УДК 550.834:553.982 DOI: https://doi.org/10.24028/gj.v48i2.350967

Complex application of the reflected and refracted wave methods in the study of the Kurinsky depression

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Received 28 January 2026

The article presents a comprehensive study of the geological and deep structure of the Kurinsky depression. The research is based on regional seismic profiles acquired using a specially designed observation system that ensures the simultaneous recording of both reflected and refracted waves along the same profile. Field surveys were carried out using the 2D common depth point method with vibratory sources and refracted-wave observations employing explosive sources to track deep geological boundaries. Analysis of the kinematic and dynamic parameters of the wavefield has shown that the most reliable information on geological structure, elastic heterogeneities, and tectonic features is primarily contained in the reflected and refracted wavefields. Combining reflected and refracted wave data, especially in the deeper zones where reflection data alone is limited, allows for the creation of higher-quality dynamic depth sections. The combination allowed for the separation of seismic signals from noise, improved the mapping of Mesozoic structures, and enabled reliable correlation of seismic horizons at depths greater than 8—10 km.

The results indicate that the joint application of seismic reflection and refraction methods significantly enhances the completeness, accuracy, and reliability of seismic data interpretation. The analysis shows that, when selecting an appropriate observation system during seismic investigations, it is possible to record different types of waves along the same profile. These waves correspond to different geological boundaries and depths and are registered at different time intervals. The proposed comprehensive methodology enables the development of a more reliable seismogeological model of deep structures and is recommended for use in other regions with complex geology, as well as in hydrocarbon exploration. The results indicate that investigations of this type should be carried out in other regions using a denser network of seismic profiles.

Key words: seismic exploration, seismogeological conditions, reflected wave, refracted wave, dynamic and kinematic parameters, boundary velocity, hodograph.

Introduction. Seismic exploration plays a crucial role in studying the geological structure of the crust and in predicting the oil and gas potential of prospective fields. Seismic methods constitute the primary information base for drilling preparation and for substantiating prospective targets, as well as for determining the optimal locations of planned deep wells during hydrocarbon exploration.

Assessing and forecasting the oil and gas potential of exploration areas, along with refining the understanding of their geological structures, requires new integrated approaches and techniques. These methods aim to improve the quality and reliability of results obtained in seismic studies [Bashir et al., 2022; Rezaei et al., 2022; Ahmedov, Aghayeva, 2022; Ahmedov et al., 2024; Kolomiyets et al., 2025].

In the search for and exploration of oil and gas fields, the capabilities of seismic explora-

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Citation: Shakarov, H.I. (2026). Complex application of the reflected and refracted wave methods in the study of the Kurinsky depression. *Geofizychnyi Zhurnal*, *48*(2), 86-94. https://doi.org/10.24028/gj.v48i2.350967.

tion are extensive, as it provides a wide range of methods for analyzing the kinematic and dynamic parameters of the wavefield. These methods enable the investigation of the geological structure of the studied areas, the prediction of lithology and reservoir properties of the sedimentary complex, and the assessment of hydrocarbon productivity [Shakarov, 2001; Di et al., 2019].

The application of innovative technologies in seismic exploration is advisable at all stages, including field acquisition, primary data processing, interpretation, and the construction of seismic section models. The diversity of seismogeological conditions over large areas of Azerbaijan Republic sometimes necessitates abandoning experimentally developed averaged seismic survey parameters in favor of approaches adapted to specific geological conditions.

With the expansion of seismic exploration capabilities and ongoing technical advancements, a new research direction has emerged. It focuses on applying integrated approaches and techniques to obtain comprehensive and reliable information from seismic data about the geological structure, material composition, hydrocarbon saturation, physical properties, and tectonics of the study area. An analysis of the characteristics of seismic wave propagation in the geological medium shows that the main information about the structure of the geological environment and its elastic inhomogeneities is contained in the wavefields of refracted and reflected waves generated by the seismic source. Accordingly, seismic exploration is primarily conducted using the method of reflected and refracted waves [Yilmaz, 2001; Ilchenko, 2002; Verpakhovskaya et al., 2017]. In this context, reflected waves are most clearly recorded in the near zone of the source, while refracted waves are most clearly observed at a certain distance from it [Sheriff, Geldart, 1985] (Fig. 1). In some sources, the refracted waves are referred to as head waves [Yilmaz, 2001; Gadallah, Fisher, 2009; Mari, 2019; Monk, 2020]. In this study, given the integrated use of both reflection and refraction data, the term refracted waves is consistently used throughout the article.

Notably, a comprehensive application of reflected and refracted wave methods, along with a comprehensive interpretation of the acquired data, can significantly enhance the reliability of the results. In Azerbaijan, between the 1940s and 1970s, several seismic profiles were developed using the correlation method based on refracted waves and deep seismic sounding, with the primary objective of studying the tectonics of the lower sedimentary complex and the surface of the consolidated crust. Most of these profiles were established primarily in the Kurinsky depression, which had favorable seismogeological conditions and, was at that time, one of Azerbaijan's potential oil- and gas-bearing regions. Based on a comprehensive interpretation of regional seismic survey data, tectonic diagrams of different structural levels and layers were compiled. These studies led to the identification of three structural levels, corresponding to distinct refractive boundaries with different boundary velocities [Kocharli, 2015].

Research Methodology. Starting in the 1970s, digital recording and processing of seismic data began with the widespread use of the common depth point (CDP) method. In subsequent years, despite the introduction of new modifications and methods, including 3D seismic surveys, researchers noted a so-called discrepancy between the results of 2D and 3D seismic surveys of recent decades and the deep seismic sounding-method of correla-

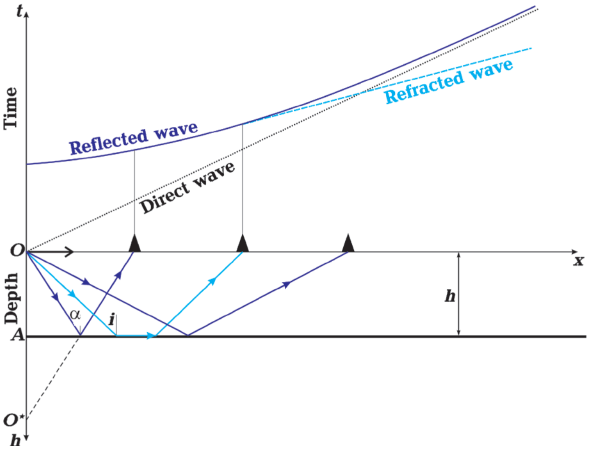

Fig. 1. Hodograph of reflected and refracted wave for a horizontal boundary [Sheriff, Geldart, 1985].

tion of refracted waves surveys of 1950—1970 regarding the internal structure of Mesozoic deposits. Specifically, the boundaries of refracted waves, assigned in the 1970s to the lower Mesozoic deposits or the surface of the consolidated crust, were not observed in the 2D-3D CDP data [Kocharli, 2015].

In our opinion, the main reason for this discrepancy was and remains the difference between the observation systems. To investigate this, the author developed regional profiles using a comprehensive approach (integration of reflected and refracted wave information) in various parts of the Kurinsky depression in 2017—2018. The observation system was designed so that both reflected and refracted waves could be recorded on the same profile.

Field seismic surveys were carried out using the 2D CDP method with a flank observation system and a vibration excitation system employing a non-explosive (vibratory) source. Four seismic vibrators arranged in a line were used to generate elastic vibrations without explosives. The observation base was 20—30 km (400—600 active recording channels), the observation step (distance between reception points) was 50 m, and the distance between excitation points was 100 m. The frequency range was 10—80 Hz, with a total recording duration of 22 s (sweep signal duration of 12 s, useful recording duration of 10 s), the number of accumulations was 4—6, and the sampling interval was 2 ms.

More powerful sources were used to track refracted waves from deep-lying boundaries during the seismic refraction method (SRM) operations. Seismic waves were excited by an explosive method. The explosions were made in a well with a depth of 40 m, with a total charge of 20 kg. The maximum removal of the explosive device during the operation of the SRM was approximately determined by the value of the seismic migration distance L using the formula: $L=H\text{tg}\alpha$, where H is the depth of occurrence of the deep refractive boundary, and α is the angle of refraction [Sheriff, Geldart, 1985].

Thus, using the chosen favorable observation system, combined CDP and SRM methods were performed on the same profile, and reflected and refracted waves were recorded on the obtained seismograms, which made it possible to study the geological section down

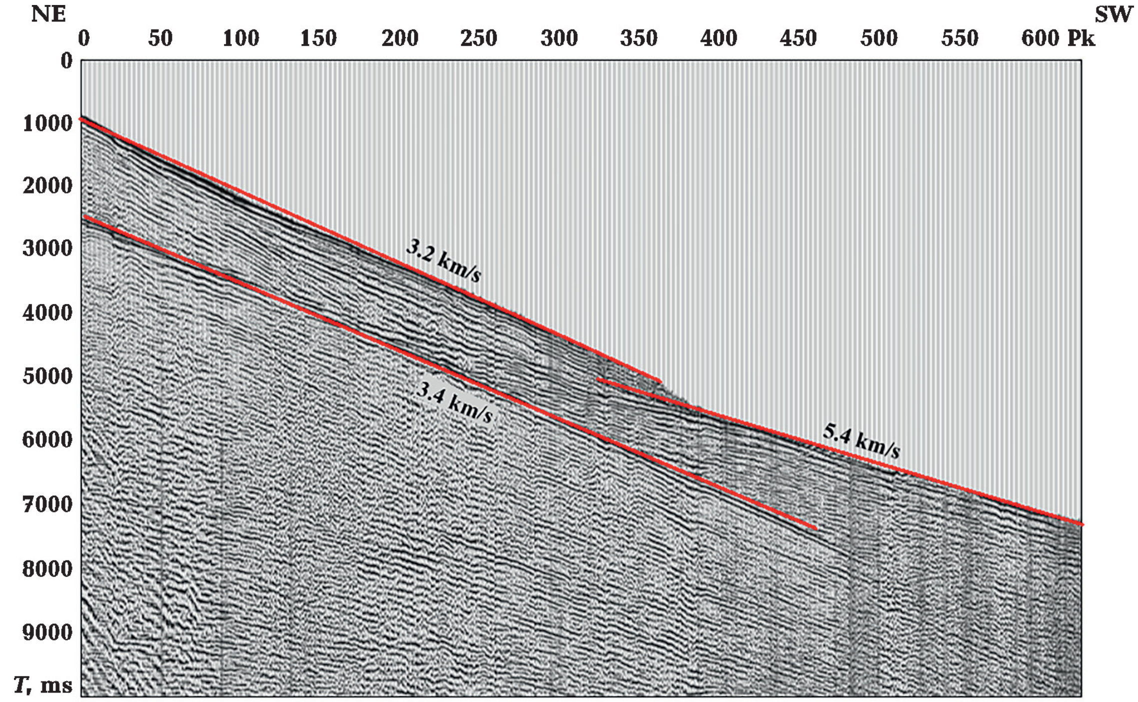

Fig. 2. Shot gather from the shot point along the regional profile (Kura-Gabirry oil and gas region).

to the surface of Jurassic deposits [Shakarov et al., 2018; Shirinov et al., 2019, 2023].

The data show that the main components of the wavefield are reflected and refracted waves (Fig. 2).

For this acquisition geometry, the distance between the shot point and the first receiver station (offset) was approximately 6 km. Therefore, no seismic arrivals were recorded within the time interval of 0—1.0 s. Beginning at approximately 1.0 s, refracted waves are observed in the first arrivals. Refracted and reflected waves associated with major stratigraphic and crustal boundaries display greater stability and coherency than waves originating from secondary interfaces. A distinctive feature of the wavefield reflected from these boundaries is its discontinuity. Statistical estimation of their correlability intervals shows that the wavefield after the initial arrival is dominated by coherent reflection events extending up to 6 km in length. These waves are frequently detected in the critical and subcritical regions, meaning they can be traced at distances far exceeding the depth of the reflection boundaries. The observation of intermittent waves indicates internal inhomogeneities throughout the entire thickness, both vertically and horizontally. The structure of the reflected wavefield consists of two groups of coherent events. One group is well defined and numerically predominant, represented by subhorizontal coherent reflection events, while the other group consists of steeply dipping axes. Their apparent velocities gradually decrease with increasing distance from the source. The shape of the hodographs and the character of variations in the apparent velocities indicate a subhorizontal occurrence of the reflecting interfaces.

In the first arrivals, the obtained seismograms reveal refracted waves propagating along two wave fronts. The first wave front is traced at offsets of up to 20,000 m within the time interval of 1.0—5.2 s between pickets (channels) 1—370, corresponding to approximately 14,800 m. The second wave front is observed within the time interval of 4.9—7.5 s between pickets (channels) 320—626, corresponding to about 12,240 m (see Fig. 2). The apparent velocity of waves along the first wave front, calculated from hodographs, varies from 3,100 to 3,300 m/s, with an average apparent velocity of 3.2 km/s. The apparent velocity of waves along the second wave front ranges from 5,200 to 5,600 m/s, with an average apparent velocity of 5.4 km/s. For the waves observed along the first wave front, the boundary velocity was calculated to be approximately 3,200 m/s, while the average velocity is about 2,400 m/s. Based on these parameters, the hypsometric position of the refractive boundary was determined. The depth of this boundary along the profile varies from 1,500 to 2,000 m, which corresponds to Pliocene deposits. A comparative analysis of refracted-wave seismograms with reflected-wave data acquired using the CDP method showed that the waves recorded in the first arrivals correspond to the boundary of Pliocene sediments [Shakarov et al., 2018]. For the waves observed along the second wave front, the calculated boundary velocity is approximately 5,400 m/s, and the average velocity is about 3,100 m/s. Using these values, the hypsometric position of the corresponding refractive boundary was determined. The depth of this boundary is about 6,000 m at the beginning of the profile, increases to approximately 10,000 m in the central part, and decreases to about 7,800 m toward the end of the profile. This boundary corresponds to the refractive boundary within Jurassic sediments.

At the same time, approximately 1.5—1.6 s after the first arrivals, an additional wave front is observed on the seismograms. It is clearly traced along the entire profile within the time interval of 2.5—7.8 s. The geometry of the constructed hodographs and the results of velocity analysis indicate that these waves are reflected waves. The depth of the corresponding reflecting boundary varies from 6,000 to 10,000 m, which coincides with the depth of the refractive boundary determined from refracted-wave data. These observations indicate that the analyzed waves are reflections from the Jurassic sediments' boundary. A similar wave pattern is observed in seismograms obtained from regional profiles acquired within the Yevlakh-Agjabadi depression (Fig. 3). In this case, the distance between the shot point and the first receiver station was approximately 15 km.

Analysis of the seismograms shows that, with a distance of 15—20 km from the shot point, refracted waves can be traced in the first breaks. They are characterized by apparent velocities V_{apr}=5.2÷5.6 km/s. These waves stand out most confidently in the area close to the first breaks. In the initial part of the hodograph, there is a curvilinearity, after which the hodograph changes to a rectilinear shape. These features in the form of a hodograph are repeated in other reversed-profile acquisitions. The apparent velocities of a group of reflected waves according to the hodograph increase with the distance from the shot point; the range of variation of these velocities varies from profile to profile, which indicates different natures of the refractive boundaries during the transition from site to site.

Thus, a qualitative analysis of the wavefield obtained from the superposition of reflected and refracted waves shows that, in the studied medium, in addition to the reflecting boundaries, there are also the refractive boundaries with varying degrees of stability. This fact once again confirms the expediency of the joint application of reflected and refracted wave methods. Seismic data processing and interpretation were carried out using the ProMax and Kingdom Suite software packages. Since the total length of the regional profile was approximately 200 km, interactive processing procedures were applied, which significantly improved the accuracy of estimating the seismogeological parameters of the section. Velocity analysis and velocity updating were performed using vertical velocity spectra, with both visual and quantitative evaluation of stacking efficiency on the final stacked section.

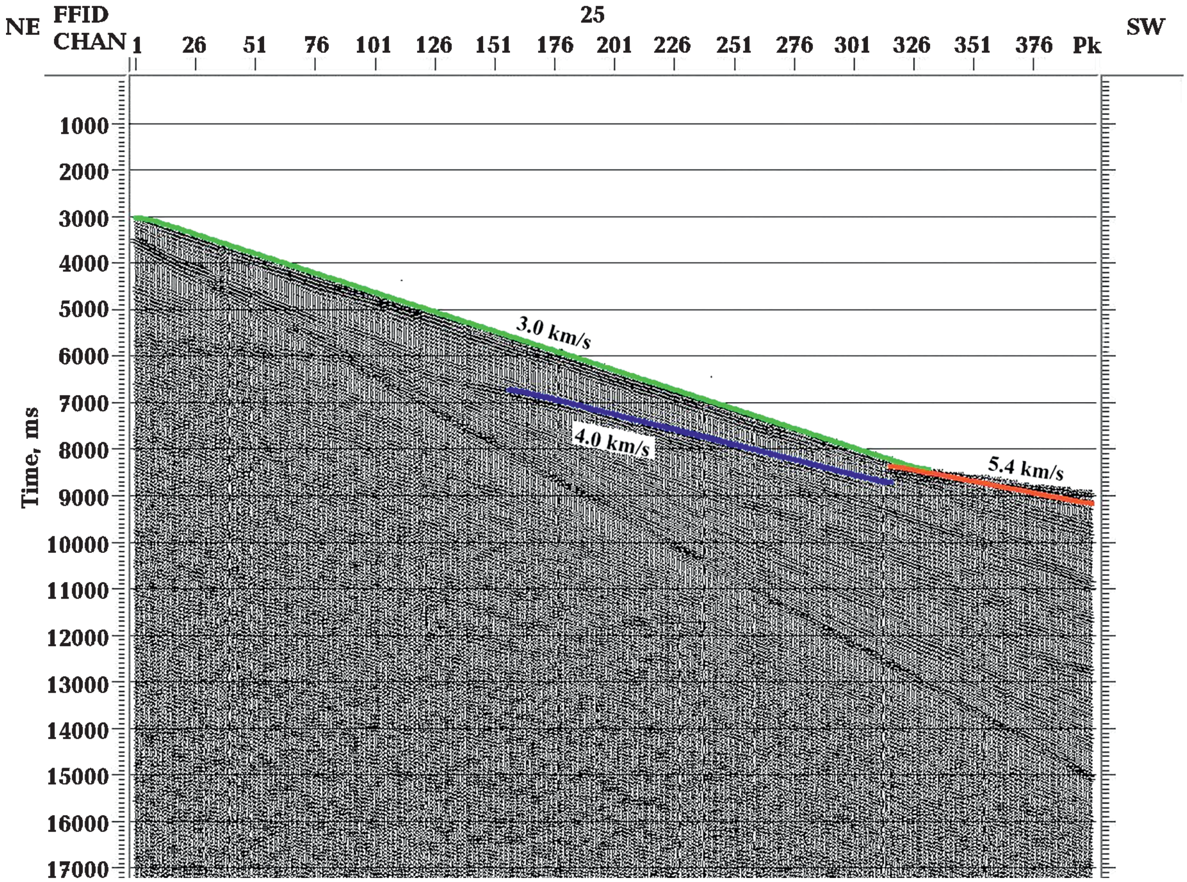

Fig. 3. Shot gather from the shot point along the regional profile in the Yevlakh-Agjabedi depression.

After applying other necessary steps of the processing workflow (including calculation and correction of static and dynamic corrections, various filtering procedures, migration, etc.) and determining velocities in different parts of the profile, depth-migrated seismic sections were constructed along the processed profiles. This made it possible to investigate the geological section down to the top of the Jurassic deposits. Time sections and depth-migrated sections were generated through the integrated processing of reflected and refracted wave data. Fig. 4 shows a depth section obtained after pre-stack depth migration (Fig. 4).

As can be seen, the dynamic depth section obtained from the joint interpretation of refracted and reflected waves can be divided into four intervals. The first interval covers the upper part of the dynamic depth sections, that is, the horizons corresponding to anthropogenic, Pliocene, and Miocene deposits. Within this interval, the quality and information content of the seismic data are significantly higher. For all acquired profiles, seismic horizons within this interval can be confidently traced. The second interval includes the middle part of the dynamic depth sections. This interval encompasses the section between the Paleogene and Mesozoic deposits and is characterized by a relatively weak wavefield. Despite a slight decrease in seismic wave dynamics, the horizons within this interval can still be confidently traced.

The third interval includes the lower part of the dynamic depth sections, representing a rock complex that reflects the internal structure of the Mesozoic sequence (Upper Cretaceous-Jurassic). In the upper portion of this interval, the seismic wavefield is characterized by higher dynamics and can be confidently traced. Although a weakening of the useful signal is observed locally in the deeper parts of the section, seismic horizons can still be confidently traced and correlated.

The fourth interval characterizes seismic waves observed within and below the Jurassic sediments in the dynamic depth sections. Within this interval, the correlation of seismic waves and the tracking of common-midpoint reflection events become difficult, and in some cases their regularity is disrupted. Nevertheless, these waves can also be regarded as useful. Below this interval, the wavefield becomes nearly chaotic, making reliable tracking impossible. To obtain a comprehensive image of the geological section, reflected and refracted wave data were jointly analyzed. As

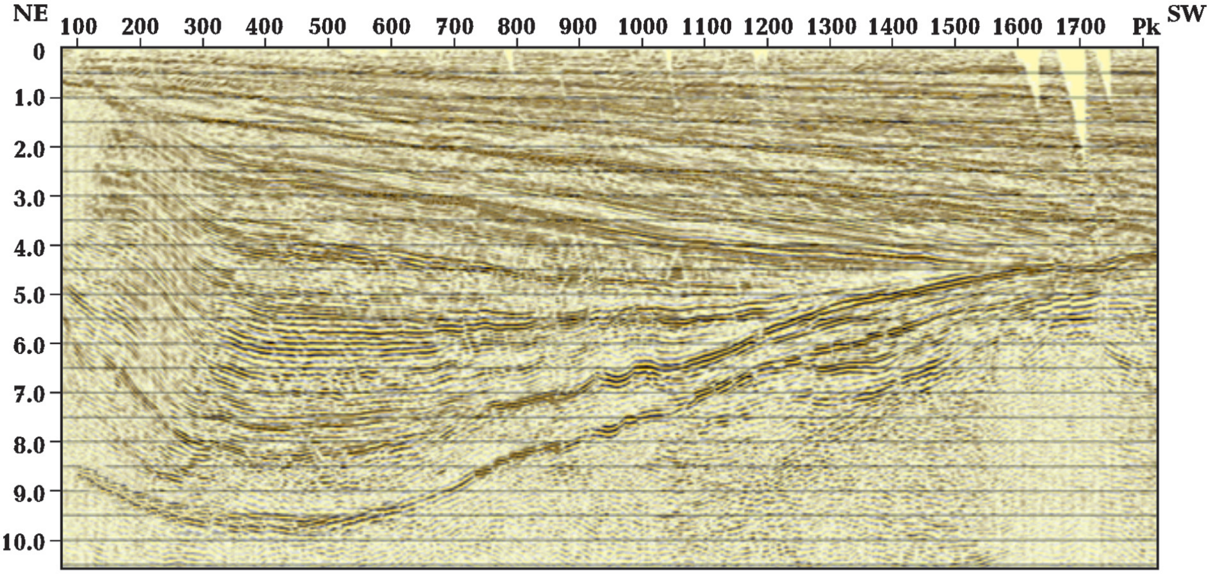

Fig. 4. Depth section along the regional profile obtained from the joint processing of refracted and reflected waves after pre-stack depth migration.

is well known, such integration enables the combination of complementary information about the wavefield. In this study, the joint processing of reflected and refracted wave data made it possible to distinguish useful signals from interference and noise, particularly in the deeper parts of the section characterized by a complex wave pattern. Since reflection data in the deeper parts of the section were incomplete, the integrated processing and interpretation of both reflected and refracted wave data (including arrival times, amplitudes, and waveform characteristics) made it possible to construct a unified model of the deep geological structure (see Fig. 4).

Conclusion. Thus, when selecting an appropriate observation system during seismic investigations, it is possible to record different types of waves — specifically reflected and refracted waves — along the same profile. These waves correspond to different geological boundaries and depths and are registered at different time intervals. For the first time in recent years, a joint composition approach, that is, the integrated use of reflected and refracted wave data, was applied, making it possible to obtain more complete information from deeper geological layers. In refracted-wave correlation studies, the length of the observation spread was approximately 30 km, whereas in surveys conducted using the CDP method, the observation spread reached about 20 km. In surveys involving both reflected and refracted waves, despite certain difficulties related to densely populated areas, drainage systems, agricultural crops, and streams, the observation spread length and other acquisition parameters were maintained constant along the profiles. This consistency made possible a reliable joint interpretation of reflected and refracted waves recorded along the same profiles at different time intervals. Based on a comprehensive comparative analysis of the kinematic and dynamic parameters of the recorded waves, the geological section was investigated layer by layer, and the conditions of formation and accumulation of the sedimentary complex and its components were determined. Thus, the joint composition — that is, the integrated use of reflected and refracted wave data — made it possible to obtain the most complete and reliable seismogeological image of the studied area. The results indicate that investigations of this type should be carried out in other regions using a denser network of seismic profiles.

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Результати комплексного застосування методів відбитих і заломлених хвиль при дослідженні Куринської депресії

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Представлено результати комплексного дослідження геологічної та глибинної структури Куринської депресії. Дослідження ґрунтується на регіональних сейсмічних профілях, отриманих за допомогою спеціально розробленої системи спостережень, яка забезпечує одночасну реєстрацію відбитих і заломлених хвиль уздовж одного профілю. Польові дослідження проводилися за допомогою методу 2D спільної глибинної точки з вібраційними джерелами, а також спостережень заломлених хвиль із використанням вибухових джерел для відстеження глибинних геологічних меж. Аналіз кінематичних і динамічних параметрів хвильового поля показав, що найбільш надійна інформація про геологічну структуру, еластичні неоднорідності та тектонічні особливості міститься переважно в полях відбитих і заломлених хвиль. Комбінування даних відбитих і заломлених хвиль, особливо в глибших зонах, де дані відбиття обмежені, дає змогу створювати високоякісні динамічні глибинні розрізи, відокремлювати сейсмічні сигнали від шуму, покращує картування мезозойських структур, забезпечує надійну кореляцію сейсмічних горизонтів на глибинах понад 8—10 км. Результати свідчать про те, що спільне застосування методів відбитих і заломлених хвиль значно покращує повноту, точність і надійність інтерпретації сейсмічних даних. Вищенаведений аналіз показує, що при виборі відповідної системи спостережень під час сейсмічних досліджень можна реєструвати різні типи хвиль уздовж одного профілю. Ці хвилі відповідають різним геологічним межам і глибинам і реєструються на різних часових інтервалах. Запропонована комплексна методологія дає змогу розробити більш надійну сейсмогеологічну модель глибинних структур і рекомендована для використання в інших регіонах зі складною геологією, а також під час пошуку вуглеводнів. Отримані результати свідчать, що подібні дослідження слід проводити в інших регіонах за допомогою більш щільної мережі сейсмічних профілів.

Ключові слова: сейсмічні дослідження, сейсмогеологічні умови, відбита хвиля, заломлена хвиля, динамічні та кінематичні параметри, гранична швидкість, годограф.