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Geological interpretation of the wave field in Mesozoic and Cenozoic sedimentary complexes of the transition zone between the South Caspian and Middle Caspian Basins using seismostratigraphic analysis method

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ABSTRACT

Purpose. This study investigates the tectonic and sedimentary evolution of the transition zone between the South Caspian Basin and the Middle Caspian Basin. The research aims to analyze seismic stratigraphic sequences to improve understanding of the basin's geological history, sedimentary processes, and hydrocarbon potential. It also seeks to clarify the structural features and tectonic mechanisms responsible for the formation and evolution of this complex geological region.

Methodology. The study employs seismostratigraphy, focusing on seismic sequence and seismic facies analysis. Seismic data were analyzed to identify sedimentary structures, stratigraphic sequences, and tectonic features. The seismic sections oriented in northwest-southeast and northeast-southwest directions were divided into ten seismic stratigraphic sequences (SS-1 to SS-10). These sequences were studied to determine their depositional environments, tectonic settings, and reflection characteristics. Seismic facies analysis helped interpret depositional conditions and sedimentary dynamics within each sequence, contributing to identifying structural traps and hydrocarbon reservoirs.

Results. Key Seismic Features: Features such as onlaps, toplaps, pinch-outs, clinoforms, and erosional truncations were identified, suggesting favorable conditions for hydrocarbon accumulation, particularly in SS-3 (Upper Cretaceous), SS-5 (Maikop Series), and SS-7 (Productive Series). Tectonic Evolution: The region's tectonic evolution includes subduction, rifting, and the platform development. These geodynamic processes controlled the sedimentation conditions and structural deformations. Seismic Reflection Patterns: Seismic reflections indicate significant variations in sedimentation rates and depositional environments. For example, Jurassic and Lower Cretaceous sequences (SS-1 and SS-2) show chaotic and discontinuous reflections, while Late Pliocene and Quaternary sequences (SS-8 and SS-10) have continuous, high-amplitude reflections, suggesting contrasting depositional conditions. Tectonic Influence: Evidence of syn-sedimentary tectonics, including fault-related deformation and subsidence-driven sedimentation, was observed, emphasizing tectonic activity's role in shaping the region's stratigraphy and influencing hydrocarbon distribution.

Scientific Novelty. The study offers new insights into the tectonic and sedimentary history of the transition zone of the South Caspian Basin and the Middle Caspian Basin. It refines existing theories regarding the basin's formation by integrating seismostratigraphy with geological interpretations. The research advances the understanding of subsurface structural complexities, highlighting the interaction of tectonic forces and sedimentary processes in shaping the region's geological framework.

Practical Significance. The findings have significant implications for oil and gas exploration. Key geological structures such as pinch-out zones, onlap unconformities, and erosional truncations provide critical information for hydrocarbon exploration. Particularly, the Upper Cretaceous and Oligocene-Miocene sections show favorable conditions for non-anticlinal traps, suggesting promising exploration targets. The study also highlights the role of tectonic activity in reservoir formation and distribution, aiding future exploration and drilling efforts in the region.

Keywords: *South Caspian basin, Middle Caspian basin, seismostratigraphic analysis, reflection, seismic sequences, seismic facies analysis, seismic sections, sediments.*

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Introduction. This study focuses on the western flank of the transition zone between the South Caspian Basin (SCB) and the Middle Caspian Basin (MCB). Tectonically, this region represents the marine extension of the southeastern termination of the Greater Caucasus Meganticlinorium [17] (Fig.1).

The question of the timing and mechanism of the SCB formation has long been a subject of debate, with several theories proposed regarding its genesis. One perspective suggests that this basin is a relic of the Greater Caucasus-South Caspian-Kopetdagh marginal sea (also referred to as the Greater Caucasus marginal sea) and represents a product of back-arc rifting and spreading associated with the development of a magmatic arc. The buried structure of this arc is well-imaged on seismic profiles, extending from Talysh through the Saatly-Geychay-Mingachevir Mesozoic uplift zone and further beneath the Alazani Valley towards the Black Sea [29].

Another hypothesis posits that the SCB formed as a result of the closure of the Mesozoic Tethys Ocean [15,16].

Another perspective views the SCB as an oceanic pull-apart structure formed through rifting along a Late Cretaceous strike-slip zone parallel to the Caucasus and Kopetdagh [24].

A different hypothesis interprets the SCB's formation as a result of meridional rifting. Additionally, it has been suggested that the SCB could have emerged due to the densification of mafic rocks in the lower part of the continental crust, driven by a phase transition from gabbro to eclogite, leading to increased density and subsidence [5].

Despite the abundance of theories, the insights from ultra-deep seismic sounding using the Common Depth Point (CDP) method cannot be overlooked. These data reveal rift-related extensional structures on the marginal part of the Turan Plate in the Central Caspian, a buried volcanic island arc in the Kura Depression, the subduction of thin oceanic crust beneath the thick (25–28 km) sedimentary cover of the SCB, and the complexly deformed accretionary prism structures with associated compressional features [10].

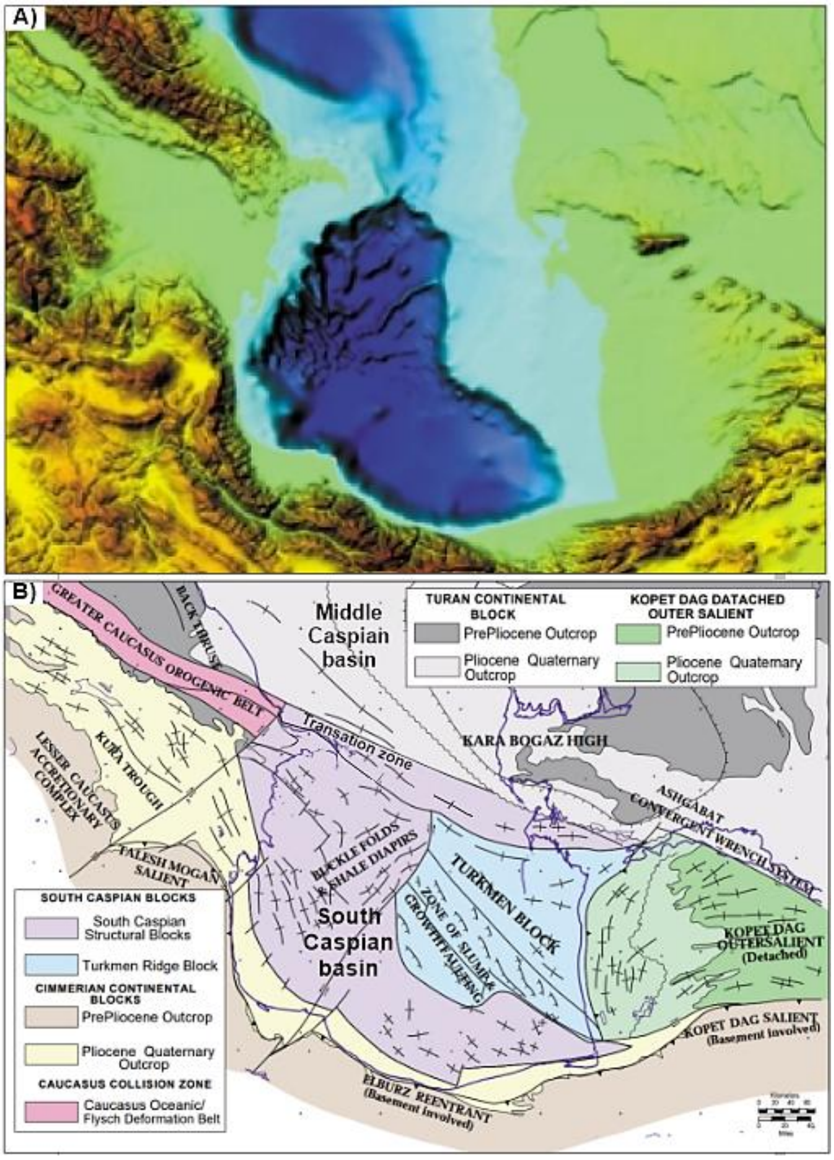

Fig. 1. A) Combined bathymetric and topographic map of the South Caspian Sea and its surrounding regions. The elongated subsea ridges visible in the bathymetry correspond to prominent anticlinal folds beneath the seafloor; B) Key structural features of the South Caspian Sea and adjacent areas [adapted from 3, 6, 11, 21, 22, 26]

The convergence zone between the SCB and the MCB, recognized as the primary oil and gas generating area of the region, has been a subject of research for several decades [2]. The SCB, characterized by the Absheron-Prebalkhan tectonic zone, originated and evolved within the Alpine-Himalayan orogenic belt. The sedimentary fill of the SCB remains relatively undeformed in certain areas compared to the neighboring folded and thrust complexes of the Caucasus, Kopetdagh, and Elburz regions (Fig. 1).

The South Caspian lithosphere is believed to subduct beneath the continental lithosphere of the MCB in this area [1, 8, 9, 13, 14, 18]. The formation of the SCB is attributed to various periods, including the Paleocene, Late Jurassic, and Early Mesozoic [12]. The SCB's sedimentary fill comprises over 20 kilometers of Mesozoic to Cenozoic deposits [7].

Materials and methods. Seismostratigraphy was employed as the primary method in this study. This geological technique is widely used for the stratigraphic interpretation of seismic data. Seismic reflections are generated from physical surfaces that exhibit abrupt changes in properties such as density and velocity, with unconformity and stratification surfaces serving as key boundaries between layers [4, 20, 27]. The analysis involves both seismic sequence analysis and seismic facies analysis [23, 25]. To achieve the study's objectives, seismic sections from the research area were divided into seismic sedimentation complexes.

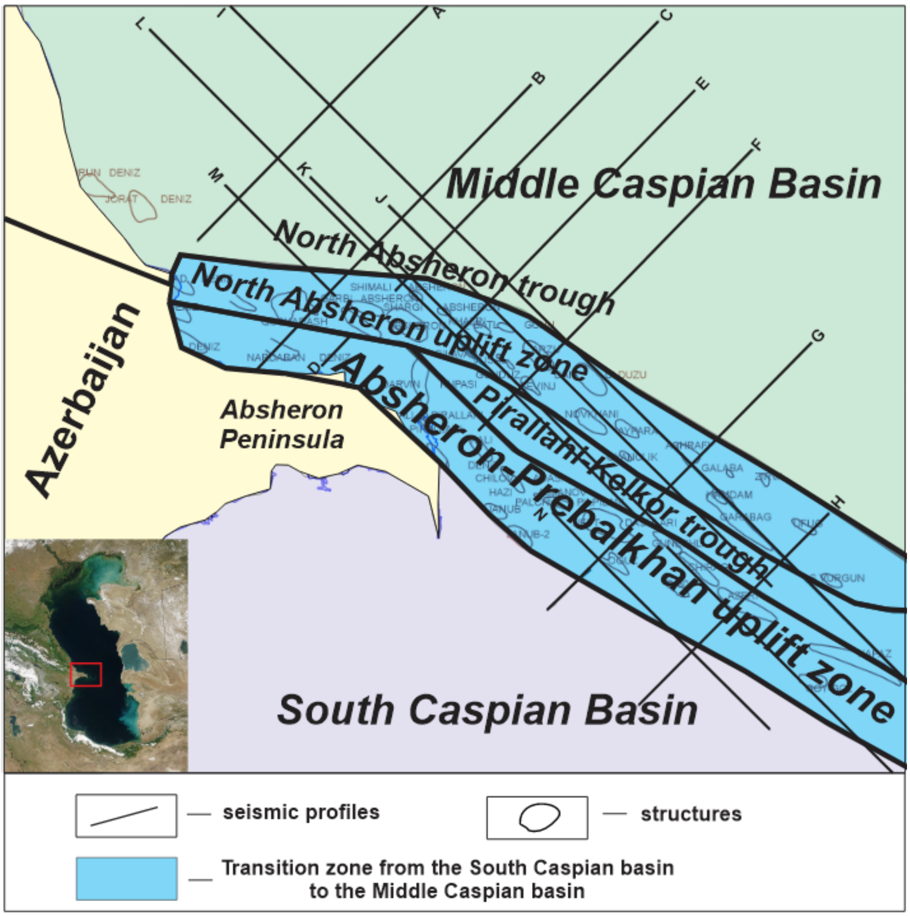

Fig. 2. Location of the study area and the arrangement of seismic profiles

These sections, oriented in the northwest-southeast and northeast-southwest directions, were analyzed to identify ten seismic stratigraphic sequences [19]. Seismic facies analysis was conducted by evaluating the dynamic parameters of seismic reflections within each sequence.

Results and discussion. In the article, seismic sections along 14 seismic profiles in the study area have been analyzed. The seismic profiles and their corresponding seismic sections have been conventionally named from A to N (Fig. 2). The seismic sequences are denoted by the abbreviation "SS" in the article (Fig. 3).

SS-1 and SS-2: These sequences represent Jurassic and Lower Cretaceous sediments. SS-1 marks the period of rift basin formation and opening. During the Late Jurassic, a marine transgression was actively progressing, accompanied by further basin expansion. Time seismic sections provide a clear view of the development of shelves and continental slopes during the process of sea expansion and platform margin inundation in the Middle Jurassic.

The Cretaceous surface exhibits an uneven relief, and in the lower part of SS-2, distinct clinoforms characteristic of carbonate escarpments along the shelf edge are identified. The irregular surface of the reflective boundaries observed in this interval is typical of deposits accumulated in shallow-water basins. Tracing reflections within these sequences is challenging due to their chaotic, low-to-medium amplitude and discontinuous nature (Fig. 4A). Some sections exhibit semi-continuous reflections, particularly near the upper boundary, which are likely associated with volcanogenic-carbonate deposits (Fig. 4B).

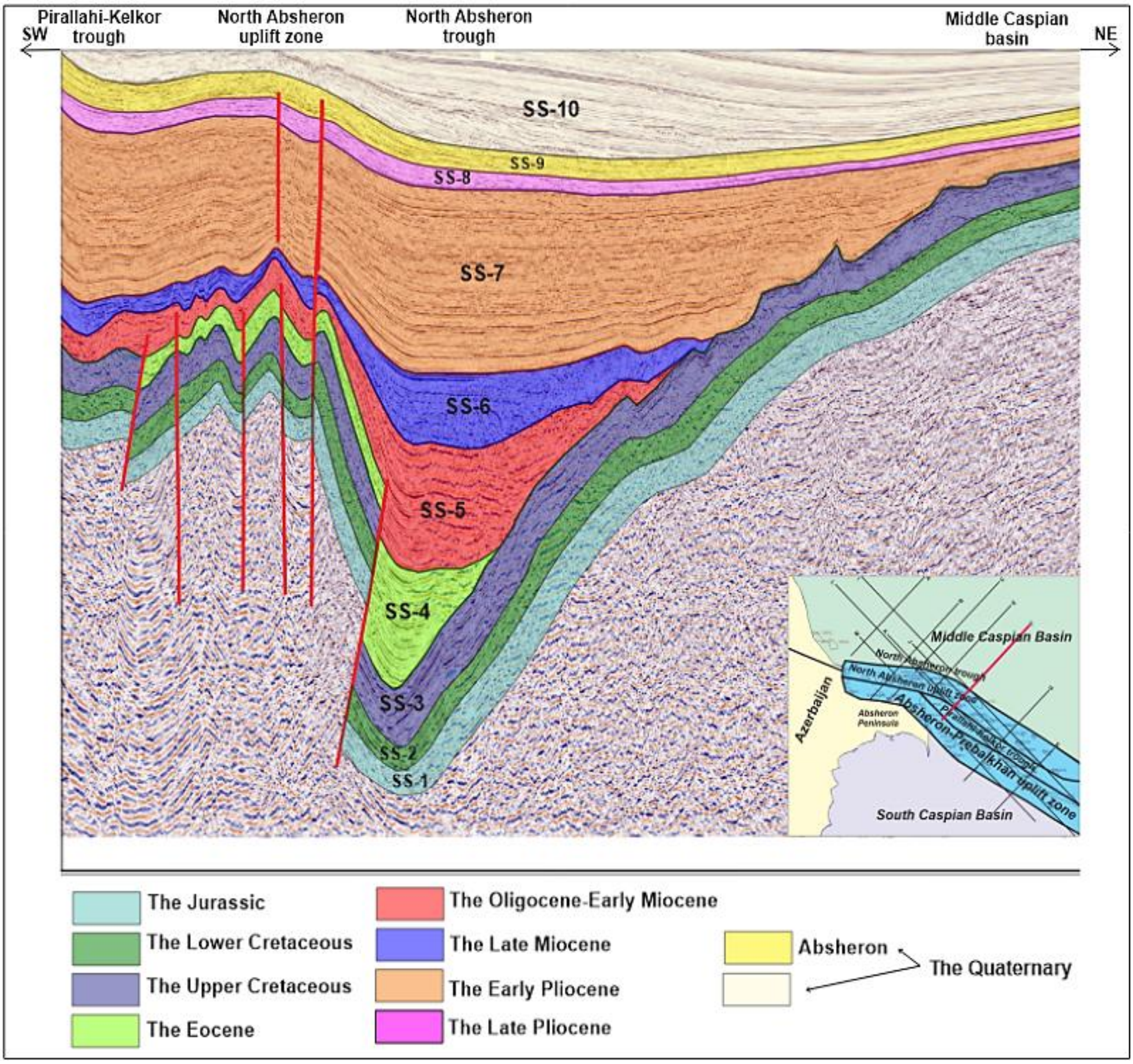

Fig. 3. Seismic sequences (SS) separated within the seismic section along the southwest-northeast oriented "F" profile within the study area

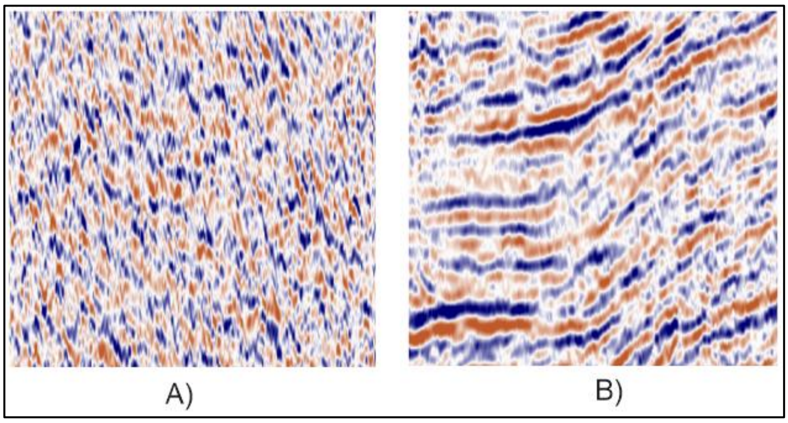

Fig. 4. A) Chaotic (seismic section “A”) and B) semi-continuous (seismic section “B”) seismic reflections within Jurassic and Lower Cretaceous sediments

SS-3: This sequence corresponds to Upper Cretaceous sediments. It is characterized by two distinct phases: low-to-medium amplitude, subparallel, and discontinuous reflections near the lower boundary

(Fig. 5A), transitioning to high-amplitude, continuous reflections near the upper boundary (Fig. 5B). The sea-level drop in the shelf zone led to active rock erosion, contributing to the formation of erosional truncations. Such areas are evident on the eroded surfaces of Upper Cretaceous deposits. Onlap unconformities are evident along the upper boundary, indicative of falling sea levels [28]. Pinch-out zones are observed above SS-3 (Fig. 5C).

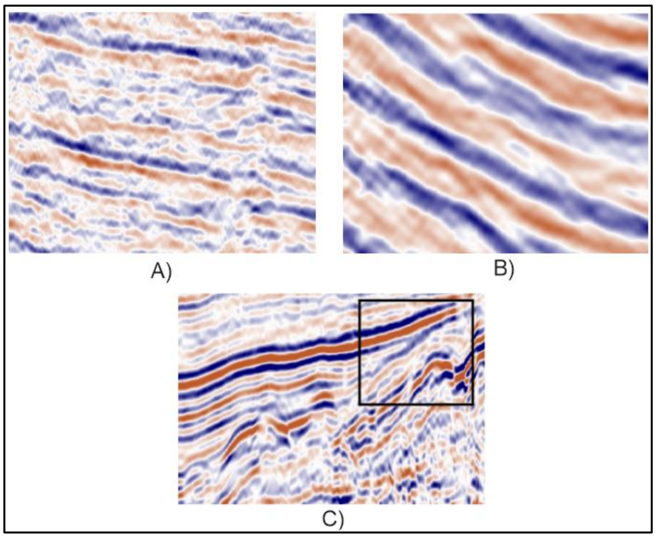

Fig. 5. A) Low-to-medium amplitude, subparallel, and discontinuous reflections (seismic section "N");
B) high amplitude, continuous reflections (seismic section "B");
C) pinch-out zones (seismic section "G") within Upper Cretaceous sediments

SS-4: Representing Eocene sediments, SS-4 lies on Upper Cretaceous deposits in the northern part of the study area. The reflections within SS-4 are weaker in amplitude and frequency compared to the overlying and underlying sequences (Fig. 6A). Paleocene and Eocene deposits lie on the eroded Cretaceous surface in the northern and north-northeastern parts of the area. The Eocene interval is predominantly represented by clayey lithofacies, though dense sandstones and fine-grained sands are occasionally encountered. Compared to the Cretaceous and Maikop (Oligocene-Early Miocene) deposits, the Eocene deposits display lower reflection frequency and weaker reflection amplitude. Pinch-outs of Eocene sediments are observed in both the northeastern and north-northeast profiles (Fig. 6B).

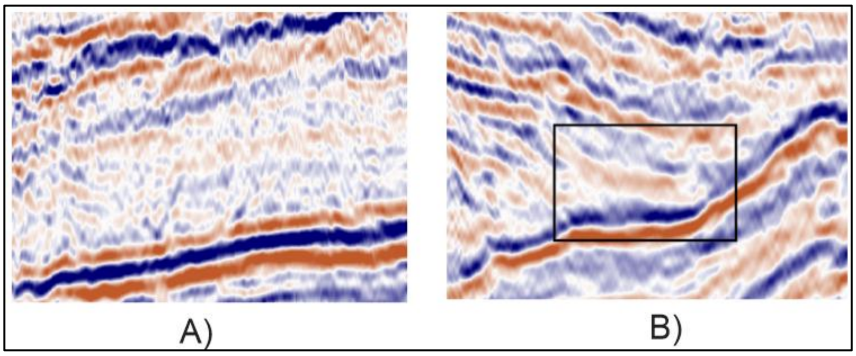

Fig. 6. A) Weak amplitude reflections (seismic section "G") and
B) pinch-outs (seismic section "K") observed within Eocene sediments

SS-5: This sequence represents the Maikop Series (Oligocene-Early Miocene). Seismic reflections within SS-5 are predominantly medium- to high-amplitude, parallel, and semi-continuous (Fig. 7A). Chaotic reflections occur in areas affected by tectonic faults and uplifts (Fig. 7B). The Maikop deposits are primarily represented by clayey lithofacies, as well as sandy-carbonate clays, dense sandstones, and thin interlayers of clay. A detailed analysis of time sections reveals that during the Oligocene-Early Miocene period, the Absheron-Prebalkhan threshold was a zone of relative uplift, separating the South Caspian subsidence area from the Middle Caspian region. Pinch-outs of Maikop sediments overlying Upper Cretaceous deposits are noted in both regional profiles (Fig. 7C).

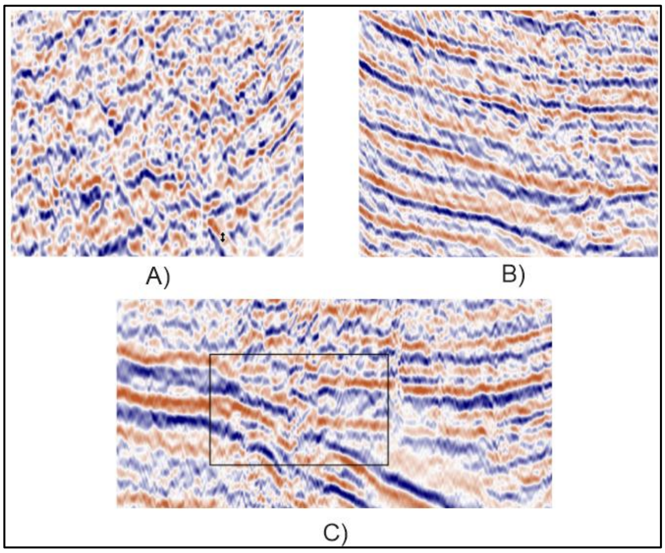

Fig. 7. A) Chaotic reflections (seismic section "J"); B) Medium-to-high amplitude, parallel, and semi-continuous reflections (seismic section "K"); C) pinch-out zones (seismic section "F") within Oligocene-Early Miocene sediments

SS-6: Corresponding to Late Miocene sediments, SS-6 shows nearly uniform thickness across the study area. Near its lower boundary, continuous, subparallel reflections become increasingly chaotic upward, suggesting a high sediment influx during this period (Fig. 8A). In terms of reflection intensity, density, and configuration on time sections, this seismic complex differs both from the Maikop SS-5, represented by lower fine-clastic molasses, and from the overlying seismic complexes associated with the Meotian-Anthropogenic upper coarse-clastic molasses. Erosion truncations at the upper boundary indicate a sharp sea-level drop towards the end of the Miocene. In some sections, synclinal-shaped "hollows" are observed, which may correspond to paleo-riverbeds (Fig. 8B).

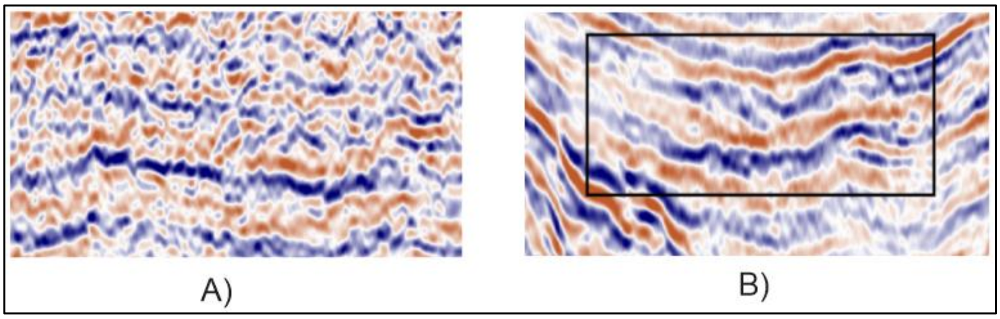

Fig. 8. A) Subparallel and chaotic reflections (seismic section "H"); B) synclinal-shaped "hollows" (seismic section "I") within Late Miocene sediments

SS-7: This sequence represents the Productive Series (Early Pliocene) sediments. Reflections within SS-7 are medium-to-high amplitude, parallel, and continuous, with weaker amplitudes near the lower boundary (Fig. 9A). Analysis of seismic dynamics suggests deep-water basin sedimentation, with a higher sedimentation rate compared to other sequences. The six-kilometer-thick Productive-Red Bed Formation was formed during the Early Pliocene, a period estimated at 1.8-2.2 million years according to a new chronostratigraphic scale. Numerous laterally extensive horizons are observed within the Productive-Red Bed Formation, which are undoubtedly associated with prolonged sedimentation hiatuses. Onlaps are observed in the northeastern direction (Fig. 9B).

SS-8: Representing Aghjagil (Late Pliocene) sediments, SS-8 features medium- to high-amplitude, subparallel, continuous reflections (Fig. 10). Such reflection characteristics indicate uniform sediment accumulation and/or stable conditions at the relatively stable basin-floor.

This suggests that the sedimentation process occurred in relatively deep-water conditions, with these deposits interfacing with unconformity surfaces that bound SS-VIII both above and below, following a toplap and downlap -contacting pattern.

SS-9 and SS-10: These sequences represent Quaternary sediments. The boundary between the two sequences is consistently traced across all seis-

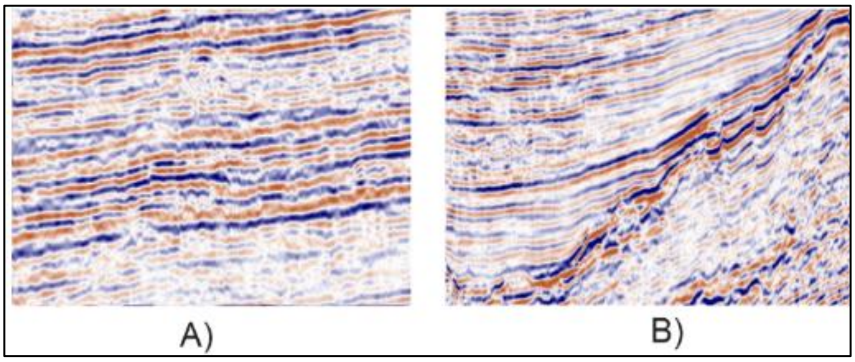

Fig. 9. A) Medium-to-high amplitude, parallel, and continuous reflections (seismic section "M"); B) onlaps (seismic section "E") within Early Pliocene sediments

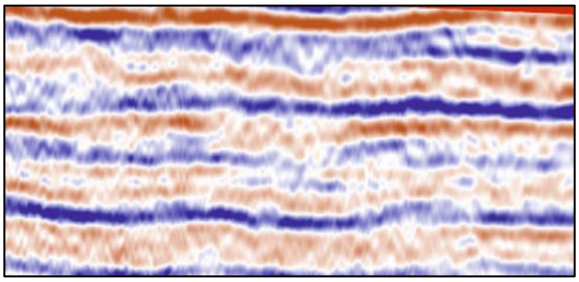

Fig. 10. High-amplitude, subparallel, continuous reflections (seismic section "L") within Late Pliocene sediments

mic sections. Reflections are medium-to-high amplitude, parallel, and continuous, with notable sigmoidal, prograding clinoforms observed within SS-10 (Fig. 11). Analysis suggests an increase in sediment accumulation rates and rising sea levels during sedimentation.

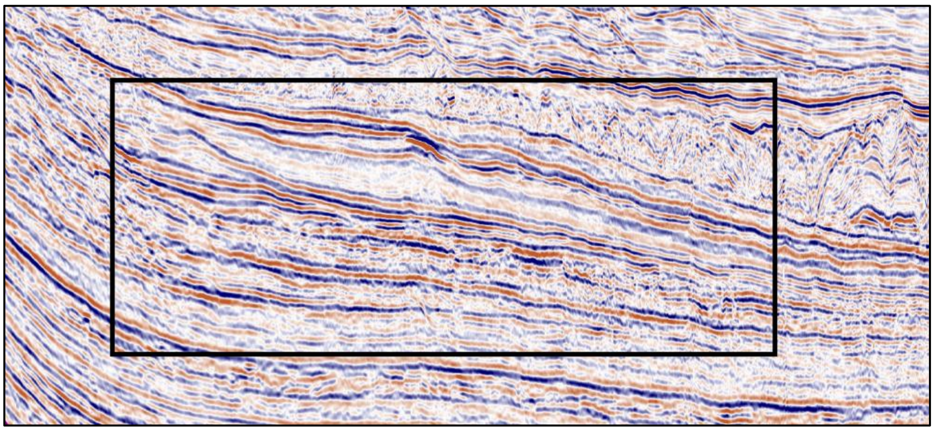

Fig. 11. Sigmoidal, prograding clinoforms (seismic section "C") within Quaternary sediments

Conclusions. This study has provided valuable insights into geological structure of the transition zone between the South Caspian and Middle Caspian Basins, focusing on the region's tectonic evolution and its potential for oil and gas accumulation. The following conclusions can be drawn from the analysis of seismic data:

1. Tectonic and Sedimentary Evolution: The seismic sequences reveal a complex tectono-stratigraphic history for the region, characterized by significant changes in sedimentation patterns linked to both eustatic sea-level fluctuations and tectonic activities, including subduction processes. These changes are reflected in the various seismic sequences identified, ranging from Jurassic to Quaternary deposits.

2. Identification of Key Geological Features: Several key geological features conducive to oil and gas accumulations were identified through seismostratigraphic analysis. These include onlap, toplap unconformities, clinoforms, and pinch-out zones, which suggest favorable conditions for the formation of hydrocarbon traps, particularly in sequences SS-3 (Upper Cretaceous), SS-5 (Maikop Series), and SS-7 (Productive Series).

3. Stratigraphic Division: The seismic stratigra-

phic sequences identified in the study area show distinct variations in reflection characteristics, corresponding to different sedimentary environments and tectonic events. For instance, chaotic and discontinuous reflections in the Jurassic and Lower Cretaceous sequences (SS-1 and SS-2) contrast with the continuous, high-amplitude reflections in the Late Pliocene and Quaternary sequences (SS-8 and SS-10), indicating changes in depositional processes and sea-level variations.

4. Oil and Gas Exploration Potential: The analysis highlights several intervals with potential for hydrocarbon accumulation, particularly the Upper Cretaceous and Oligocene-Miocene sections, where tectonic activity has created favorable conditions for non-anticlinal traps. The identification of pinch-out zones, erosional truncations, and onlap unconformities in these sequences provides crucial information for future oil and gas exploration in the region.

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Authors Contribution: All authors have contributed equally to this work
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Геологічна інтерпретація хвильового поля у мезозойських і кайнозойських осадових комплексах перехідної зони між Південнокаспійським і Середньокаспійським басейнами методом сейсмостратиграфічного аналізу

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Це дослідження вивчає тектонічну та осадову еволюцію перехідної зони між Південно-Каспійською та Середньокаспійською западинами. Дослідження має на меті проаналізувати сейсмостратиграфічні послідовності для покращення розуміння геологічної історії басейну, осадових процесів та вуглеводневого потенціалу. Воно також спрямоване на з'ясування структурних особливостей та тектонічних механізмів, відповідальних за формування та еволюцію цього складного геологічного регіону. У роботі застосовано метод сейсмостратиграфічного аналізу, зокрема аналіз сейсмічних послідовностей та сейсмічних фацій. Було виконано аналіз сейсмічних даних для ідентифікації осадових структур, стратиграфічних послідовностей і тектонічних особливостей. Сейсмічні розрізи, орієнтовані в напрямках північний захід-південний схід та північний схід-південний захід, були розділені на десять сейсмостратиграфічних послідовностей (SS-1 до SS-10). Ці послідовності були вивчені для визначення їхніх умов відкладення, тектонічних обстановок та характеристик відбиття. Аналіз сейсмічних фацій допоміг інтерпретувати умови відкладення та осадову динаміку в межах кожної послідовності, сприяючи ідентифікації структурних пасток та вуглеводневих резервуарів. Основні сейсмічні особливості: Було визначено такі особливості, як онлапи, топлапи, виклинювання, кліноформи та ерозійні зрізи, що вказують на сприятливі умови для накопичення вуглеводнів, особливо в SS-3 (верхня крейда), SS-5 (майкопська серія) і SS-7 (продуктивна товща). Тектонічна еволюція: Тектонічна еволюція регіону включає субдукцію, рифтинг і розвиток платформи. Ці геодинамічні процеси визначали умови осадонакопичення та структурні деформації. Закономірності сейсмічних відбиттів: сейсмічні відбиття вказують на значні варіації швидкості седиментації та умов відкладення. Наприклад, юрські та нижньокрейдові послідовності (SS-1 і SS-2) демонструють хаотичні та переривчасті відбиття, тоді як пізньопліоценові та четвертинні послідовності (SS-8 і SS-10) характеризуються безперервними високоамплітудними відбиттями, що свідчить про контрастні умови відкладення. Тектонічний вплив: Спостерігалися докази синседиментаційної тектоніки, включаючи деформацію, пов'язану з розломами, та седиментацію, спричинену опусканням, що підкреслює роль тектонічної активності у формуванні стратиграфії регіону та впливі на розподіл вуглеводнів.

***Ключові слова**: Південно-Каспійський басейн, Середньо-Каспійський басейн, сейсмостратиграфічний аналіз, відбиття, сейсмічні послідовності, сейсмофаціальний аналіз, сейсмічні розрізи, осади.*

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