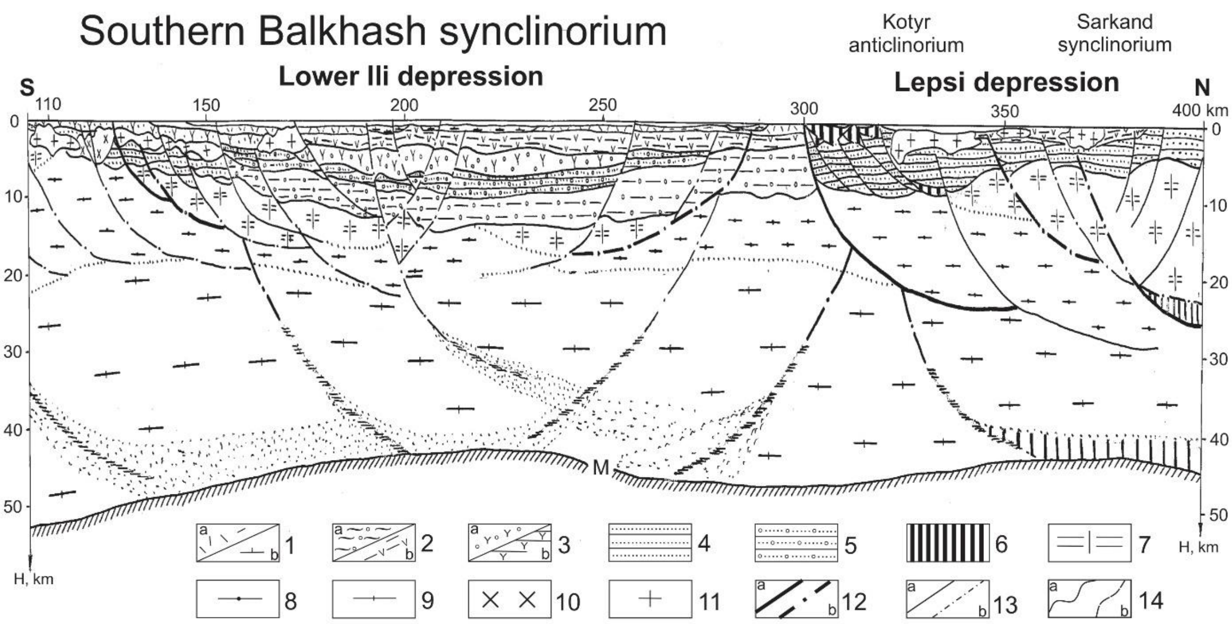


Fig. 3: Regional profile of the ECWM and the Sayak southern DSS. 1 - Continental orogenic volcanogenic-molasse (a), with predominant development of plateau basalts (b); 2 - Lagoonal-marine and marine carbonate-terrigenous (a), volcanogenic-carbonate-terrigenous (b) of the Early Hercynian troughs; 3 - Orogenic volcanogenic-molasse (a), volcanogenic-molasse green-colored (b); 4 - Late geo-synclinal flysch, flyschoid, flyschoid-molassoid, carbonate-flysch; 5 - Protoplatform and molasse variegated undifferentiated in the Caledonian basement of late Paleozoic volcanogenic basins; 6 - Riftogenic; 7 - Pre-Riphean continental basement (on formation maps); 8 - Pre-Rifesque granite-gneiss basement with a model density of 2.70 g/cm^3 (on sections); 9 - Metabasite geophysical layer with a model density of 2.85-2.90 g/cm^3 (on sections); 10 - Intermediate and tonalite-granodiorite composition; 11 - Acid composition; Faults: 12 - Regional: a) established, b) inferred; 13 - Other: a) established, b) inferred; 14 - Granites between formation complexes, contacts of intrusive massifs: a) established, b) inferred. M – Mohorovicic boundary.

segment of the Earth's crust. A fragment of this scheme for the Southern Balkhash region highlights the main rift-forming faults and the troughs separating them, within which higher-order structures of potential interest for oil and gas exploration may exist. Identifying local structures promising for oil and gas based on gravity survey data is difficult due to the extremely differentiated field of local anomalies and their large number. Additional material, such as common depth point (CDP) seismic data, is required to identify them. Without this, the interpretation of anomalies is ambiguous, potentially caused by structural-tectonic factors or lithological variations, such as alternations of terrigenous, effusive, and intrusive rocks. Based on the ratio of the intensity of magnetic fields, the Lower Ili trough is assessed as containing an increased amount of volcanic-terrigenous material, and the Lepsi trough contains predominantly terrigenous material.[41] In the structural wells drilled in 1958, studies of the content of organic matter, bitumen, and other specific analyses were not carried out. It was carried out only after 1973.[66]

Jurassic deposits with coal seams showed that these deposits may contain significant organic matter in the brown coals.[67] Analysis for rock-dispersed organic matter (DOM) was not performed. A remarkable amount of hydrocarbon gases could be released during the transformation of organic matter, and facilitated by Paleogene clay deposits as a cover.[68] However, the shallow depths of Jurassic deposits (the first hundreds of meters in the area of coal deposits) do not allow us to count on the generation of hydrocarbons in significant quantities.[35] According to the available data from seismic exploration and drilling of wells for other minerals, anticlines or other traps have not been identified.[69] Meso-Cenozoic deposits, due to their low thickness and insignificant depth, no more than 1000 m in the deepest part near the Dzungarian Alatau, cannot be included in the oil and gas generation category due to their incomplete inclusion in the catagenesis zone (PC_3).[70]

The existing data on the Balkhash depression suggest that the Meso-Cenozoic sediment complex has limited potential for hydrocarbon deposits due to shallow depths and low thickness,[71] with exceptions for small deposits along fluid migration paths from the presumed QPC - the quasi-platform Paleozoic complex, assuming the presence of oil and gas traps.[72] The QPC can be identified as a possibly promising oil and gas-bearing complex in the Balkhash depression.[35] The supposed deposits of the Paleozoic quasi-platform complex (D_3+C+P) within the basin by wells drilled for other minerals, even discovered in intervals a few meters thick, were not studied for hydrocarbons. Hydrocarbons may be preserved in Paleozoic sediments, in the supposed QPC.[73] In the complete absence of factual data on the geological structure of the QPC, this remains a hypothesis that requires confirmation in the form of regional seismic work and drilling of reference (parametric) wells. The QPC source rocks for oil and gas may include gray and dark-colored terrigenous sediments, such as sandstones, siltstones, and limestones.[74] Analogous basins with established signs of hydrocarbons in Paleozoic sediments are located in the west of the Chu-Sarysu depression, containing gas deposits in Devonian, Carboniferous, and salt-bearing Permian deposits.[75] The Zhaisan depression, with gas-bearing deposits below the Lower Paleogene and oil shows in Permian and Triassic-Jurassic deposits, and the Zharkent trough, with gas readings in Permo-Triassic deposits, degassing of drilling fluids, and gas dissolved in water. The oil and gas source deposits may be the Permian coastal-marine, effusive-terrigenous, and Jurassic coal-bearing sandy-clayey formation.[76] Upper Permian deposits overlie Lower Carboniferous formations with strata of carbonate deposits interbedded with Upper Devonian volcanic-sedimentary deposits.[77] Their potential for oil and gas may be indicated by the discovery of bituminous limestone packs of Visean age in the eastern part of the Ketmen ridge, in the Zhaisan depression, oil shale, and oil-bearing deposits at the Sorbulak structure.[78]

Reservoir horizons can be fractured effusive and tuff sandstones in the weathering crust of the basement, as well as sandy layers in Permian, Upper Triassic, Lower and Middle Jurassic, and possibly Cenozoic deposits. Within the Balkhash depression in Meso-Cenozoic sediments, Paleogene clay layers are possible fluid seals. It is advisable to conduct seismic surveys along a system of profiles across the strike of the depression and along the strike, with a spacing of about 30 km and a length of 250 km. For the larger Lower Ili trough, the volume is 1500 linear meters. The assessment of potential hydrocarbon resources for the sedimentary basins of Kazakhstan carried out in the report,[79-81] including for the Balkhash basin, is given without changes: geological resources of 1997 million tons, recoverable reserves of 399.5 million tons. The Ili depression is one of the systems of intermountain depressions, it has a sub-latitudinal strike and is limited by the Zailiysky Alatau, Dzungarian Alatau, and Ketmen ridges. It consists of two troughs - Almaty and Zharkent, separated by the Boguty saddle. The dimensions of Almaty are up to 200×50 km, and Zharkent is 100×70 km (Fig. 4).[81] The entire area is covered by geological surveys at a scale of 1:200000 and partially at 1:50000, along with aeromagnetic and gravimetric surveys, where extensive work on solid minerals has been conducted. The study of its gas content began in 1930, from the search for helium sources by the Central Research Institute of Geological Exploration.

These searches continued in the post-war years. Signs of increased helium content of springs were established in the villages of Dubun and Chundzha and small structural wells in the northern part of the trough. Subsequently, these areas were assessed as unpromising for industrial helium content, and the eastern part of the trough was evaluated as more promising.[82] In the post-war years, geological and geophysical exploration in the area included prospecting activities in the following periods: 1) 1955-1960, 2) 1980-1990, and sporadic works in 1997-1998. Parameter drilling, along with the Chesky well 1-P Zharkent, was completed in 2007, accompanied by 2D seismic exploration on the right bank of the river (Fig. 5).

In the 1950s, a Geological survey carried out by the Sredaznefterazvedka trust in the northern part of the trough revealed a group of small structures (Lesnovski, Khorgos, Baskunchi, Koiby, Bestyubi, Aktau, *etc*.). The peculiarities of these structures are flat northern and steep southern wings, because they are confined to sub-latitudinal faults and appear on the day surface. There are no Jurassic deposits here, and the foundation was exposed by wells at depths of 0.4-1.0 km and is represented by porphyrites and tuffs of basic composition and weathered tuff conglomerates. This group of structures was searched during geological surveys using structural drilling and assessed as unpromising for oil and gas based on Cenozoic and Cretaceous deposits. Systematic geological and geophysical studies of the Ili depression began in the late 1950s and early 1960s with geophysical surveys in the Zharkent Trough. These included seismic prospecting using RWM and CMRW, electrical prospecting through vertical electrical sounding and Telluric currents method, as well as gravity prospecting. As a result, initial data on the deep geological structure of the trough were obtained. The depths of the foundation were established, and major structural complications were identified in its internal part.[81] During these same years, deep drilling was carried out in the trough, mainly by the South Kazakhstan Oil Exploration Expedition. Seven wells were drilled – 1-G, 2-G, 3-G, 4-G, 5-G, 6-G, 7-G. Of these, G-4 and G-5 are on the northern side of the

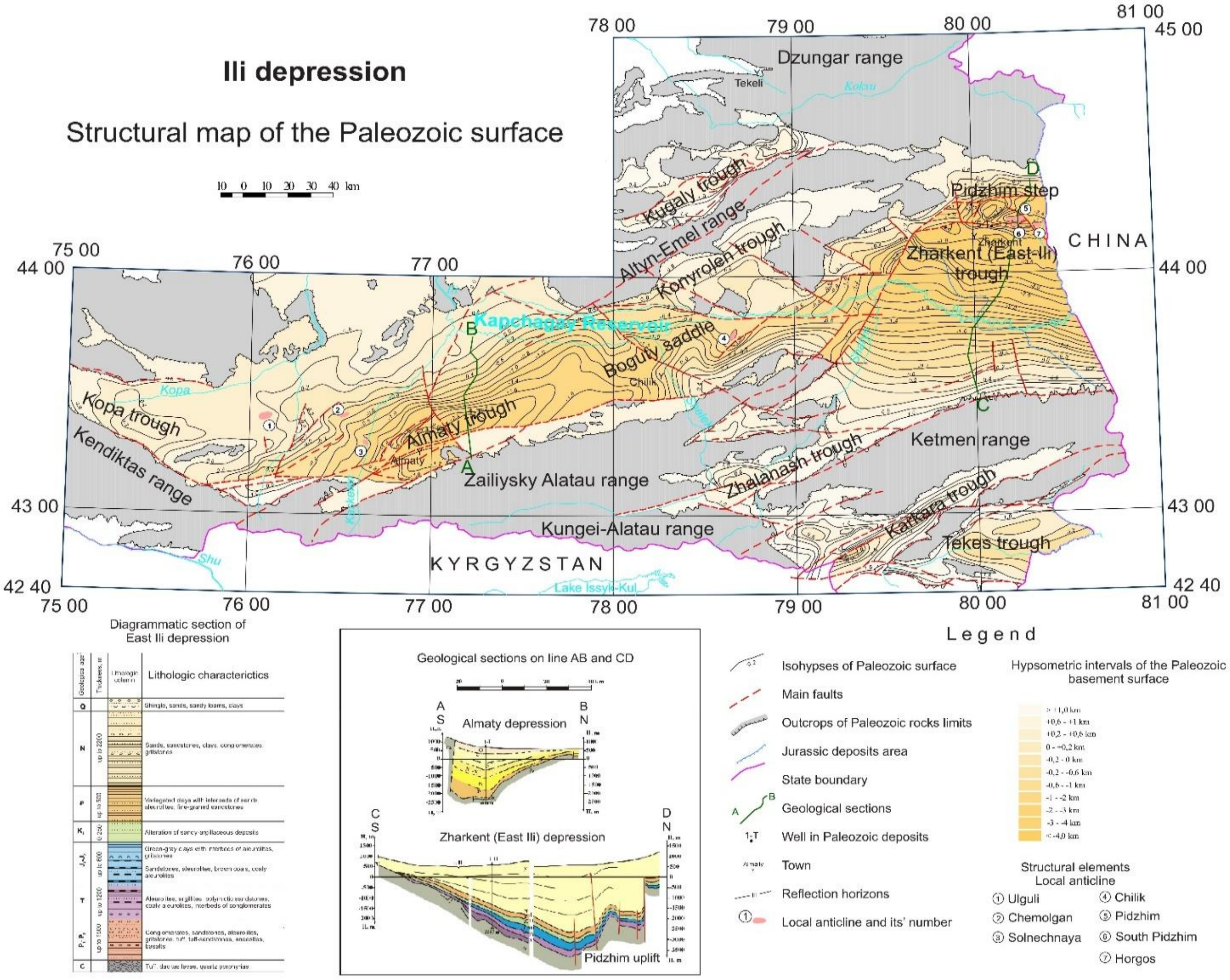


Fig. 4: Ili depression. Structural map of the Paleozoic surface.

depression, the rest are on the southern side. Well 1-G, with a depth of 2800 m, located at the south side of the trough near the bed of the Ili River, discovered porphyrites of Lower Permian-Carboniferous age at a depth of 2753 m, overlain by predominantly sandy deposits of Upper Cretaceous age. Well 2-G, located northeast of 1-G in the axial part of the trough, was halted at a depth of 3000 m in Neogene deposits for technical reasons, though it was designed to reach a depth of 4500 m. Wells 3-G, 6-G, and 7-G were drilled in the southeastern part of the trough in the sub-meridional profile, starting from 3-G located in the river bed or near the border with China. They uncovered Jurassic deposits with thicknesses of 535, 418, and 252 m. Their depths are, respectively, 3150, 2400, and 1400 m, and they are stopped in Permian effusive-sedimentary deposits. According to gas logging data, increased contents of methane and helium were noted, including intervals with coal seams. Well 4-G was drilled in the northwestern part of the trough on the “adyr” Koiby structure in the shallow (400-500 m) depths to the basement represented by porphyritic and tuffs of basic composition. Well, 5-G with a depth of 2400 m was drilled in the vicinity of the Bestyubi structure and stopped in Cretaceous deposits. According to geophysical work and deep drilling in the period 1950-1960, the section of Permian, Triassic, Jurassic, Cretaceous, and Cenozoic deposits was studied for significant depths of the foundation in the central part of the trough, and major structural complications were identified. In the southeastern part of the trough, the presence of Jurassic deposits of significant thickness (up to 525 m in well 3-G) and Triassic sedimentary deposits have been established.

Data from deep and structural drilling were summarized in the South Korean People's Republic by Filipev and Rabkin.[79] Based on well-testing data, the central part of the trough was recommended as the main promising gas-bearing area. Paleozoic, Mesozoic, and possibly, Paleogene (at depths of more than 2.5 km) sediments were assumed to be the oil and gas source strata.[79] After the work conducted between 1950 and 1960, there was a 20-year break until 1980. The resumption of geological and geophysical work in the Zharkent trough began in the 1980s, after other promising areas developed in the Republic of Kazakhstan. In 1980, seismic exploration work using the CDP method by the IGE (Ili Geophysical Expedition) was resumed in the Zharkent trough, employing a new technical and methodological approach with non-explosive energy sources. This was a continuation of regional work begun in the 1960s on a grid of profiles every 8-12 km, sometimes 15-20 km. Reflecting horizons were traced from the Permian surface to the Neogene base, which made it possible to study the structure of lithological-stratigraphic complexes promising for oil and gas.

Structures on the northern side of the trough, on the Pidzhim stage, were recommended as priority objects for further study. These objects were further studied in 1985–1988 using a denser network of profiles with the same method. As a result, the Pidzhim anticlinal structure and the adjacent South-Pidzhim subthrust structure, located to its south, were prepared and recommended for deep drilling for oil and gas. Further east, an analogous structure, the Khorgos structure, was identified, though only its western part is within the study area, while its eastern portion extends into the People's Republic of China.[83,84] To the west of the Pidzhim structure lies the Zharkent (Panfilov) structure, a complex faulted formation divided into multiple blocks. It is recommended for further study. The Karakum structure, identified through CMP seismic surveys conducted between 1955 and 1960 in the eastern part of the trough, was later found to be unconfirmed in Mesozoic deposits based on CDP data from the 1980s. In 1980–1990, the Central Asian expedition "Soyuzburgaz" drilled deep hydrogeological wells in the Zharkent trough to search for thermal waters for agricultural enterprises. A total of 10 hydrogeological wells were drilled in the Zharkent trough during this period. On the northern side, these included wells 4-T (3315 m, Pz), 5-T (3691 m, P), 7-T (2966 m), 8-T (3820 m), and 9-T (4200 m, P). On the southern side, the wells included 1-T (2902 m, Pz), 2-T (3160 m, Pz), 3-T (3281 m, Pz), 1-TP (3013 m, Pz), 2-TP (2938 m, Pz), and 1-RT (2760 m). An industrial influx of fresh hot water was obtained from chalk deposits in wells 1-T and 3-T, and aquifers with fresh water in Neogene sediments were found in all deep wells. In 1997–1998, within the Zharkent trough, parametric well 1-P Zharkent was drilled on the southern side for wells 1-T, 2-T, and 3-T. The geological map of the Zharkent Basin is presented in Grützner *et al.*,[85] which includes a digitized version of the Geological Map of the Kazakh SSR (1979). and a simplified Permian-to-Quaternary lithostratigraphy along with major tectonic phases. According to the geological assignment, the purpose of this well was to study the Lower Cretaceous, Triassic-Jurassic, and Permian deposits, stratify the reference seismic boundaries, and assess the oil and gas potential of the “sand body” at the base of the Jurassic deposits.[86]

The well, at a depth of 3365 m, penetrated Lower Permian deposits at the base. All identified reservoirs were assessed as aquifers. From 1987 to 2007 (20 years), no geophysical surveys for oil and gas were conducted in the Zharkent trough. Under the issued license, Erkin Oil LLP conducted 2D seismic exploration (CDP-2D) in 2007, covering 1748 linear

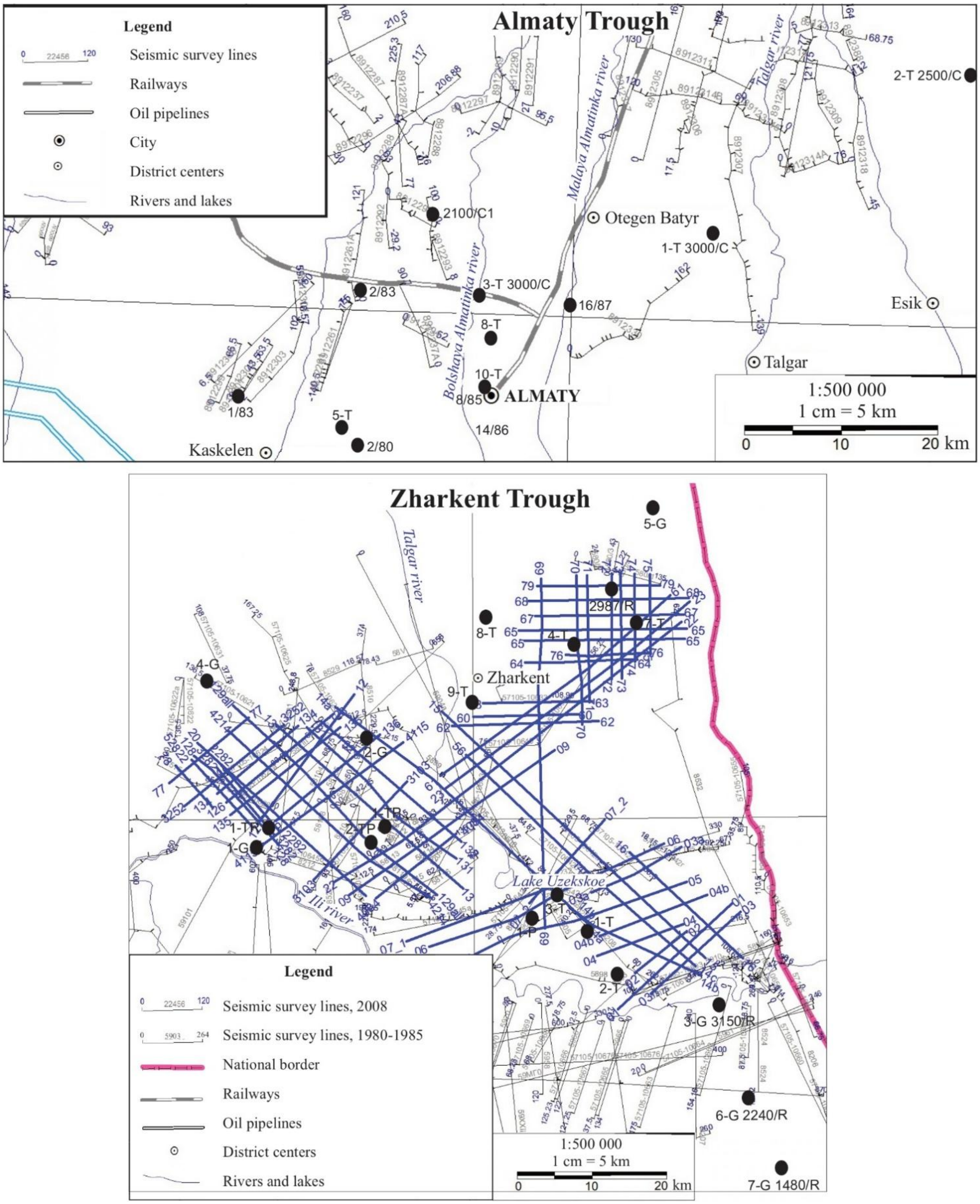


Fig. 5: Scheme of seismic and drilling exploration for Ili depression.

kilometers along the right bank of the Ili river, from its channel to the Pidzhim structure (overlapping a portion of the area surveyed in the 1980s). The search network of CDP profiles was developed over a 3-5 km network, and within the Pidzhim structure over a 2×2 km network. Structural maps were constructed for 5 horizons from the basement surface to the Neogene base (RH I-V).[87] The Pidzhim structure has been confirmed, and additional details have been clarified; a near-fault structure is presumed on the extreme western flank of Aidarly (a half-arch), requiring further study. Seismic exploration (CDP-2D) in this trough was carried out from 1983 to 1989 to study the geological structure and identify formations suitable for creating underground gas storage facilities. Several structures have been identified that are promising for further study of their structure. Additional studies of these objects were not carried out.[88] Between 1957 and 1987, the Almaty Hydrogeological Expedition drilled 17 deep hydrogeological wells. Four wells (1-T, 2-T, 3-T, and 8-T) uncovered Paleozoic effusive-sedimentary deposits, while the rest were stopped mainly in Neogene deposits. There were no signs of oil and gas in all wells. The deepest well T-10 with a depth of 3232 m (1957) was stopped in Paleogene deposits and is located within the city of Almaty (territory of KazVIRG). During the period under review for work carried out before 1960, generalized the accumulated information on the intermountain depressions of South-Eastern Kazakhstan and on later works after 1980.[89-92] The foundation of the Ili depression is composed of Paleozoic rocks, the most ancient of which are represented on the Boguty saddle by Middle-Upper Cambrian marbled limestones, quartzites and shales.[93-95]

Within the Zharkent and Almaty troughs, only Upper Paleozoic sediments and their Permian-Lower Triassic part were exposed by deep wells.[96] The sedimentary cover of the depression highlights the main formations: brownish-red volcanogenic-sedimentary Upper Lower and Upper Permian; gray-colored coal-bearing Upper Triassic - Jurassic; and continental red-colored polymictic Upper Cretaceous - Paleocene Kz - P_1 (ancient Ili formation). The gray coal-bearing formation (T_3 - J_{1-2}) is the least developed.[97] They are present only in the eastern half of the Zharkent trough, wedge out to the west, and are completely absent in the Almaty trough.[95] The Permian system is a red-colored volcanic-sedimentary formation. Deposits of this formation are known in the mountain frame of the depression and were exposed by deep wells within the northern and southern sides of the Zharkent trough and the northern side of the Almaty trough, in the Dzungarian Alatau mountains.[98-100] Based on lithological characteristics, Lower Permian deposits are divided into two strata: lower–effusive and upper – effusive-sedimentary. The lower one is effusive, characterized by alternating lavas of rhyolitic and rhyolite-dacite composition with interlayers of acidic tuffs. Upper Permian deposits are also divided into two strata.[35]

Undifferentiated deposits of the Upper Permian and Lower Triassic are known in the mountain frame of the trough and were exposed by deep wells in the trough.[101] During the Mesozoic and subsequent Late Alpine folding era, a powerful cover of continental sedimentary formations formed within the Ili depression, constituting the upper structural level. The gray-colored coal-bearing formation is developed in the Zharkent trough and is completely absent in the Almaty trough. Rocks of this formation are present in the frame of the Zharkent trough in the Borokhudzir and Ketmen ridges and traced according to drilling and CDP seismic data under the cover of Cretaceous and Cenozoic formations in the inner part of the trough.[102]

Deep oil exploration wells 3-G, 6-G, 7-G, and 1-P Zharkent, along with hydrogeological wells 1-T, 2-T, 3-T, and 4-T, were discovered. In wells, 1-G Borokhudzir, 4-G Koibyn, and hydrogeological 1-TP and 2-TP, the rocks of the Permo-Triassic complex are overlain by sandy deposits of Cretaceous age and Jurassic deposits, respectively, are absent. The maximum thickness of the formation is 800-900 m according to seismic data and located in the central part of the trough. They pinch out in the side areas of the trough and the southwestern direction. On the eastern continuation of the trough in the territory of the People's Republic of China in the Chapchal well, the thickness of this formation increases to 2327 m (T_{2-3} - 1229 m, J_{1-2} - 1142 m) (Fig. 6). The composition of the gray coal-bearing formation, according to lithological characteristics, includes deposits of the Middle-Upper Triassic: silty-clayey strata of the Middle Triassic and conglomerate-sandy-argillite strata of the Upper Triassic (Kolzhat). The Middle Triassic deposits are not consistent in the area with an ambiguous correlation, they are combined with the Upper Triassic in the form of a single undivided formation T_{2-3}.[103] Sediments of the Kolzhat formation T_{2-3} are exposed on the slopes of the Ketmen ridge and were exposed at depths from 180-700 m (Kolzhat coal deposit) to 1975-2265 m in the 3-G well with a thickness of 389 m and in the territory of the People's Republic of China at a depth of 2759 m with a thickness of 1229 m. Jurassic sediments overlie an eroded Late Triassic surface. In the Kazakh territory of the trough, these formations do not come to the surface, but in the adjacent territory of the People's Republic of China, they have outcrops of coal seams in ravines.[104] The depths of Jurassic deposits in the south of the monocline are 25-450 m. The maximum thickness in the region was identified in the well 3-G which reached 1450-1975 m. In the "Chapchal" section, Jurassic formations are characterized by a cyclic alternation of conglomerates, sandstones, siltstones, mudstones, and coals within a depth of 1284–2759 meters. They are represented by the continental river, lake, lake-swamp, and swamp facies and are divided into 2 formations: Kairlagan (J_1 t - J_2 bi) and Zharkent (J_2 bt - kl) formation.[35] It lies on the eroded surface of the Triassic. The lower horizons of the Kairlagan formationare distinguished by the appearance of large layers

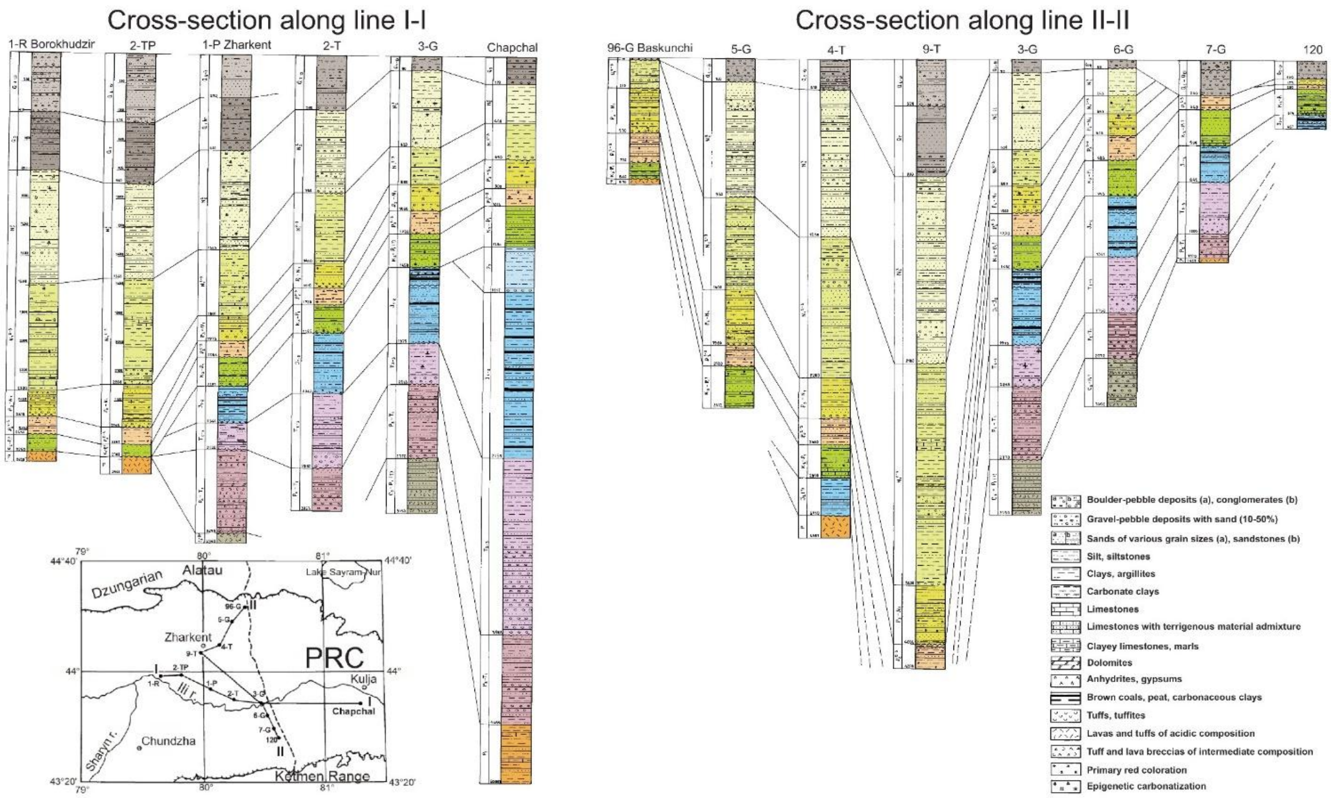


Fig. 6: Zharkent trough. Scheme of comparison of deep well sections.

of inequigranular cross-bedded sandstones with the inclusion of pebbles and hetero-pebble conglomerates. The upper part of the formation ends with layers of brown coal of simple structure, the lower part usually includes carbonaceous siltstones with lenses of high-ash coals of small (up to 0.5-0.7 m) thickness. The total thickness of the formation varies from 150 m in the south of the monocline to 335 m in the riverbed.

The Zharkent Formation has undergone chemical weathering processes but does not exhibit visible angular unconformity, as it rests on an eroded Toarcian-Bajocian surface.[105] A complete section of the formation was revealed by borehole 3-D, with a depth range of 1450-1640 m. The lower half consists of gray sandstones, mudstones, and siltstones, while the upper half, made up of sandstones and siltstones, contains coal seams. The upper half, composed of sandstones and siltstones, includes coal seams. The maximum total thickness in the basin of the Jurassic coal-bearing deposits (Toarcian-Callovian) was established in the well Chapchal, where it reaches 1140 m. At the end of the Middle Jurassic, there was a hiatus in sedimentation. The Upper Jurassic and Lower Shoals practically vanished. In the section, it is fixed by a pack of kaolinized siltstones and clays, corresponding to the weathering crust. The Meso-Cenozoic section in the Almaty trough begins with this formation.[106] It lies transgressively on all underlying formations - from the Jurassic to the Paleozoic. On the southeastern side, the thickness is represented by the interlayering of light gray sandstones with variegated clays 70-200 m thick. In the western part of the central zone (1-G, Borohudzir, and 1-RT) the thickness of the chalk is 120-125 m; it is composed here of loose quartz sands with a member of red siltstones at the base. In the southernmost part of the trough (Kolzhat area), the Upper Cretaceous-Paleocene is divided into two horizons: the lower, composed of deluvial-proluvial red formations, and the upper, represented by alluvial clay-sand deposits.[107] A unit of sandy-clayey whitish rocks (10-20 m) with spotted carbonatization ("carbonate slab") is recorded everywhere in it. These deposits are represented by strata of molassoid formations with a predominance of red-colored sediments in the lower part of the section. Eocene formations are widespread in the region, consisting of brick-red, ocher-yellow, and brown clays interbedded with sandstones, marls, and sands. At the base, gravelites or conglomerates are developed, resting on the weathering crust of Paleozoic rocks or the Old Ili cycle. In the middle part of the Eocene, the presence of foraminiferal microfauna was identified in well 1-G, indicating a relatively brief marine sedimentation regime in this part of the section. Oligocene deposits are allocated to the Aktau formation with a thickness of about 200 m. It consists of ocher-yellow sandstones with interlayers of conglomerates, red and brown clays. Higher up the section there are reddish-brown clays and siltstones with subordinate layers of green-colored rocks.[108] Neogene deposits in the Zharkent trough make up the main part of the Cenozoic section. Since they are represented by essentially clayey formations, the Neogene sequence is the main seal in the sedimentary section. Quaternary deposits are represented in the depression by all their departments. The composition of these formations encompasses an entire set - from proluvial-deluvial coarse clastic rocks and loess-like loams of the foothills to alluvial, aeolian, lacustrine, and chemogenic rocks in the central parts of the trough. Their thickness varies widely - from a few meters to 540-600 m.[109]

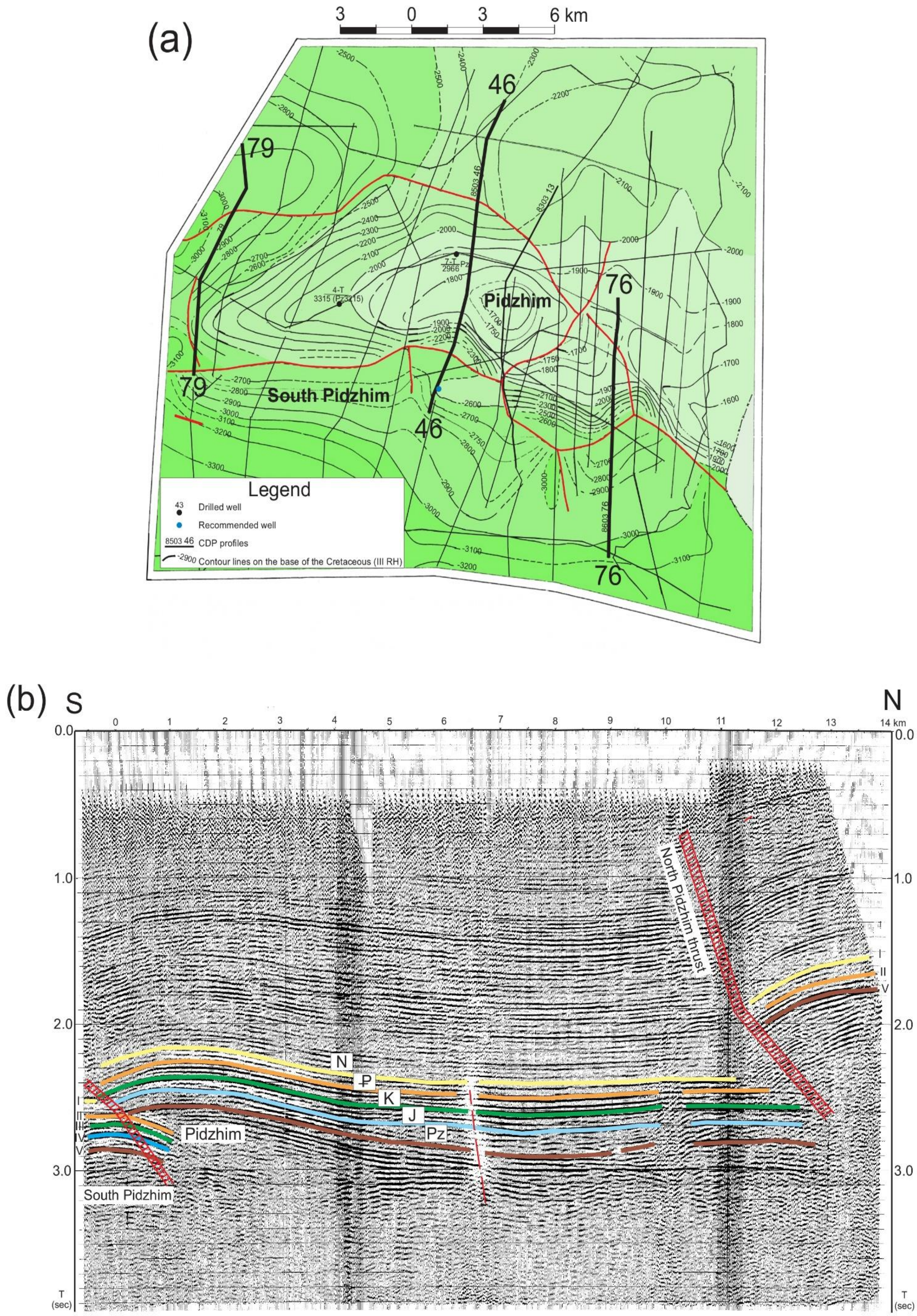
2.3 Structural-tectonic zoning

The Ili basin is a typical intermountain depression that arose in the process of epiplatform mountain-building movements and is filled with effusive-sedimentary deposits of the Upper Paleozoic and sedimentary deposits of the Meso-Cenozoic.[110,111] The depression extends from west to east over a distance of about 450 km and consists of two troughs: Almaty and Zharkent, as well as the Boguty saddle separating them. The Almaty trough ends in the west with a shallow (a few hundred meters) synclinal formation - the Kopy trough. The Zharkent trough, with its eastern continuation, goes into the territory of the PRC. The mountain frame of the depression is represented in the north by the spurs of the Dzungarian Alatau, and in the south by the Trans-Ili Alatau and the Ketmen ridge.[112] The structure of the troughs is asymmetrical: one side is steep (for the Almaty it is the southern side on the border with the Trans-Ili Alatau, and for the Zharkent it is the northern side complicated by thrust-type faults), and the opposite sides are flat.[113] It is advisable to begin the consideration of the internal structure of the depression with the Zharkent trough as the most studied by geophysical methods and deep drilling, and then with the Almaty trough. In the Zharkent trough, there is a large accumulated thickness of Neogene-Quaternary sediments of up to 4 km and up to 1.5 km of Mesozoic (Triassic-Cretaceous). Its southern gentle side occupies 70-75% of the trough area, which is also divided by the sub-latitudinal channel of the Ili river into left-bank and right-bank parts (Fig. 7). The bulk of seismic exploration and deep drilling was carried out on the right bank and the left bank, CDP seismic exploration was carried out only along a sparse network of regional profiles. Deep drilling is represented by three wells 3-G, 6-G, and 7-G in the southeastern part of the left bank.

The northernmost part of the trough, located between the Dzungarian Alatau mountains and the Ili depression, is known as the Dzungar monocline. This is an area of shallow depths to the foundation (400-1000 m). According to geological survey data using structural drilling, the presence of "adyr" structures - small anticlines located along faults (Aktau, Zhambyl Bateau, Baskunchi, *etc*.) - has been established here.[114,115] These structures are characterized by flat northern sides and steeper southern sides, resulting from the overthrusting of the Dzungarian Alatau mountains onto the Zharkent trough. There are no Jurassic deposits here. All these structures were studied during geological surveys and assessed as unpromising for oil and gas based on Cenozoic sediments. The Dzungar monocline is separated from the deeper part of the trough by a large Aktau-Khorgos fault (thrust) of sub-latitudinal strike with an amplitude of up to 1.5 km.[116] This fault, in the western part of the Dzungarian monocline, changes its strike to the southwest and separates the Zharkent trough from the Boguty saddle, now referred to as Sharyn-Aktau.[117] To the south of the Dzungar monocline and the Aktau-Khorgos thrust is the Pidzhim structural-tectonic step, which is limited by another South Pidzhim thrust. This structural stage spans approximately 15×45–50 km. Within this area, three anticlines have been distinguished: the central Pidzhim structure, which is prepared for drilling, the Khorgos structure to the east, and the Panfilov (Zharkent) structure to the west, the latter of which remains insufficiently studied.

Adjacent to the step along the thrust from the south is its lowered part, the South the Pidzhim sub-thrust semi-anticline measuring up to 15×1.5 km, limited along the Paleozoic surface (RH-V) by isohypsum – 3750 m (Figs. 8 and 9). Sub-thrust part of the structure adjacent to the South Pidzhim thrust from the south can be traced on CDP time sections quite confidently both in the data of the 1980s and 2007 in Fig. 10. Seismic exploration of CDP-2D at the Pidzhim structure in 2007 was performed on a limited area without covering the adjacent Panfilov (Zharkent) anticline to the west and the east of the Khorgos anticline (Fig. 10). On structural maps constructed using 2007 data, the Pidzhim structure appears similar to those from the 1980s along RH-I-IV, with no noticeable displacement of the arch across different horizons.

On maps based on RH-I-V contouring isohypses, its amplitude is 500-600 meters, with an area of 56-63 square kilometers. At the same time, on the eastern flank, the apical part of the structure is more clearly visible with a sharp increase in amplitude along all RHs I-V, and the western half looks like a flat anticlinal part. But along the RH-V (basement surface) another peak is localized in the west of the structure. The seismic geological section constructed along the line of wells 4-T – 1-P clearly shows the ratio of the thicknesses of stratigraphic units relative to the boundary of the main oil


(a)
3 0 3 6 km
46
79
76
Pidzhim
South Pidzhim
7-T
2966
4-T
3315 (Pz3315)
Legend
Drilled well
Recommended well
8503 46 CDP profiles
Contour lines on the base of the Cretaceous (III RH)
(b)
S
N
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 km
0.0
1.0
2.0
3.0
T (sec)
North Pidzhim thrust
N
P
K
J
Pz
Pidzhim
South Pidzhim
I
II
V

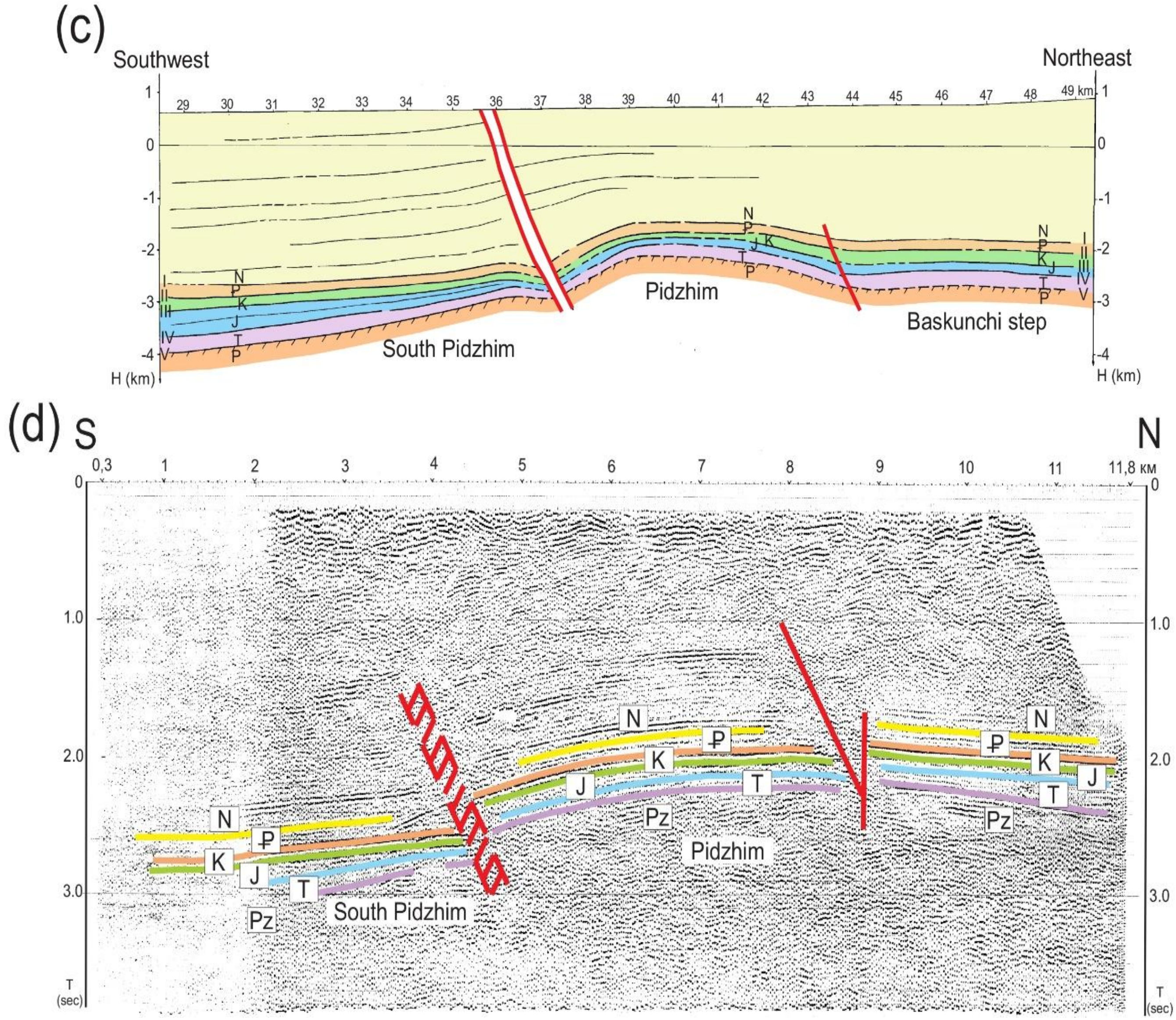


Fig. 7: Structure of Pidzhim. (a) Structural map at the base of the Cretaceous, (b) Western pinch-out, seismic profile 79, (c) Seismological section, profile 46-46, and (d) Seismological section, profile 86-76.

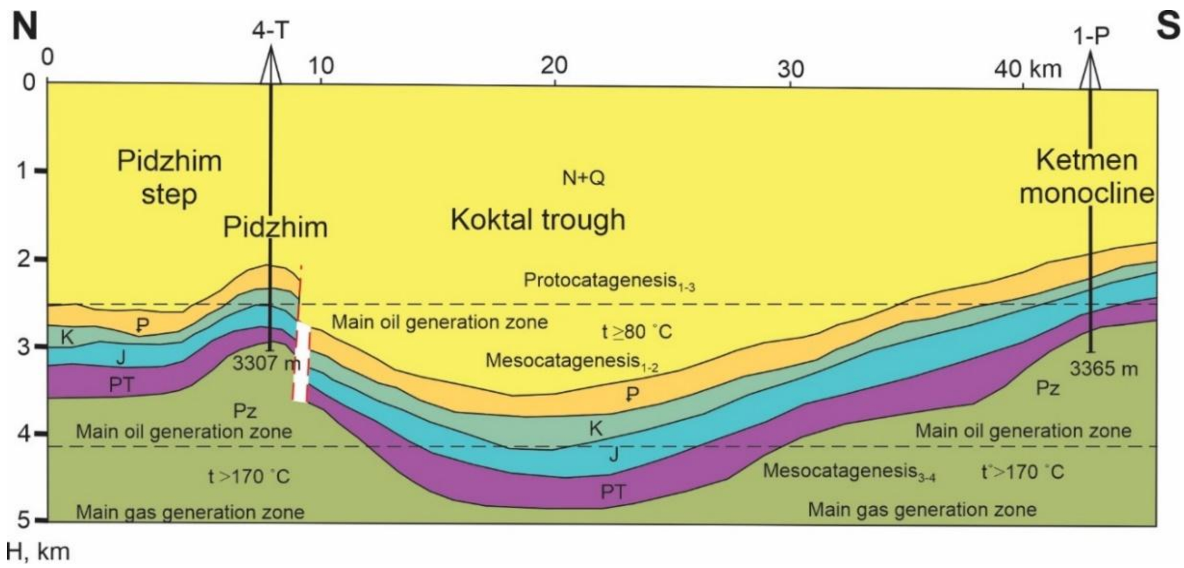


Fig. 8: Zharkent trough. Seismogeological section along the line of wells 4-T - 1-P.

generation zone. The position of the Pidzhim structure with the MOGZ is optimal (Fig. 8). The southern side of the Zharkent trough is located in the interval from the center line of the Koktal syncline in the north to the Ketmen ridge in the south.[118] The first information about its geological structure as a monocline was obtained from seismic surveys conducted between 1955 and 1960 and remained unchanged in subsequent CDP data from the 1980s and 2007. The Kara-Kum structure, assumed in the southeastern part of the area based on reflection wave method RWM data from 1959–1960, was not confirmed in Mesozoic deposits according to CDP data from the 1980s.[119]

In the western part of the trough near the Sharyn-Aktau fault, three structures were identified that were recommended for further study: Sharyn and North Sharyn on the left bank of Ili, according to CDP data from the 1980s,[120] and Aidarly on the right bank of Ili according to CDP-2D 2007 data.[121] The southern monoclonal side is complicated by RH-V with three protrusions similar to a structural nose. The largest of them (I), measuring up to 30×6-8 kilometers with a sub-meridional strike, begins in the north at the Koktal syncline, where it divides the syncline into two parts, like a saddle. In the south, it extends to the riverbed, or possibly further along the left bank. The CDP profiles from 1980 on the left bank are also oriented in the meridional direction at intervals of 10–12 km, which does not allow for resolving the issue of the continuation and size of the protrusion to the south on the left bank.[122] This amplitude in the cross-section (west-east) is about 300 m and it is presented on a fragment of the time section along profile 07 - 14a, near the Ili channel its amplitude is already 100-150 m (Fig. 9). The possible significance of this high is that it may serve as a barrier to hydrocarbon migration and create conditions for the formation of non-anticlinal traps in Mesozoic, and possibly Paleozoic, sediments.

In other basins, particularly in the South Turgai basin, anticlinal and other traps can form on such ledges (horst-anticlines), provided there are complications such as faults and terraces.[122] Complications of this type on the Koktal ledge are absent in the RH-V data and the overlying sediments, according to CDP survey data from 2007, but they may exist in the Ili riverbed zone and on its left bank, where seismic profiles from the 1980s are located 10-12 kilometers apart. Two smaller protrusions resembling a structural nose are identified in the southern part of the 2007 CDP survey, in the Ili riverbed area (between lake Osek and the Ili River). The larger of them II has a northeastern strike with dimensions of 12×3 km in the depth range along the RH-V isohypses from 2.1 to 2.9 km and borders on object III. Object III is located to the north, has a northwest strike with dimensions up to 7×3 km, and is along the RH-V in the isohypsum interval from 2.9 to 3.0 km. Object II is noteworthy in that its long axis is located on the CDP 06 profile and in that the 1-P Zharkent and 3-T wells, which are used to identify reflective horizons, are located on this profile. And on the structural nose along the exhaust gas horizon - V in its middle part, there is an interval with a reduced gradient of depth changes. That is, against the background of the structural nose there is a gently sloping terrace-like area (Fig. 10 (a)). And deeper, along the reflecting horizon RH-V this terrace corresponds to a tectonically disturbed block, possibly a fragment of a former anticline in Paleozoic deposits. On the neighboring 05 profile, located 2-2.5 km to the south, another object appears - the pinch-out of Jurassic and Cretaceous deposits under the regional Paleogene clay cover. This may be a prerequisite for the discovery of non-anticlinal traps here in the floodplain of the Ili river (Figs. 10(b) and 11). The appearance of structural complications against the background of the monoclonal side of the trough in the floodplain of the Ili River may be a sign of a more complex tectonic environment, including faults that contribute to the formation of oil and gas traps on the left bank.[123]

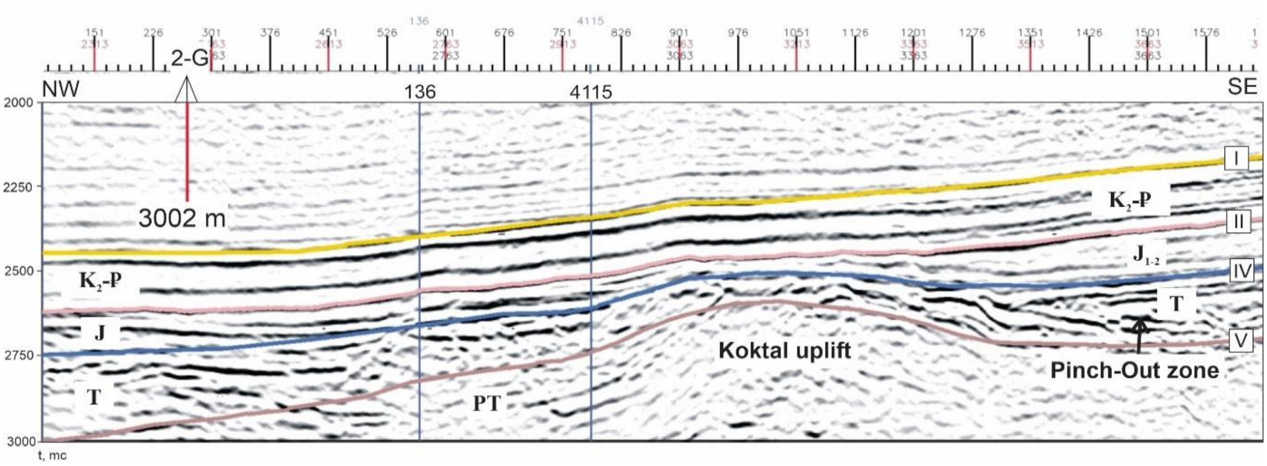


Fig. 9: Zharkent trough. Seismic section along profile 07 - 14a.

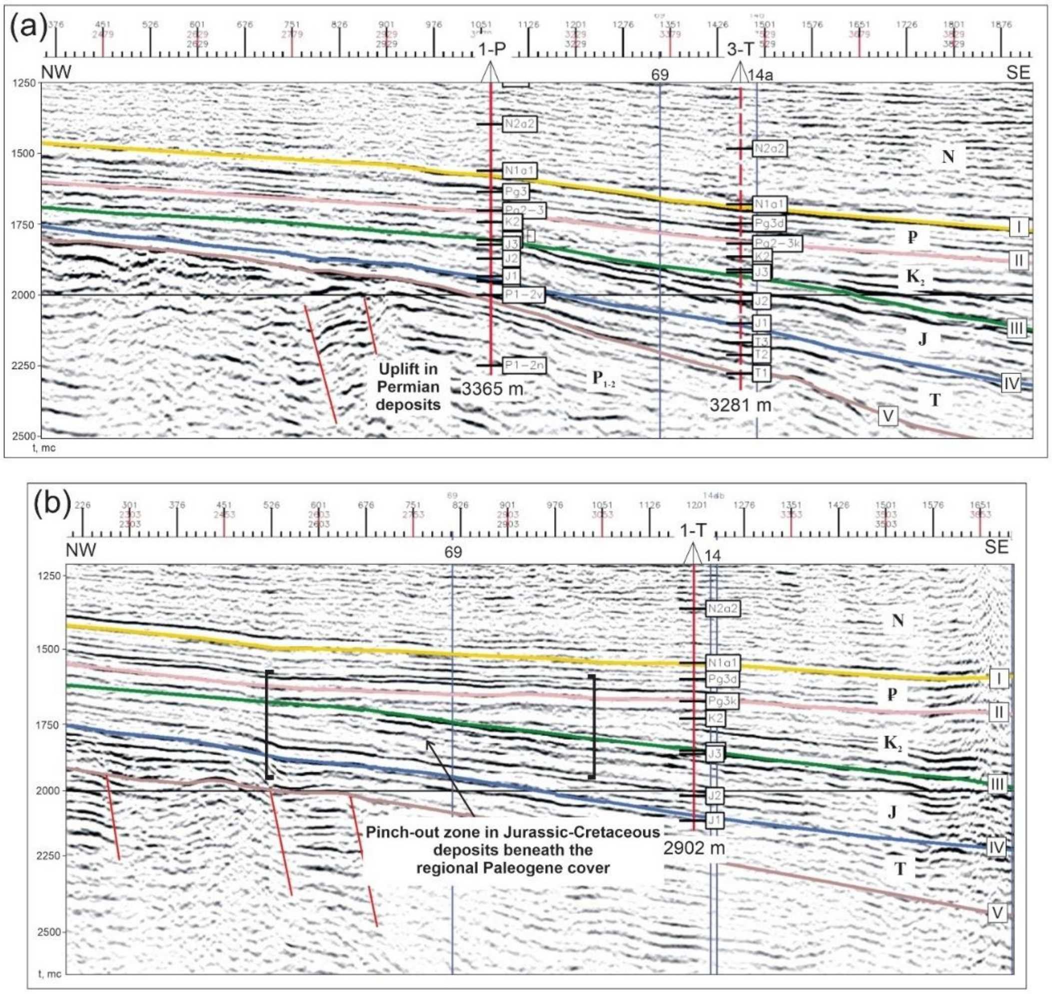


Fig. 10: Seismic section along profile for Zharkent trough. (a) Line 07 - 06 and (b) Line 07 - 05.

2.4 Assessment of oil and gas prospects

Available geological data on the Ili depression suggest that the Zharkent trough and, to a lesser extent, the Almaty trough are promising for oil and gas potential.[103] There are no oil and gas outcrops in the Zharkent trough, only on its continuation to the east within the PRC near the city of Kuldzha. I.V. Mushketov noted occurrences of oil in Jurassic deposits in the ravines of the Mailisu stream and south of the trough in the mountain frame on the Ketmen ridge, where bituminous limestones of the Visean stage were discovered. Signs of possible gas content in the Zharkent trough were identified between 1955 and 1960 based on geological survey data using mapping and structural prospecting drilling in its northern part, with shallow depths (400–1000 m) reaching the Paleozoic basement. During the same period, deep drilling was conducted in other parts of the trough, resulting in the completion of seven deep exploratory wells for oil and gas. In deep hydrogeological wells drilled between 1980 and 1991, no oil or gas shows were detected. All deep oil exploration and hydrogeological wells were drilled outside of prepared anticlinal structures.

In the mapping wells, there was degassing of the drilling fluid, the manifestation of gas dissolved in water, and weak manifestations of flammable gas in adyr structures. In well 96 at the Khorgos structure, degassing of the drilling fluid with hydrocarbon gas content up to 12-79% and helium at 1.6% was observed. In the Koibyn structure, well 55 exhibited a weak release of flammable gas from the Oligocene sand pack in the interval of 320-420 meters. Similar manifestations were observed in the Aktau, Zhambylbastau, Baskunchi structures, and others.[124] Nitrogen gas with a helium content of up to 1-2% and a low content of hydrocarbon components. Perhaps these gas manifestations are the influence of the Aktau-Khorgos fault (thrust) with an amplitude of up to 1.5 km. Based on the results of the work performed, the deposits of the Cenozoic complex were assessed as unpromising for oil and gas. There were no inflows of oil and gas in deep wells. Only degassing of the drilling fluid and the presence of dissolved gas were observed during reservoir horizon testing.

In well 1-G (2800 m), degassing of the drilling fluid was observed when drilling Neogene sandy-clay deposits in the interval 1442-2016 m. During testing, influxes of water with dissolved gas were obtained, which consisted of 72-92%

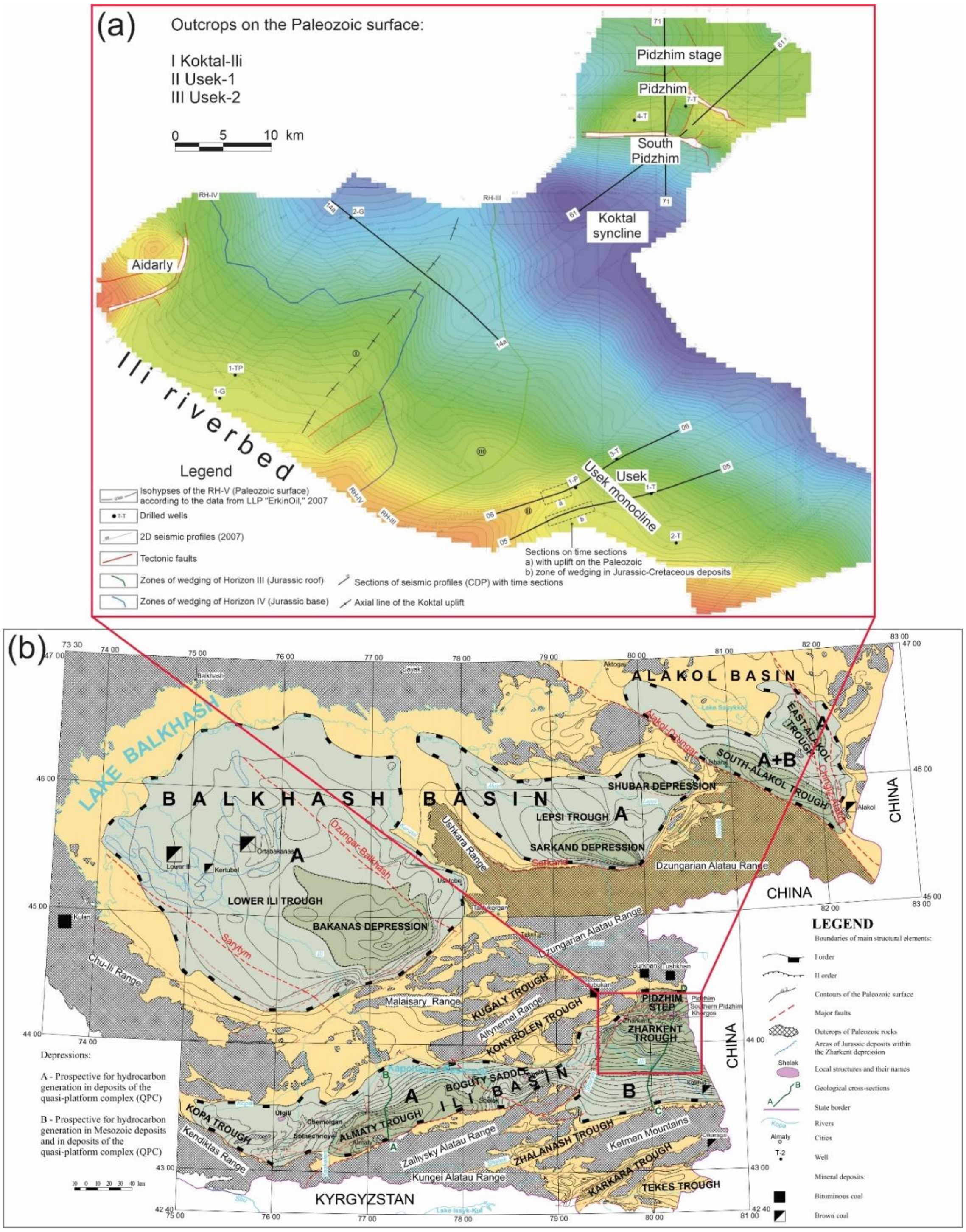


Fig. 11: (a) Ili riverbed, (b) Composite map of oil and gas (Alakol, Balkhash and Ili basin prospectively).

nitrogen, 0.87-11.75% methane, 0.73-2.1% ethane, and 0.1-0.15% butane. In well 3-G (2150 m), gas shows were observed from the Permian effusive-sedimentary strata in the intervals of 2919-2971 m and 2977-2992 m. When testing them, an influx of highly degassed water of the chlorine-calcium type was obtained. Nitrogen gas containing helium 2.5%, methane 0.15%, and CO_2 2%. From the intervals of 2861-2880 m and 2842-2770 m, there are inflows of calcium chloride-type water with a methane content of up to 22.4% and mineralization of up to 8.5 g/l. Here, from the Triassic-Jurassic deposits, an influx of salt water with a flow rate of 128 m^3/s and a gas factor of 18 m^3 was obtained. In Permian deposits, the content of chloroform bitumen was 0.14-0.39%, and in Triassic deposits, it was 0.1%, and in overlying deposits, it was no higher than 0.004%. In the area of well 4-G Koibyn (915 m), weak releases of flammable gas were recorded from intervals of 320-420 m in Neogene deposits (structural well K-55). In well 5-G Bestyube (2400 m), gas shows were noted from Neogene deposits in the interval 2265-2275 m. The total gas content is 3-9%, of which hydrocarbon components account for up to 23-63%.

In well 6-G, a strong inflow of fresh water was obtained from chalk deposits at a depth of 860 m, and during drilling of the interval 1015-1025 m with coal seams, gas anomalies with a methane content of up to 15% were noted. From 1390 to 1440 m in the Upper Triassic, the content of combustible components in the siltstone-mudstone strata ranged from 0.2% to 5%. A spontaneous outflow of salt water with a gas factor of 0.06 m^3 was obtained from the chemogenic-terrigenous strata of the Upper Permian. In well 7-G (1400 m), a helium content of up to 1.2% was noted from Permian deposits in which water salinity reaches 21 g/l, and degassing of the drilling fluid during excavation of Jurassic and Triassic deposits. In the parametric well 1-P Zharkent, drilled in 1998–1999, no oil or gas shows were detected, and all reservoirs identified from GIS data were assessed as water-saturated. Similarly, no manifestations were observed in deep hydrogeological wells drilled between 1980 and 1990. However, in wells 1-T (1980) and 4-T (1983), oil seepage through concrete bollards at the surface was discovered years after abandonment. During an inspection in 2007, well 1-T showed an outflow of saltwater with oil, and after sedimentation, a 30 cm column of oil was observed in the well. However, repeated logging did not identify oil-bearing horizons.

The results of the re-inspection of well 1-G were assessed as the consequences of eliminating stuck drilling tools using an oil bath. In the hydrogeological well 4-T on the western pericline of the Pidzhim structure, the bollard was not opened, and the oil show was probably also a consequence of the “oil bath”. But, there is a peculiarity that this oil-like fluid, corresponding to the specific gravity of heavy oil, is not flammable. It is appropriate to note here that in the neighboring Zhaisan basin, heavy oil from the Upper Triassic and Lower-Middle Jurassic deposits in the Eastern Sarybulak field also does not ignite. The reason for this is that this product is an oil-water emulsion with a water content of up to 15-20%, and dehydration of oil is difficult. However, a key question remains unresolved: from which sediments and at what depth does the oil-like fluid originate? Tests in hydrogeological wells 4-T and the nearest 7-T were carried out only on Cretaceous aquifers. The question of the nature of this manifestation will probably be resolved when prospecting for oil and gas is resumed. Based on data on the geological structure and signs of gas content in the Upper Paleozoic and Mesozoic deposits, two complexes of potential gas and oil fields are identified - Upper Paleozoic-Triassic and Mesozoic-Cenozoic. The main fluid seal for the first is the chromogenic-terrigenous strata of the Upper Permian; for the second, the clayey strata of the Miocene and Paleogene can serve as a regional seal.

The Upper Paleozoic-Lower Triassic complex is of interest mainly for the search for gas deposits formed at the Paleozoic stage of the basin's development. This zone has a favorable hydrogeological situation and high gas saturation of aqueous solutions, which makes it possible to predict the discovery of gas deposits. Lower Permian black clay rocks of the coastal-marine effusive-terrigenous formation and Triassic coal-bearing sediments can be used as oil and gas source rocks. These deposits in the Zharkent trough are comparable to the Permian sedimentary sequence in the Zhaisan depression, where oil shale is known in the Kenderlik field, and heavy oil was obtained from the Upper Permian Maychat formation in the Sarybulak field. In well G-3 of the Zharkent trough, bitumen “A” was obtained from the Lower Permian with a content of 0.19-0.39%. The Mesozoic-Cenozoic complex includes a series of terrigenous rocks contained between the gas-resistant strata of the Permian-Lower Triassic and the clayey strata of the Miocene. As oil and gas source rocks, there may be carbon-bearing gray deposits of the Jurassic and Upper Triassic with a thickness of up to 700-900 m in the Kazakhstan part of the trough and up to 2000 m in the People's Republic of China (Chapchal well). They are distributed mainly in the Koktal zone at the Pidzhim stage and the east of the North-Ketmen monocline.

In the neighboring Zhaisan depression, oil-bearing deposits are the Jurassic sediments of the Tologoi formation (J_1 - T_3) and the Kust formation (J_2 kt) under the regional cover of Lower Paleogene clays, as well as oil and gas deposits of the Upper Permian. The Sarybulak deposit may be the closest analog for comparison with the Pidzhim promising structure. At shallow depths in the Kolzhat coal deposit, coals are weakly metamorphosed to the P-C_3 stage, but when buried to depths of up to 2.5-3 km, they can be a source of flammable gases. In the trough, granular reservoirs are widely developed throughout the section. In the Upper Permian, the porosity of sandstones ranges from 7% to 17%, with permeability up to 6 m/darcy; in the Triassic, porosity increases to 18-23%. In gray-colored sediments of the Upper Triassic-Jurassic, reservoirs occupy up to 50-70%, porosity up to 20-26%, and permeability up to 1800 m/darcy. Reservoirs in Cretaceous-Paleogene and Neogene deposits are well-sorted sandstones with a porosity of 20-30%, from which a water influx was obtained with a flow rate of 1500-4000 m^3/day, which indicates their high permeability and capacity. The main seals (clays) are found in the Upper Triassic, Paleogene, and

Miocene. In the internal parts of the trough, thick layers of clay appear in the Jurassic section. In the lower parts of the Upper Permian, the seal-fluid seal may be a dolomite-limestone stratum.

From the above information, it follows that in the Zharkent trough, there are real prerequisites for the generation of oil and gas from potential oil and gas source rocks: Lower Permian dark-colored clayey rocks and Triassic-Jurassic gray-colored coal-bearing deposits. There are also potential terrigenous chromogenic strata of the Upper Permian (fluid seal for the Lower Permian deposits) and clayey strata in the Jurassic, Paleogene, and Miocene deposits. But to realize the prerequisites for the generation potential of oil source strata, a long-term and stable influence of two factors on them is necessary: temperature and pressure. Such conditions exist in the Zharkent trough. There are conditions for the accumulation of migrating hydrocarbons in anticlinal and non-anticlinal traps on the northern side and, possibly, non-anticlinal ones on the southern monoclinal side. The effect of temperature on the process of hydrocarbon generation is determined by the magnitude of the geothermal gradient and the depth of occurrence of petroleum gas (in the main zones of oil and gas formation). For intermountain depressions, according to data on CDOM catagenesis, the MOGZ is located in the depth range from 3 to 6 km, and the MGGZ is from 6 to 9 km. The potential in the trough is somewhat reduced by the predominantly humus composition of the DOM, which consists of the remains of higher vegetation with reduced generation capabilities (compared to sapropel DOM).

In all sedimentary basins, the main oil generation zone (MOGZ) is confined to the gradation of catagenesis of DOM from the end of P-C_3 to 1-mesocatagenesis (MC-1) and to the end of 2-mesocatagenesis (MC-2), which corresponds to temperatures from 80-90 °C to 150-170 °C, and for the main gas generation zone (MGGZ) temperatures from 180 °C up to 250 °C.[16] The depressions under consideration (Alakol, Balkhash, and Ili) belong to the class of alpine troughs. The thermal regime of these troughs can be characterized by the magnitude of the geothermal gradient. For the Zharkent trough, stock materials contain data on measuring temperatures in deep wells (Table 1).

According to these averaged data (2.7º /100 m of section), a depth of 2 km should correspond to a temperature of 54 ºC, 3 km - 81 ºC, 4 km – 108 ºC. This is an approximate estimate based on a limited database, but it indicates the low-temperature regime of the Zharkent and Almaty troughs, which is typical for intermountain alpine basins, compared to the generally accepted average value of G.g. 3.3º /100 m. In the Zhaisan Depression, the Sorbulak-1 well recorded a temperature of 100 °C at a depth of 4400 meters. This adversely affects hydrocarbon generation, delaying its onset and shifting it to greater depths. Paleotemperature measurements in this region are available only for the Zhaisan depression.

In the Almaty trough, the sedimentary complex is represented by sediments identical to the Zharkent trough but, only from the Upper Cretaceous to the Neogene, by continental red molasse with alternating sandy and clayey strata. There are no oil and gas manifestations (there are no Lower Cretaceous and Jurassic deposits).[125] The maximum depth of the sedimentary complex is located in the area of Almaty and its immediate surroundings, where the basement surface is located at elevations from -2.0 km to -2.4 km. The depth, taking into account the altitude of the daytime relief of 500-700 m, is about 3 km. All hydrogeological wells in the Neogene contain fresh water, that is, most of the section is located in the zone of free water exchange.[14] No reliable data exist regarding the internal structure of the Paleozoic complex. Deep wells 1-T, 2-T, 3-T, and 8-T have encountered Paleozoic effusive deposits. With a maximum thickness of the

Table 1: Geothermal gradients of wells in the Ili depression

Well	Depth Interval (m)	Temperature, ºC	Gradient (°C/100 m)	Years of Study	Remarks
1-G	394-2068	21.5-79	3.43	1956-1960	
5-G	447-1600	24.3-46.9	1.95		
1-TP	400-2800	22.0-89	2.79		Average value for items 1-8 G.g. = 2.70/100 m for depths up to 2900 m
1-T	20-2617	12-85	2.81		
2-T	20-2750	12-85	2.68	1980-1990	
3-T	20-2350	12-79	2.88		
9-T	2950-4140	78.3-107.3	2.44		
1-P	2660-2903	75-81	2.47	1998	
Zharkent	2903-3275	81-102	5.75		
10-G Almaty KazVIRG	1991-3116	58.7-84.1	2.28	1957	80 °C at a depth of 2900 m

sedimentary complex in the central part of the trough up to 3500 m, the thickness of the Neogene-Paleogene deposits is about 2500 m, and the total thickness of the Cretaceous-Paleogene is about 500 m, Quaternary up to 500-600 m. The deepest well 10-G was stopped at a depth of 3232 m in Paleogene sediments. These data determine the assessment of the Almaty trough as a less promising object for oil and gas, compared to the Zharkent trough. The oil formation zone of about 3 km corresponds to the maximum depth of the Paleozoic surface in the center of the trough in the vicinity of Almaty.

3. Results and recommendations for further work in the Ili depression

In the northern part of the Zharkent trough, there is a Pidzhim tectonic step of latitudinal strike located between the Aktau-Khorgos and South Pidzhim faults (thrusts). Step sizes up to 50×15km. It is divided by faults into several blocks in the basement above which three near-fault anticlines are formed in the sedimentary complex: Zharkent, Pidzhim, and Khorgos. The main promising object for oil and gas exploration in the Zharkent trough is the Pidzhim anticlinal structure and its subthrust part, which was identified by seismic exploration work of the IGE in 1980, and after detailing, it was prepared for drilling in 1987. Between 2007 and 2008 it was again covered by the CDP-2D survey of Erkin Oil LLP. The parameters of the structure are confirmed and there is no fundamentally new information on it. Its dimensions are 15×6 km, amplitude is up to 500 m. The structure is presented according to data from the 1980s and according to 2007 data. Fig. 7 shows that the structure developed inherited from the surface of the Paleozoic to the Neogene in a quiet platform regime with a corresponding uniform accumulation of sediments from the Triassic to the Paleogene inclusive. At the Paleogene-Neogene boundary, accelerated subsidence of the basin began, because of which the accumulated thickness of Neogene sediments (up to 4 km) exceeded the total thickness of the Triassic-Paleogene (1500 m) by 2.5 times.

Thrusts, along which northern structural-tectonic blocks are thrust onto southern ones, are clearly expressed on CDP time sections, including the South-Pidzhim subthrust structure. On the southern side of the trough, previously considered monoclinal based on the 2007 CDP work, signs of non-anticlinal traps are highlighted. The Pidzhim structure was prepared for drilling 33 years ago, and the 2007 survey confirmed all its parameters. Therefore, the primary recommendation is the need to organize test (exploration) drilling at the Pidzhim structure. Positive drilling results will serve as the basis for resuming exploration work in all depressions of South-Eastern Kazakhstan. The assessment of potential hydrocarbon resources for the sedimentary basins of Kazakhstan, including the Ili basin, remains unchanged in the report: for the Almaty trough in the Paleozoic, geological resources are 2073 million tons, with recoverable reserves of 36.8 million tons.[19] For the Zharkent trough in the Paleozoic, geological resources are 146.3 million tons, with recoverable reserves of 43.9 million tons.

The Upper Paleozoic-Lower Triassic complex is of interest mainly for the search for gas deposits formed at the Paleozoic stage of the basin's development. This zone has a favorable hydrogeological situation and high gas saturation of aqueous solutions, which makes it possible to predict the discovery of gas deposits. Lower Permian black clay rocks of the coastal-marine effusive-terrigenous formation and Triassic coal-bearing sediments can be used as oil and gas source rocks as unconventional oil.[126,127]

Despite the high capital intensity of UGS projects, their long-term economic efficiency has been confirmed by international experience. The main costs include geological exploration, infrastructure construction, and operational expenses, averaging $100-150 million for facilities of a similar scale. At the same time, UGS significantly reduces price fluctuations during the winter season, enhances energy security, and creates opportunities for commercial gas storage by third-party consumers. An analysis of similar projects in Europe shows that investments in UGS pay off within 10-15 years, making this project economically justified in the long term.

In addition to geological risks, UGS involves potential environmental and safety challenges that must be considered in project implementation. The main environmental risks include methane leakage, groundwater contamination, and land subsidence, particularly if the storage integrity is compromised. To mitigate these risks, strict monitoring measures are implemented, including regular seismic surveys, pressure and gas composition control, and advanced leak detection technologies. Furthermore, international experience shows that the enforcement of stringent regulatory standards and emergency response systems significantly reduces the likelihood of environmental incidents during UGS operations.

The analysis of previous studies (Fig. 12) indicates that research efforts have predominantly focused on the Ili and Lepsi troughs, while other potentially viable regions remain underexplored. This may be attributed to historical data availability, the strategic significance of these areas for hydrocarbon exploration, and the relative accessibility of geological structures. However, a comprehensive assessment of UGS feasibility requires a broader regional perspective.

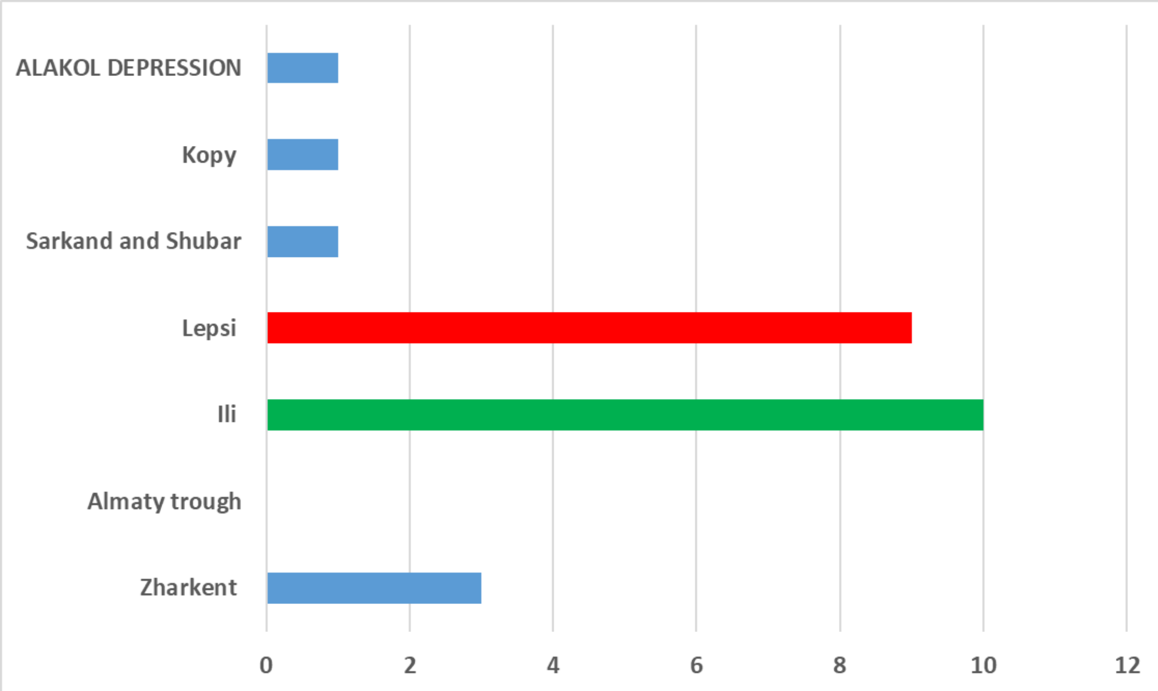


Fig. 12: Number of previous studies for troughs in the study area.

Fig. 13 reveals that approximately 66% of studies concentrated on geological field characteristics, whereas only 21% addressed gas injection processes and merely 13% focused on gas storage mechanisms. This trend suggests that most scientific work has been centered around conventional hydrocarbon exploration rather than adapting geological formations for long-term gas storage. To bridge this gap, targeted research is needed to investigate gas flow dynamics, the impact of injection cycles on reservoir stability, and potential leakage risks.

A deeper statistical examination (Fig. 14) further demonstrates that 73% of studies primarily focus on geological aspects, often overlooking critical properties such as reservoir performance, geomechanics, petrophysical properties, geochemistry, seismic data analysis, and drilling activities. These factors are essential for assessing the efficiency and safety of UGS facilities. For instance, geomechanical studies can help determine the rock formation's resilience to cyclic gas injection and withdrawal, while petrophysical analyses provide accurate insights into porosity and permeability.

Therefore, for a comprehensive evaluation of UGS feasibility in the Zharkent Trough, future research must extend beyond traditional geological assessments. It should encompass a detailed analysis of reservoir properties, advanced modeling of injection and extraction processes,

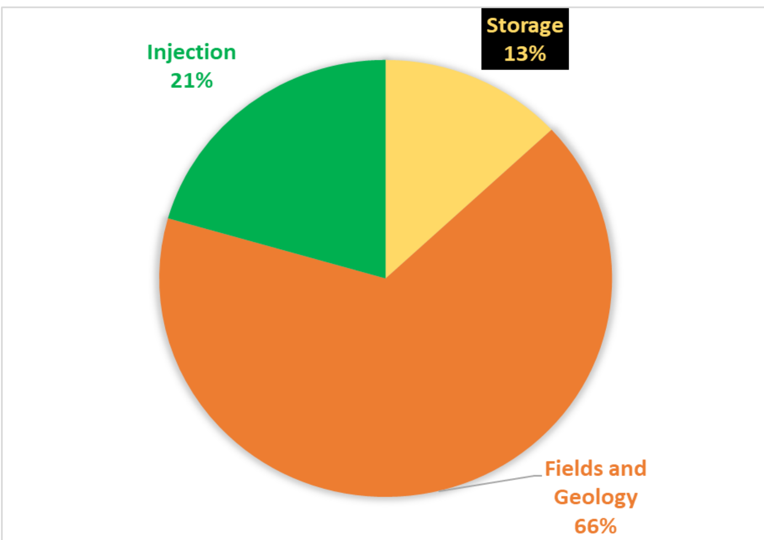


Fig. 13: Subjects covered in the previous studies (Fields and geology, injection, and storage) - in percentages.

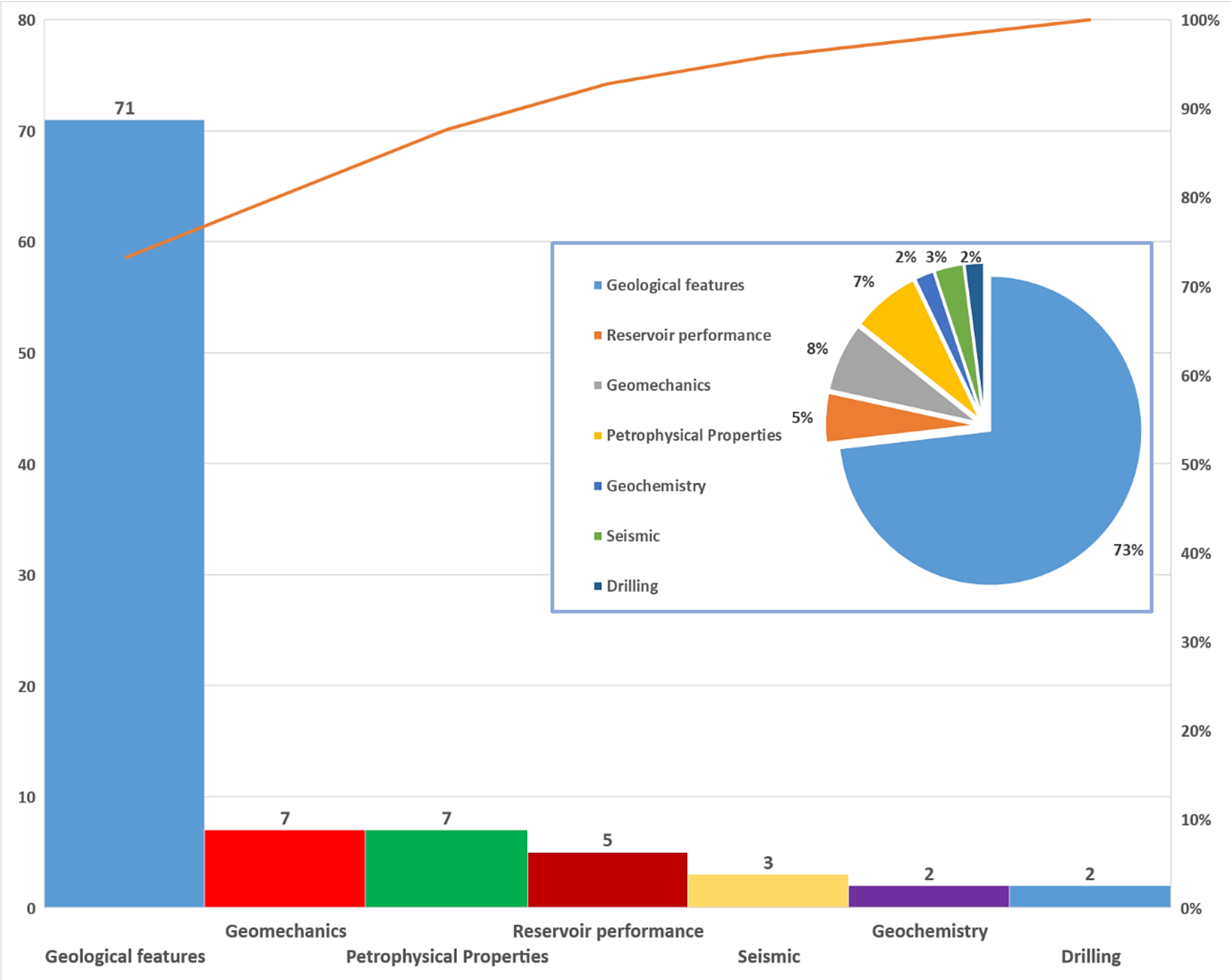


Fig. 14: Geological features in comparison with reservoir performance, geomechanics, petrophysical properties, geochemistry, seismic data, and drilling activities in the previous studies.

rigorous assessment of the mechanical impact of gas storage, and the development of cutting-edge monitoring technologies to ensure long-term storage integrity and operational safety.

4. Conclusion

The exploration and assessment of the Ili depression, with particular emphasis on the Zharkent and Almaty troughs, have revealed significant geological and geophysical insights that underline the potential for hydrocarbon exploration in the region. Positive results from these recommended studies could establish the Ili depression as a key hydrocarbon province, contributing to Kazakhstan's energy security. Continued exploration could unlock renewable geothermal energy development opportunities, leveraging the region's geological settings.

- For geological viability, the Zharkent trough demonstrates favorable geological features for hydrocarbon accumulation, including Upper Paleozoic-Triassic and Mesozoic-Cenozoic complexes with potential oil and gas source rocks.
- Structural features such as anticlines, fault-related structures, and fluid seals, combined with adequate pressure and temperature conditions, support the possibility of hydrocarbon generation and entrapment.
- For exploration challenges, previous exploratory wells have shown indications of hydrocarbons, including degassing of drilling fluids and minor gas shows, but no significant commercial discoveries have been made.
- The absence of detailed seismic exploration and limited drilling data in key promising zones has hindered the complete evaluation of the Ili depression's hydrocarbon potential.
- Enhanced seismic surveys with high-resolution seismic studies must be conducted, particularly in unexplored and underexplored areas like the southern monoclinal side of the Zharkent trough, to better understand structural complexities and identify non-anticlinal traps.
- Drilling deep wells in the Pidzhim structure and associated features to test the identified traps and confirm hydrocarbon presence.

- Further analyze the geothermal gradient and basin modeling to optimize the identification of zones within the main oil and gas generation zones (MOGZ and MGGZ).
- Multi-disciplinary studies combining geophysical, geological, and geochemical techniques can be implemented to refine hydrocarbon assessments.

Therefore, the Pidzhim structure has significant potential for UGS, which could enhance Almaty's energy security and regional stability. Further research should include UGS performance modeling, storage capacity assessment, and evaluation of environmental and economic aspects of project implementation.

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Conflict of Interest
There is no conflict of interest.

Supporting Information
Not applicable.

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