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Low-amplitude faults revealed by seismic attribute analysis in the Khasilat field of the Absheron oil and gas bearing region

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The Khasilat field, located within the Absheron oil-and-gas-bearing region, was selected as the primary research object due to its geological complexity and proven hydrocarbon potential. A concise yet informative description of the research site is presented, emphasizing the comprehensive suite of geological and geophysical investigations. These include stratigraphic and lithological analyses and advanced geophysical methods such as vertical seismic profiling. Particular attention is paid to the Qala Suite deposits that represent the main oil-bearing horizon within the study area; their lithological composition, structural setting, and reservoir characteristics are briefly outlined.

The main issue of the paper concerns the detection and interpretation of tectonic disturbances manifested in the seismic wave-field. Seismic methods, especially when applied in high-resolution formats, are recognized as essential tools for revealing the structural fabric of subsurface formations. Disjunctive dislocations, including faults and fractures, play a critical role in the evolution of hydrocarbon systems.They influence both the accumulation and migration of fluids, as well as the integrity of reservoir traps. For this reason, the detailed mapping of such structural features is crucial for reliable geological modelling and resource evaluation. In this study, seismic attribute analysis techniques including coherence, dip, and azimuth cubes were applied to identify and delineate fault systems. The interpretation results revealed numerous faults aligned in a north-south orientation, along with several transverse faults trending west-east, indicating a complex and potentially productive tectonic framework within the region.

Key words: tectonic disturbance, seismic, Productive Series, Qala Suite, coherence cubes, azimuths, seismic attributes.

Introduction. Khasilat field is located in the south-eastern part of the Absheron Peninsula. The structure of the Absheron Peninsula consists of sedimentary formations of Upper Cretaceous to Quaternary age, represented mainly by clays, sands and sandstones, less frequently by clay shales, marls and conglomerates (Fig. 1). Its total thickness is 5000—5500 m.

All these deposits tend to dip in the south-eastern direction [Mamedov, 2010]. The studying of this area began in the 19th century with the drilling of an exploration well within Surakhany-Karachukhur. Since the 1930s, a geological survey of a 1:50000 scale (a larger scale in some areas), geophysical surveys (electrical explorations and gravimetric works), and gas surveys have been carried out in the area [Guliyev et al., 2003].

Seismic surveys were repeatedly carried out in the Khasilat field using the Reflected Wave method from the early 1930s to the end of the 1950s. In 1977—1978 they used the total Depth Point method. In 1996 and 2003—

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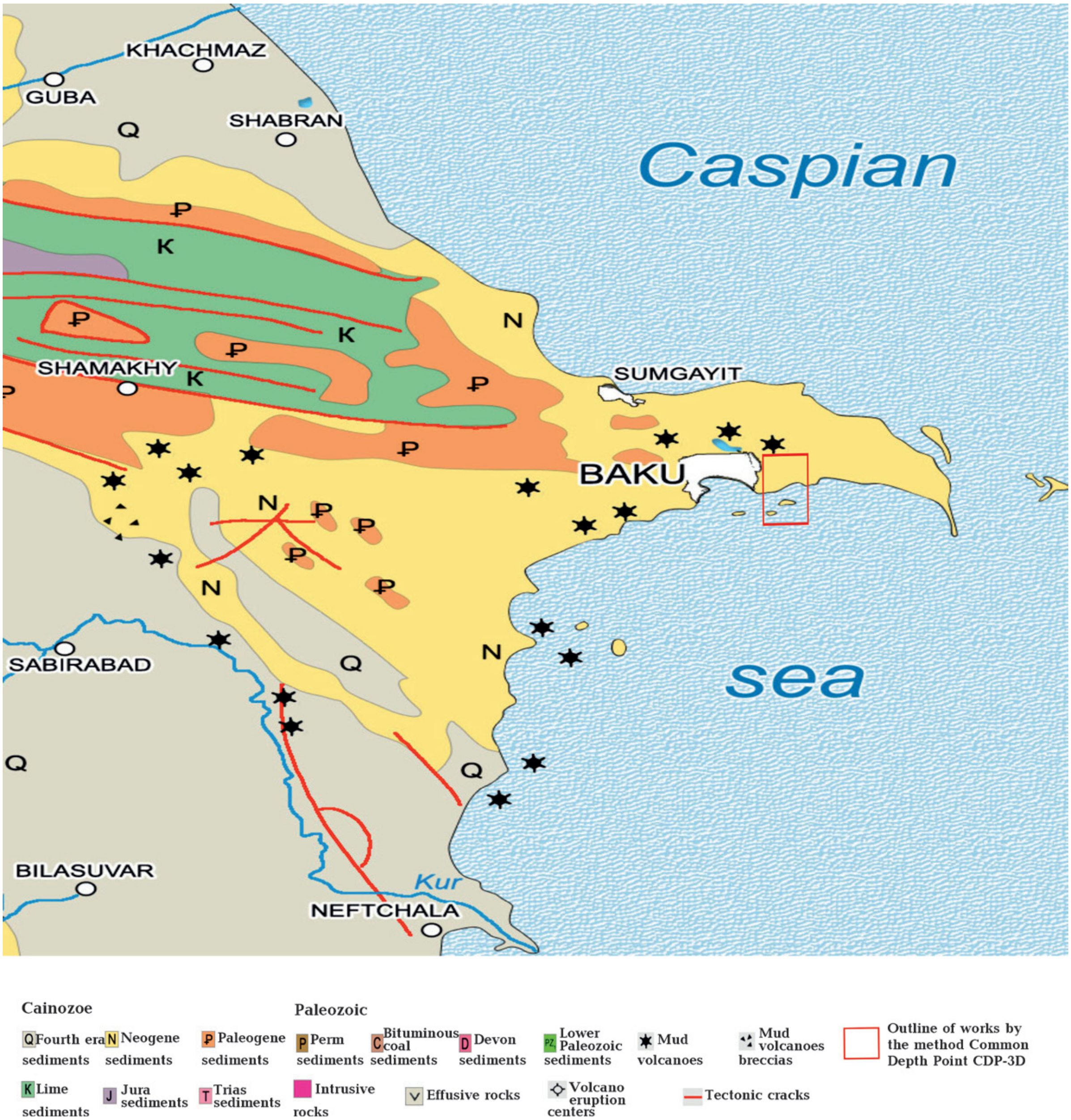

Fig. 1. Geological map of the study area (from the Geological Map of Azerbaijan, https://boundtoazerbaijan.com/maps/).

2004, detailed seismic surveys were carried out using the Common Depth Point (CDP) method. Based on the results of geological and geophysical surveys and deep drilling, two fields were discovered: in the west — Zykhone and in the eastern part — the Khasilat field. Drilling in the Khasilat field was started in the 1930s. In 1948, the Khasilat oil field was discovered in the Qala Suite of the Productive Series and put into commercial development. The present paper discusses the results of identification and tracking of Disjunctive Dislocations (DD) by attribute analysis of 3D seismic data carried out in 2011—2012 in the Khasilat-Zykh area.

The Akchagyl and Absheron formations are the most widespread on the surface of the Absheron Peninsula, covered in some places by Quaternary deposits. The other part of the section is only exposed by boreholes. The most studied sections are the Absheron and Akchagyl stages and the Productive Series. Deposits underlying the Productive Series have not been studied sufficiently yet, as they have been penetrated only by a few wells.

Lithologically, the Productive Series stands out among other stratigraphic units of the Neogene age due to its sandy content and is represented by a thick series of interlaced clays, sands and sandstones overlapping each other [Kerimova, Samadzadeh, 2023]. The thickness of the deposits of the Productive Series varies significantly from 1300 to 3400 m. Fig. 2 shows an integrated stratigraphic-logging model of the structure of the Qala Suite formation, both the upper part of the formation well studied by drilling, and the lower — prospective part of the formation. The diagram clearly shows that the lithological and stratigraphic boundary separating the two parts is distinguished by the Well Logging methods. The lower part is most likely represented by sandstones deposited during the transgressive phase of development of this part of the Absheron Peninsula, while the upper part is characterized by complete and incomplete regressive cycles. The wavy line in the figure shows the boundary of stratigraphic unconformity, and the boundary of thermobaric system change can be related to it at the same time.

QaS1—QaS5 represent stratigraphic subintervals of the Qala Suite. SER (specific electrical resistivity) reflects the reservoir properties of rocks, primarily porosity, permeability, and fluid saturation. SP (spontaneous potential) indicates lithological boundaries and permeable layers. R-T cycles (regressive-transgressive cycles) show fluctuations of relative sea level. The wavy line marks a stratigraphic unconformity. The yellow column represents lithology (terrigenous sandstones, siltstones, and clays). Orange triangles indicate regression, and blue triangles indicate transgression.

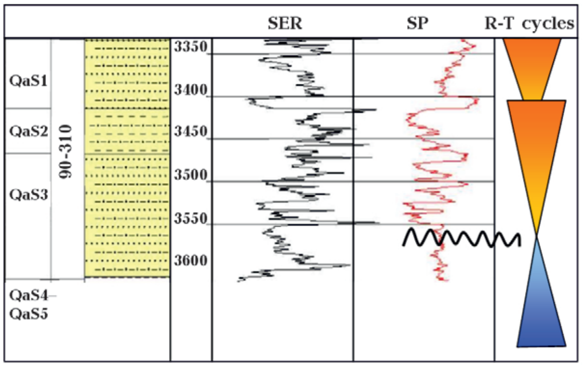

Fig. 2. Integrated Stratigraphic-Logging Model for the Qala Suite Intervals.

The Qala Suite (QaS) is the bottom formation of the Productive Series that occupies only the southern and southeastern part of the Absheron Peninsula. Its thickness increases in the southern direction downward to the dip of the strata. The thickness increase of the Qala Suite occurs due to the stratigraphic increase in its section as a result of the appearance of new strata at the bottom of the formation. Here, geological prospecting and exploration works also revealed a decrease in the thickness and, in some places, outcropping of the Qala Suite layers, which lie on the eroded surface of tectonic sediments with a clearly marked angular unconformity. Only the Qala Suite contains the oil-bearing deposits at the Khasilat field.

The sediments of the formation are divided from top to bottom into three sandy-siltstone packs: QaS1, QaS2, and QaS3. This division was possible due to the differences in the packs' lithology and oil-bearing capacity. The top of the QaS3 formation is associated with Seismic Horizon (SH) SH-IIIa, which can be traced only within the Bina-Hovsan syncline. SH-III, traceable over the entire area, is confined to the top of the Qala Formation. In recent years, a fourth oil-bearing horizon, QaS-4, has been identified in the Qala Suite.

Methods. Disjunctive dislocations (DDs) are the most valuable elements of the geological section; they play a special role in the formation and destruction of hydrocarbon deposits [Salaev, Kastryulin, 1977; Marfurt, Alves, 2015; Ercoli et al., 2023]. Therefore, the study of DD is of great importance for compiling a model of the study field and assessing the prospects of oil and gas content. There are no special studies of the DDs, and seismic survey is the only method that detects them in detail.

In 2011—2012, a 3D seismic survey was carried out in the Khasilat-Zykh area, covering the structures located in this area. Coherence, dip, and azimuth cubes were used to identify tectonic elements and faults in the 3D wave field. The coherence cube is calculated on the basis of the source cube data. The coherence cube is the cube of correlation coefficients between seismic recording traces. The part of the seismic field without complications and faults will be equal to ~1, and the part of the section with faults corresponds to less than 1. The criterion for the presence of faults is a rapid change in the coherence parameter (Fig. 3). As can be seen from this cube, there are several longitudinal faults of different depths oriented approximately north-south and several transverse faults oriented in the west-east direction.

The dip and azimuth cubes are calculated on the basis of instantaneous phase and instantaneous frequency. It is also an attribute for the identification of tectonic disturbances [Hussein et al., 2021; Wang et al., 2021]. The criterion of reliability of mapping the faults (or DDs) is a steep change in the gradient of the dip slope. The location of tectonic faults was determined visually, from changes in the seismic recording dynamics and phase sequence, as well as phase shifts of the reflected waves on the time section and on the map of angular unconformities (dip) of the corresponding horizons (Figs. 4 and 5). The calculation was performed by the time cube in the interval of the relevant reservoir.

Based on the obtained attribute maps and taking into account the geophysical and field characteristics of wells falling into one tectonic block, tectonic faults were identified and traced (Figs. 6 and 7). Figs. 3—7 show maps of coherence, dip, azimuth, frequency, and compression attributes for the interval RHIIIa (the QaS3 formation), which were used to correct the fault delineation from the seismic data.

Results. The fault system obtained for the QaS3 formation has two directions: latitudinal along the centre of the Khasilat uplift and meridional. In Fig. 8, the reflected horizon RH IIIa corresponds to the top of the QaS3 formation. It is located in the middle part of the seis-

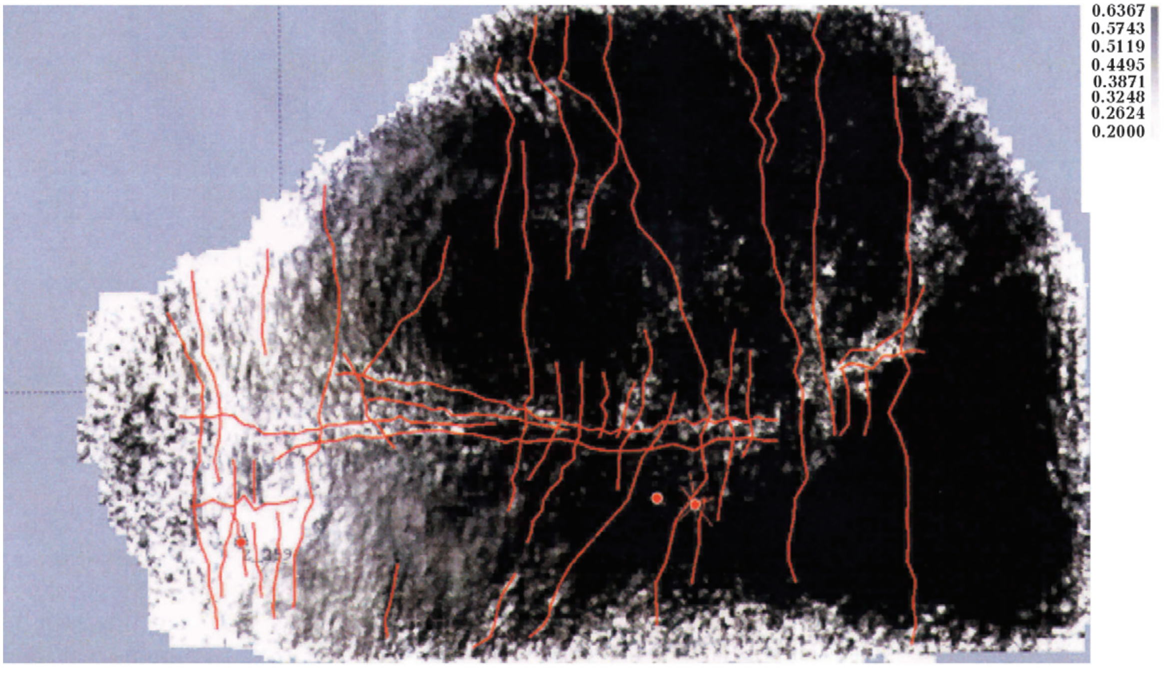

Fig. 3. Coherence attribute map in the interval of Reflected Horizons (RH) IIIa (QaS3 formation). The study area is located within the red rectangular outline in Fig. 1. Bright tones (high coherence, ~0.6) indicate continuous and homogeneous reflections, while dark tones (low coherence, ~0.2) highlight discontinuities and fault zones. Red lines show interpreted fault traces.

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mic section, approximately at ~3100 ms (T), where the main fault system and the flower structure are observed.

This behavior of faults in plan view (see Figs 3—7) and in vertical cross section (see Fig. 8) is characteristic of the shear-type faults. Meridional faults are mainly normal faults, which are considered to be the second-

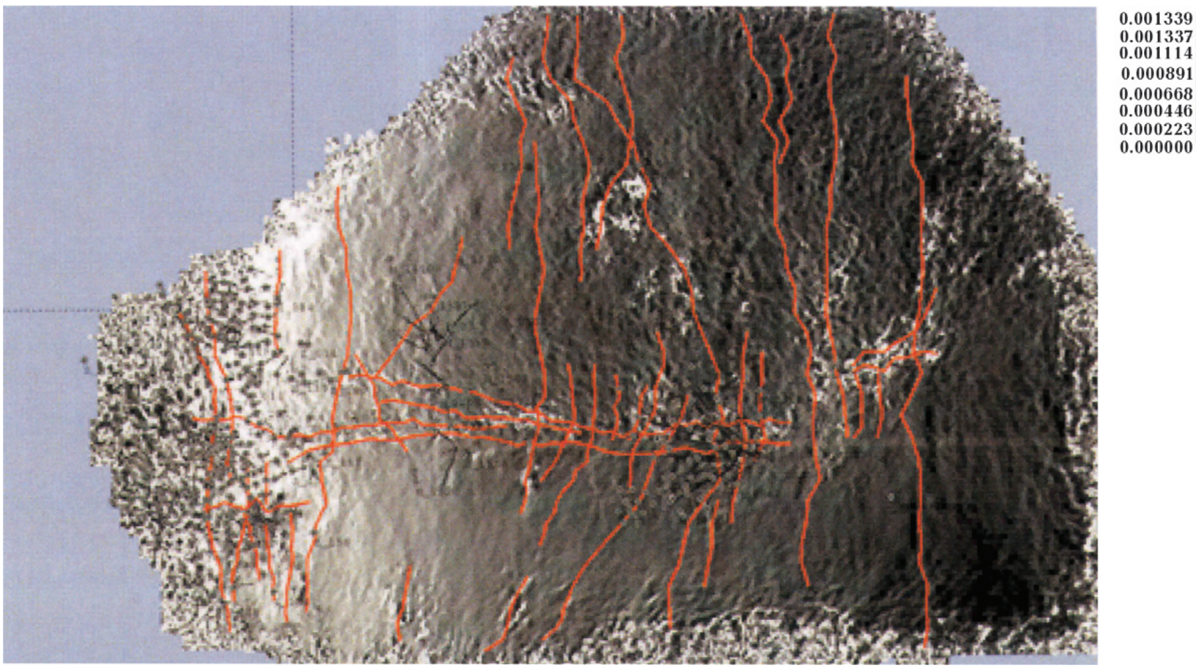

Fig. 4. Dip attribute map in the interval of RH IIIa (QaS3 formation). Variations in dip values highlight zones of tectonic disturbances, where steep gradients indicate faulting. The digital scale in the upper right corner shows dip attribute values. Red lines show interpreted fault traces.

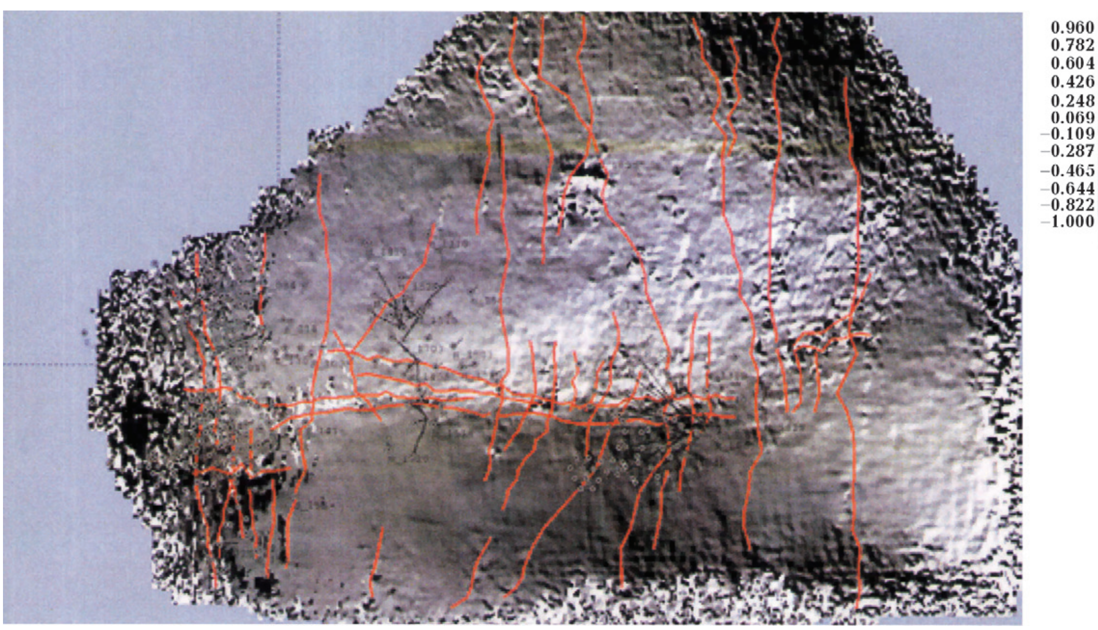

Fig. 5. Azimuth attribute map in the interval of RH IIIa (QaS3 formation). Variations in azimuth values emphasize the orientation of the fault-related discontinuities and structural features. The digital scale in the upper right corner shows azimuth attribute values ranging from –1.0 to +0.96. Red lines show interpreted fault traces.

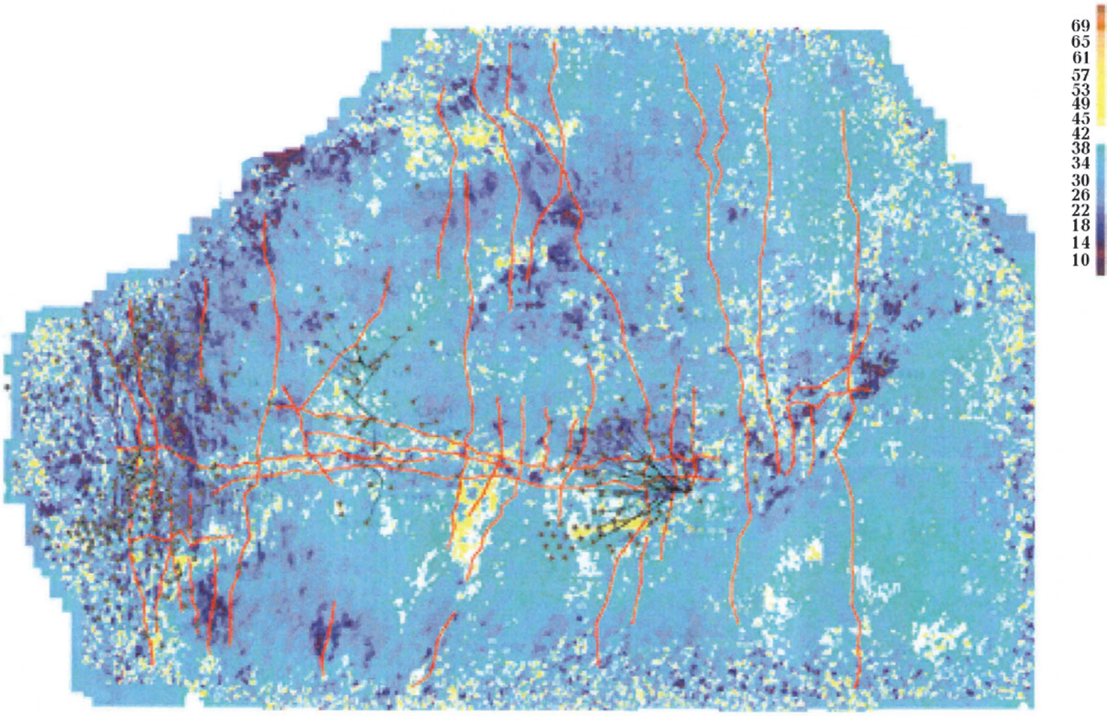

Fig. 6. Attribute map of frequency in the interval of RH III_a (QaS3 formation). Zones of lower frequencies highlight areas of tectonic disturbance and attenuation of seismic energy, whereas higher frequencies indicate more continuous and homogeneous reflections. The digital scale in the upper right corner shows frequency attribute values. Red lines show interpreted fault traces.

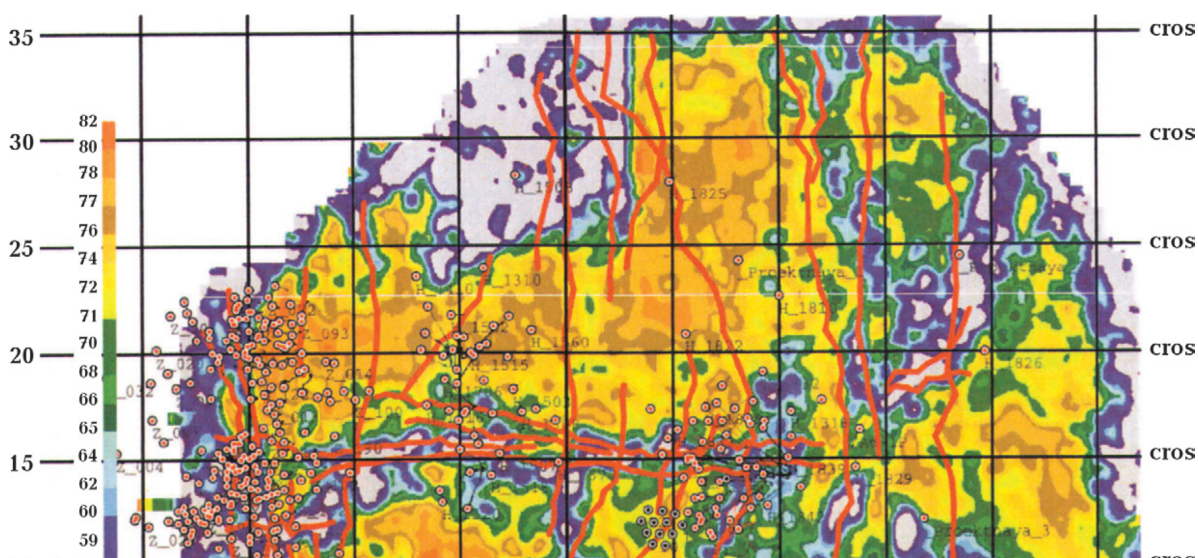

Fig. 7. Attribute map of compression in the interval of RH IIIa (QaS3 formation). Zones of reduced compression values indicate discontinuities and fault-related deformations, while higher values correspond to more intact and continuous strata. The digital scale in the upper left corner shows compression attribute values. Red lines show interpreted fault traces, and well locations are marked by circles.

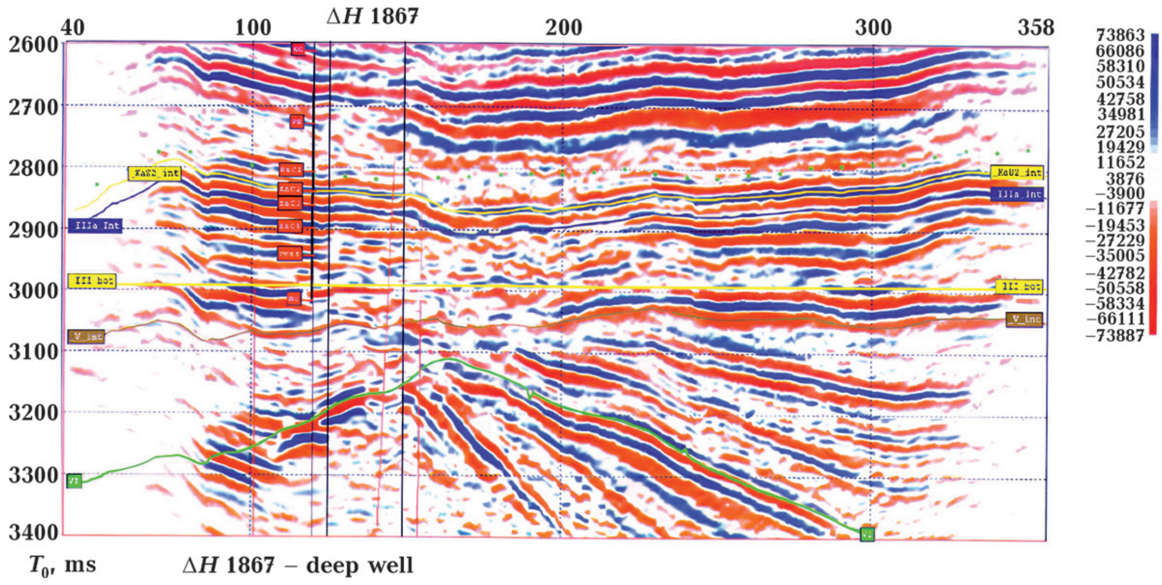

Fig. 8. Extra-range and partial disturbances with vertical fault planes. The location of this cross-section is indicated in Figs 3—7. Colored lines correspond to interpreted seismic horizons: yellow — SH-III (top QaS2), red — SH-IIIa (top QaS3), blue — lower QaS3, green — base QaS3. The section demonstrates longitudinal and transverse faults, with a flower-structure geometry observed above RH-IIIa. The color scale on the right shows seismic reflection amplitude (relative units). The vertical axis is given both as two-way travel time (ms) and converted depth (m). The location of the deep well H-1867 is indicated by a thick black line, while thin vertical black lines correspond to seismic lines.

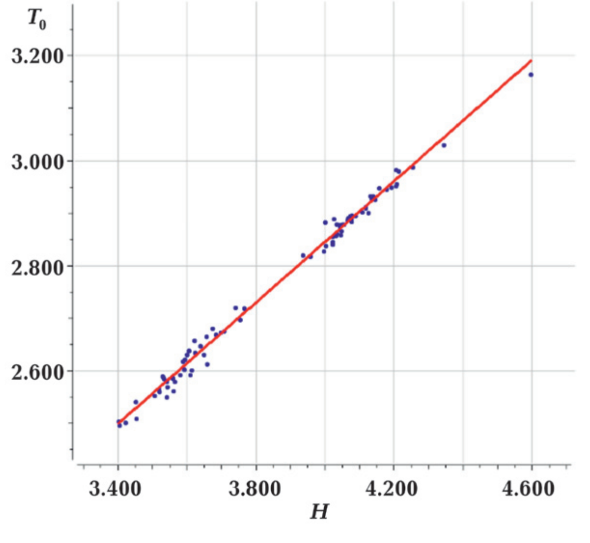

Fig. 9. Time-depth dependence for the top of the QaS3 formation. It is based on the data from more than 83 wells within the study area, combined with CDP seismic data. The method applied here is the time-to-depth conversion using an average velocity model derived from the well control. The vertical axis represents two-way travel time (s), and the horizontal axis shows depth to the top of the QaS3 formation (km). The red line corresponds to the regression (best-fit) line, indicating the stable time-depth correlation that was used for constructing the structural surface of the QaS3 top.

ary faults relative to the system of latitudinal faults. They are characterized by gentle dip, and most of them, located to the east of the Khasilat uplift, are lystric faults associated with the prolonged grows of the uplift and with the abrupt deflection of the area eastwards. Fig. 9 shows the time-depth dependence for the top of the QaS2 formation, plotted on the data of 83 wells. The clear and stable correlation between these parameters made it possible to construct the structural surface for the QaS2 formation top by converting seismic time to depth using the average velocity model derived from the well and CDP seismic data. Deviations from the assumed regression line may be caused by local lateral variability of the structural surface, which is not recorded in the seismic field, as well as by the influence of tectonic disturbances.

The final variant of the structural surface for the top of the QaS3 formation was constructed by correcting the predicted surface based on the well data and taking into account tectonic disturbances identified from

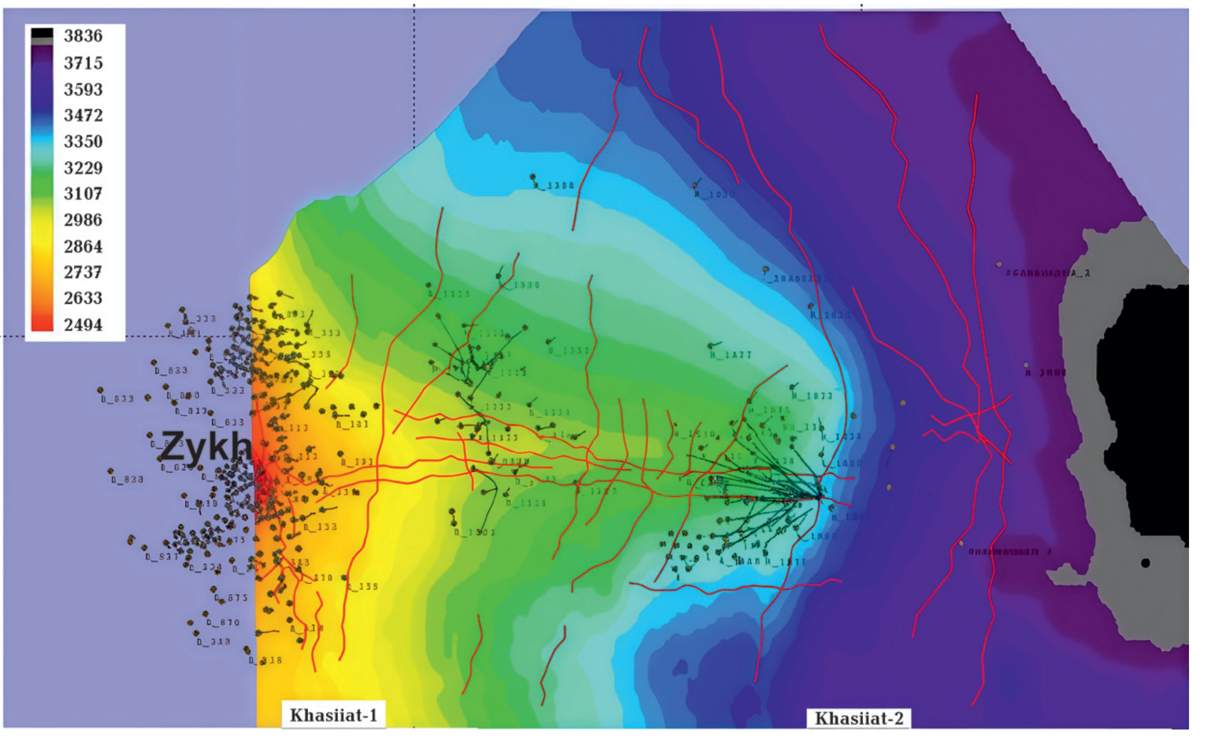

Fig. 10. Isochron maps for the QaS3 RH with a consideration of selected faults. The isochron map of the QaS3 horizon clearly delineates the structural framework of the Khasilat area within the southeastern Absheron region. The color gradient represents the time thickness of seismic reflections: warm tones (yellow-red) indicate relatively shallower zones, while cool tones (green-blue-violet) correspond to greater reflection times and, therefore, to deeper parts of the section.

seismic attribute analysis. Fig. 10 presents the structure map of the QaS3 reflected horizon (RH-IIIa), which was obtained by converting the isochron (time) map into depth using the average velocity model and calibration with the well data. The map shows the structural surface of the formation top with the distribution of fault polygons interpreted from the seismic data.

Two main structural blocks are distinguished in Fig. 10 — the Zykh uplift to the west and the Khasilat uplift to the east. Between them, one can see a transition zone characterized by a system of N-S oriented faults (shown in red in Fig. 10), most of which show listric geometry. These faults form a complex block-fault structure and reflect the late tectonic deformation associated with the differential uplift of the Zykh and Khasilat structures. The denser clustering of wells and fault intersections in the central part indicates areas of enhanced structural heterogeneity and potential hydrocarbon migration pathways. The map in Fig. 10 illustrates the overall tectonic framework of the QaS3 horizon and confirms the influence of low-amplitude dislocations on the morphology of the structure.

Conclusions. In this study, a comprehensive analysis of geological and geophysical was conducted for the Khasilat field within the Absheron oil and gas bearing region. The research integrated 3D CDP seismic data interpretation, well log analysis, lithological and stratigraphic correlation, as well as seismic attribute studies, including coherence, dip, azimuth, frequency, and compression attributes.

The results of the isochron and structural mapping for the QaS3 reflecting horizon made it possible to identify a system of low-amplitude tectonic disturbances that define the block-and-fault structure of the area. Two major listric normal faults were revealed in the eastern part of the region, which developed following the uplift of the Khasilat structure and are genetically linked to shear-thrust movements. Between the Zykh and Khasilat uplifts, several N-S-oriented strike-slip faults were delineated, reflecting the intensive vertical displacement during the formation of the Zykh uplift.

Attribute analysis confirmed the presence of these tectonic zones, showing localized reductions in reflection amplitude, frequency, and continuity, as well as small angular dips of seismic events in the time domain. These features correspond to zones of enhanced deformation and serve as indicators of fault activity.

The integration of seismic attribute analysis with geological and stratigraphic data has proven effective for detecting and characterizing low-amplitude tectonic disturbances that are often not resolved on conventional structural maps. The identified fault system provides new insights into the structural evolution of the Khasilat uplift and contributes to a more reliable assessment of the hydrocarbon potential of the Absheron region.

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Низькоамплітудні розломи, виявлені за допомогою атрибутивного аналізу сейсмічних даних на родовищі Хасилат Апшеронського нафтогазоносного регіону

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Родовище Хасилат, розташоване в Апшеронському нафтогазоносному регіоні, було обрано основним об'єктом цього дослідження через його геологічну складність і доведений вуглеводневий потенціал. Представлений стислий, але інформативний опис району дослідження підкреслює, що тут було проведено комплекс геологічних і геофізичних досліджень, а саме: стратиграфічний та літологічний аналіз, а також передові геофізичні методи, такі як вертикальне сейсмічне профілювання. Особливу увагу було приділено відкладам світи Кала, основному нафтоносному горизонту у досліджуваній області: стисло описано літологічний склад, структурні параметри та характеристики колекторів.

Стаття в основному присвячена виявленню та інтерпретації тектонічних порушень, що проявляються в сейсмічній хвильовій зоні. Сейсмічні методи, особливо застосовані у форматах високої роздільної здатності, визнані важливими інструментами для виявлення структури підповерхневих утворень. Диз'юнктивні дислокації, включно з розломами та тріщинами, відіграють вирішальну роль в еволюції вуглеводневих систем, впливаючи як на накопичення та міграцію флюїдів, так і на цілісність пасток-колекторів. З цієї причини детальне картографування таких структурних особливостей має вирішальне значення для надійного геологічного моделювання та оцінки ресурсів. У цьому дослідженні для ідентифікації та визначення систем розломів були застосовані методи атрибутивного аналізу сейсмічних даних, зокрема обчислення кубів когерентності, падіння та азимута. Результати інтерпретації виявили численні розломи, розташовані в напрямку з півночі на південь, а також кілька поперечних розломів, що простягаються із заходу на схід, що вказує на складну та потенційно продуктивну тектонічну структуру в регіоні.

Ключові слова: тектонічне порушення, сейсміка, продуктивна серія, світа Кала, куби когерентності, азимути, сейсмічні атрибути.

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