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PREDICTION OF ABNORMALLY HIGH FORMATION PRESSURE ZONES USING 3D SEISMIC INVERSION DATA

(Представлено членом редакційної колегії д-ром геол. наук, доц. Г.Д. Лісним)

Background. The article provides information about the location of the Hovsan field under study, the history of its investigation by various geological and geophysical methods, and the main results obtained. It is noted that the study of this area began as early as the 19th century from the adjacent Surakhany-Karachukhur area, where the first exploratory well was drilled (Karachukhur area). From the 1930s to the 1940s, various geophysical surveys were also carried out within the study area, and as a result of electrical prospecting, the first understanding of the tectonics of the Bina-Hovsan syncline was obtained. Gas survey data later made it possible to identify anomalous zones within the Hovsan field. Seismic exploration was conducted from the 1930s to the mid-1950s using the reflection-seismic method (RM), and in 1977–1978 using the common depth point (CDP) method. Individual seismic profiles were acquired in 1993 and 1999. Detailed CDP surveys were carried out in 1996 and in 2003–2004. In 1948, oil was discovered in well No. 1308 in the Kalin Suite of the Productive Series, after which the Hovsan oil field was put into commercial development. The field is currently exploited only onshore, since its offshore boundaries remain undefined due to insufficient study.

Methods. In 2011–2012, 3D CDP seismic surveys were carried out in the Zykh-Hovsan area. These surveys were conducted under varying near-surface seismic-geological conditions, covering a total area of 70 km². Information is provided on the field operations: four types of seismic energy sources and three types of recording receivers were used in this area. During the field setup, source matching was not properly implemented, which created difficulties during data processing. In addition, receiver calibration was only partially completed, leading to further complications. Special attention is given to the implementation of seismic inversion.

Vertical seismic profiling (VSP) surveys were successfully conducted in two wells of the Hovsan field wells 1856 and 1867. Brief information is presented regarding the borehole surveys and the processing of the acquired data.

Results. Pseudo-acoustic inversion (PAC inversion) was obtained, and a comparison of vertical slices of the absolute and relative acoustic impedance cubes along one of the 3D survey lines of the Hovsan field showed that, in both sections, a strong decrease in acoustic impedance values is observed at the level of the underlying PS deposits. This decrease is mainly associated with a sharp reduction in seismic wave velocities and densities from 110 to 2598 (m/s)×(g/cm³) in clay-rich, fluid-saturated formations, which are typical for zones of abnormally high reservoir pressure (AHRP).

The presence of an AHRP zone is also confirmed by the VSP results obtained from the two wells in the field.

Surface and borehole seismic studies made it possible to identify an AHRP zone in the Hovsan field section. Stratigraphically, the AHRP interval encompasses the underlying PS deposits, which are represented lithofacially by clay-rich sediments with interbedded sands. These sand interlayers did not appear on conventional seismic sections. However, seismic inversion of the 3D seismic data made it possible to distinguish these sandy intervals.

Conclusions. A very important conclusion is that the AHRP zone is clearly identified on vertical sections of both the absolute acoustic impedance and the relative impedance. Thus, it can be stated that seismic inversion of 3D seismic data can be used to predict the AHRP zone.

A well drilled into the Miocene deposits in 2015 confirmed our assumptions and produced a flow of approximately 100 tons of oil per day, further confirming the hydrocarbon potential of the underlying PS deposits within the study area.

Keywords: oil and gas content, seismic inversion, seismic section, VSP, Miocene deposits, 3D seismic survey.

Background

The Hovsan field, located within one of the oldest oil and gas-bearing regions in the world, the Absheron oil and gas province is currently among the most actively developed onshore fields of Azerbaijan (Fig. 1). In the Absheron region, the main hydrocarbon-bearing reservoirs are situated within the Productive Series (PS) of the Lower Pliocene. Over roughly two centuries of industrial development of Azerbaijan's oil fields (primarily on the Absheron Peninsula), more than 2 billion tons of oil and condensate have been produced from PS deposits (Abdullayev, Riley, & Bowman, 2012; Salmanov et al., 2023). In recent years, geologists and

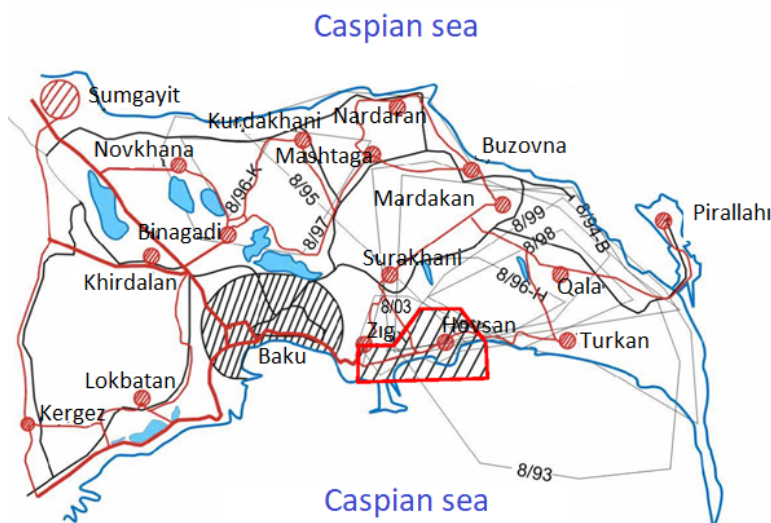
geophysicists in the country have increasingly focused on formations lying deeper than the PS (Leila et al., 2022). In this regard, the Hovsan field is no exception.

The study of the area began in the 19th century from the neighboring Surakhany-Karachukhur area, where an exploratory well was drilled (Karachukhur area). From the 1930s to the 1940s, various geological and geophysical studies of different scales were also carried out (Ahmedov, Kerimova, & Khalilova, 2024) within the study area. As a result of electrical prospecting, the first understanding of the tectonics of the Bina-Hovsan syncline was obtained, and gas survey data made it possible to identify anomalous zones

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within the Hovsan field. Seismic exploration was conducted in 1937–1941, 1945–1949, 1949–1951, and 1955 using the reflection-seismic method (RSM), and in 1977–1978 using the common depth point (CDP) method. Individual profiles

were acquired in 1993 and 1999. In 1996 and in 2003–2004, detailed CDP seismic surveys were carried out by the "Azneftegeophysics" Trust (Exploration Geophysics Department) (Akhmedov, & Khalilova, 2024).



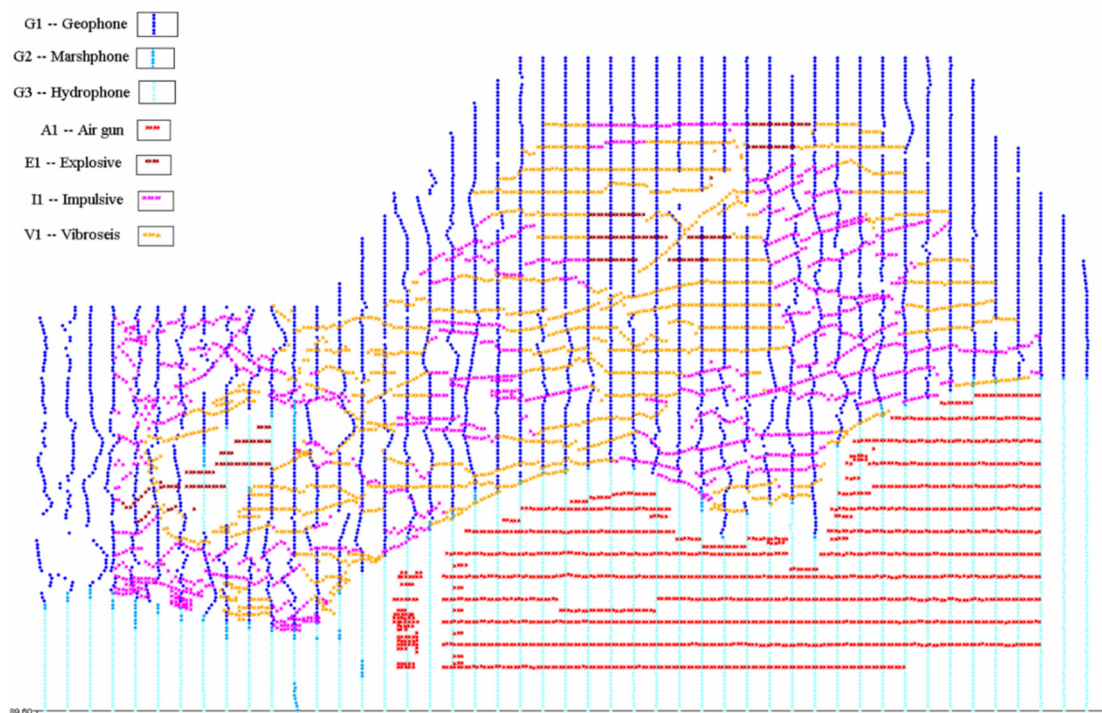


Fig. 2. Seismic sources and receivers used

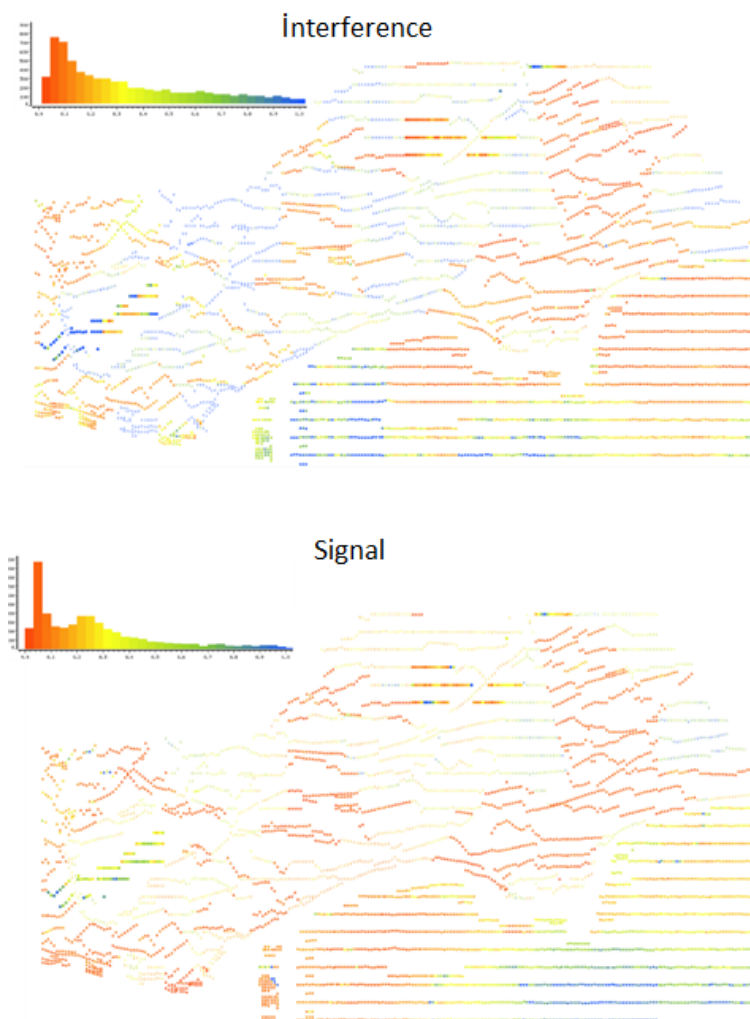


Fig. 3. Amplitude spectra of the useful signal and noise within the cone

The amplitude spectrum of the useful signal (Fig. 3) was calculated at offsets of 850–1500 m within a time window of 800–2500 ms, while the amplitude and frequency of low-velocity surface-wave noise were determined at offsets of 0–500 m within the same window. Analysis of the results showed that areas with different types of sources are clearly distinguishable on the amplitude map. The lowest amplitude values were observed for the impulsive source. In addition, seismograms from the acoustic source also differ from one another. The dispersion of dominant frequencies across the area varies significantly, which may be related to the different

types of sources (Fig. 3). In general, the signal frequencies across the area range from 5 Hz to 35 Hz, with most of the data having signal frequencies between 10 Hz and 20 Hz. Figures 4 and 5 show fragments of representative field seismograms of the sources and their amplitude frequency spectra. Overall, the seismograms are complicated by surface-wave cones of varying intensity and frequency. For the impulsive source, a high noise level and a low signal-to-noise ratio are characteristic. Additionally, the use of overlay charges on the lake proved to be ineffective, as the seismograms exhibited strong surface noise and low useful-signal frequencies.

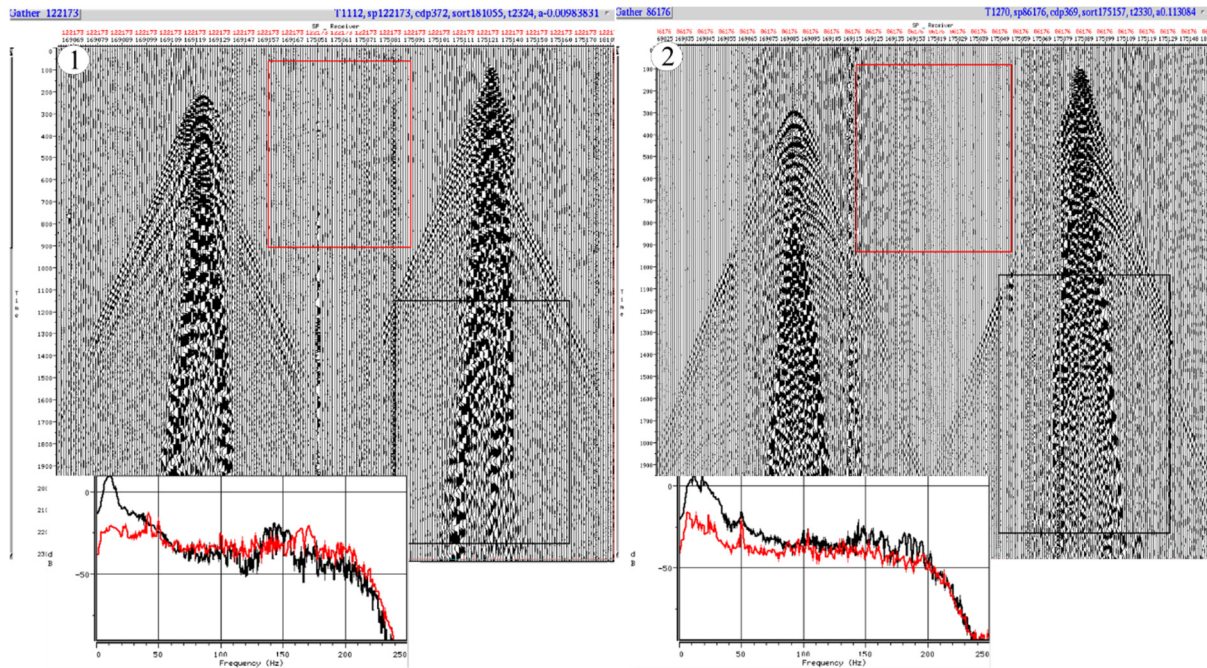


Fig. 4. Fragments of field seismograms with amplitude spectra of the corresponding windows:
1) explosive source; 2) impulsive source

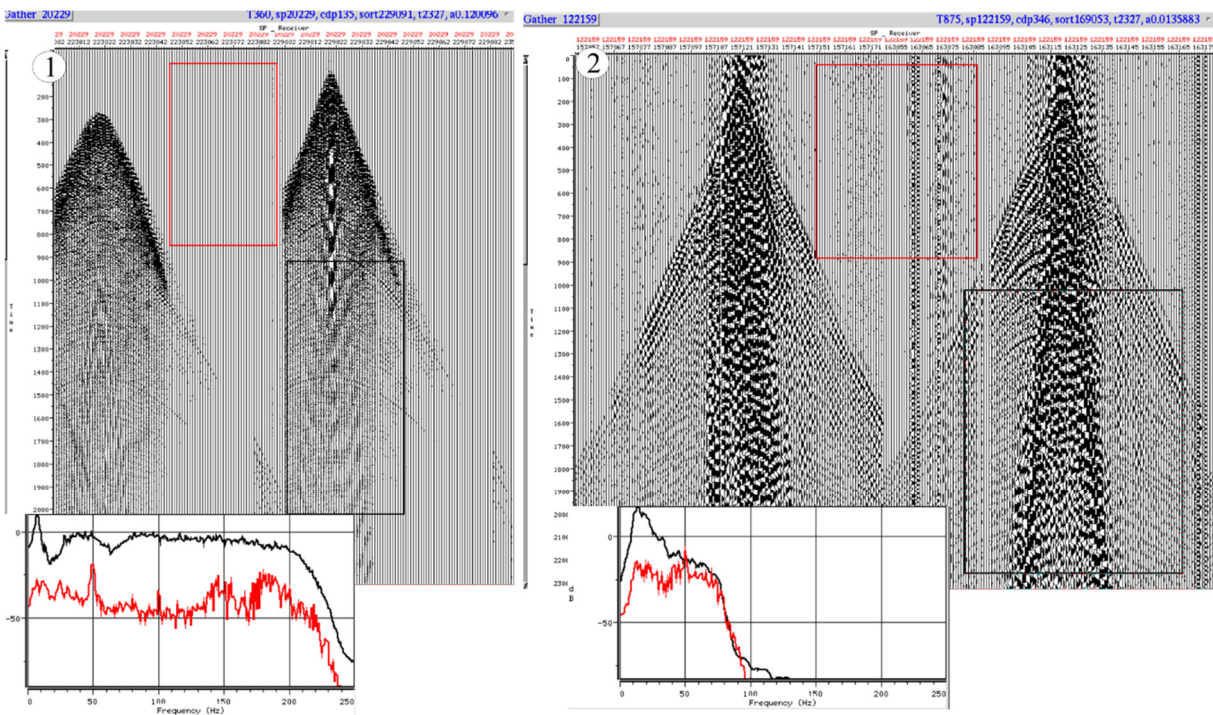


Fig. 5. Fragments of field seismograms with amplitude spectra of the corresponding windows:
1) acoustic source; 2) vibratory source

To obtain a combined seismic cube, the most important processing task was to bring the seismic signals from all source types to a unified form, specifically to minimum phase (Abdolahi, Chehrazai, & Kadkhodaie, 2022; Russell, 1988; Veeken, & Da Silva, 2004). As noted earlier, four types of sources and three types of receivers were used in this area. From a theoretical standpoint, the signals from explosive and impulsive sources are similar and have a minimum-phase impulse shape, whereas the vibratory source produces a zero-phase signal, and the acoustic source generates a mixed-phase signal.

To convert the impulse from the vibratory source to a minimum-phase form, modeling was performed based on the available sweep-signal data (linear sweep in the 8–80 Hz frequency band, duration 10 s, taper 0.5 s) to generate a Klauder wavelet, for which a minimum-phase conversion filter was then calculated (Fig. 6). During the modeling, a conversion filter was successfully obtained; however, its subsequent application to real data proved ineffective, as the filter altered the signal phase inconsistently across frequencies. In contrast, using a minimum-phase filter over the frequency band of the sweep signal yielded better results, which is why this filter was ultimately chosen.

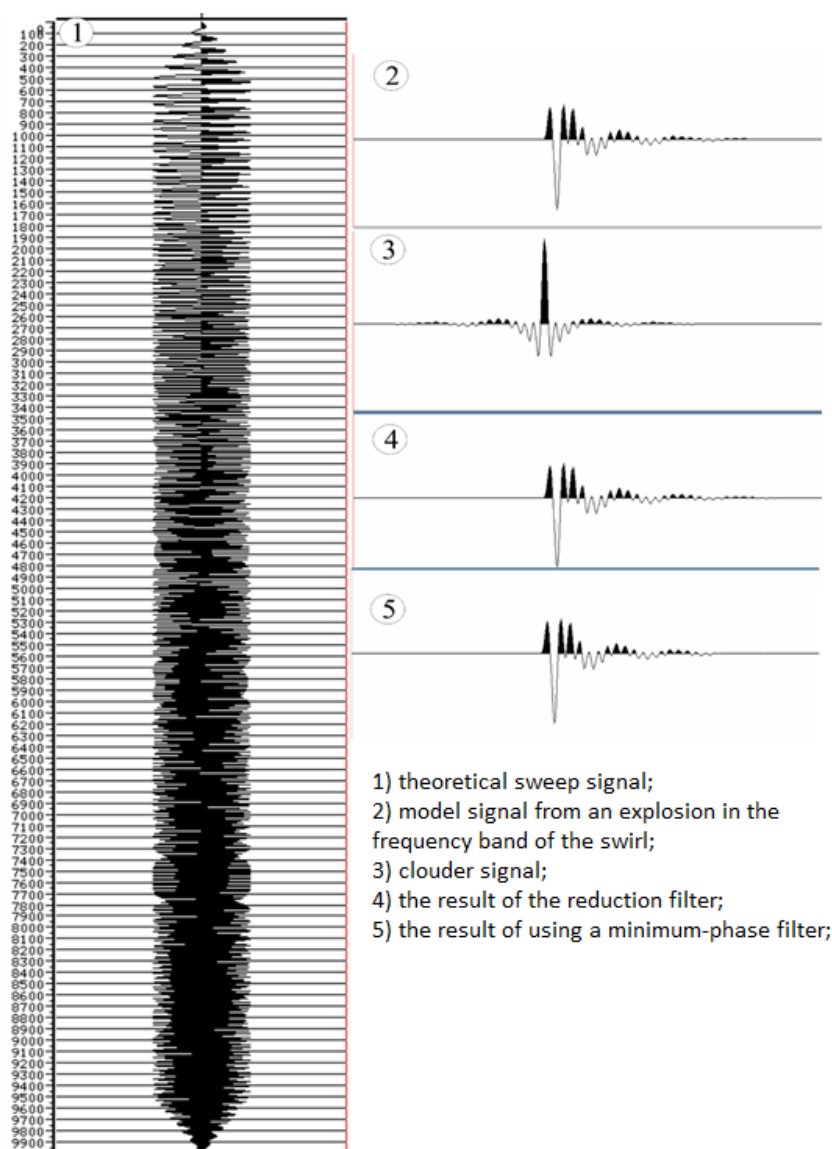


Fig. 6. Conversion of the vibratory source to a minimum-phase impulse form using modeling

The acoustic source has a mixed-phase signal characteristic. To convert it to a minimum-phase form, statistical deconvolution was applied, bringing the pneumatic gun signature to a unified minimum-phase equivalent (Russell, 1988; Veeken, & Da Silva, 2004). This procedure was carried out within a broad time window of W800–W2500 ms, with a noise factor of 1 % and an operator length of 400 ms.

Due to the use of different types of receivers in the area (geophones, hydrophones, and transition-zone receivers), a correction for non-identity was applied (Abdolahi, Chehrazai,

& Kadkhodaie, 2022; Veeken, & Da Silva, 2004). For this purpose, amplitude and frequency maps of the signal were constructed. Based on the analysis of these maps and seismograms from different sources using various receivers, it was concluded that the signal frequency and phase do not depend on the type of receiver. The only difference was in amplitude, which varied across the area. This variation was corrected by applying a surface-consistent dynamic correction for both sources and receivers.

Discussion and conclusions

Due to the complex and difficult-to-interpret interference patterns in the intervals corresponding to the main target objects, it was decided to apply seismic inversion (Abdolahi, Chehraz, & Kadkhodaie, 2022; Russell, 1988). This inversion, by removing interference effects, allows for a direct representation of geological objects on seismic

sections (within the achieved resolution), while direct calibration of the PAC traces with well log data enables work at the level of reservoir elements, such as the top and bottom of the layer (Fig. 7). In other words, PAC inversion makes it possible to transition from a quasi-synchronous seismic time section to an approximate lithological section.

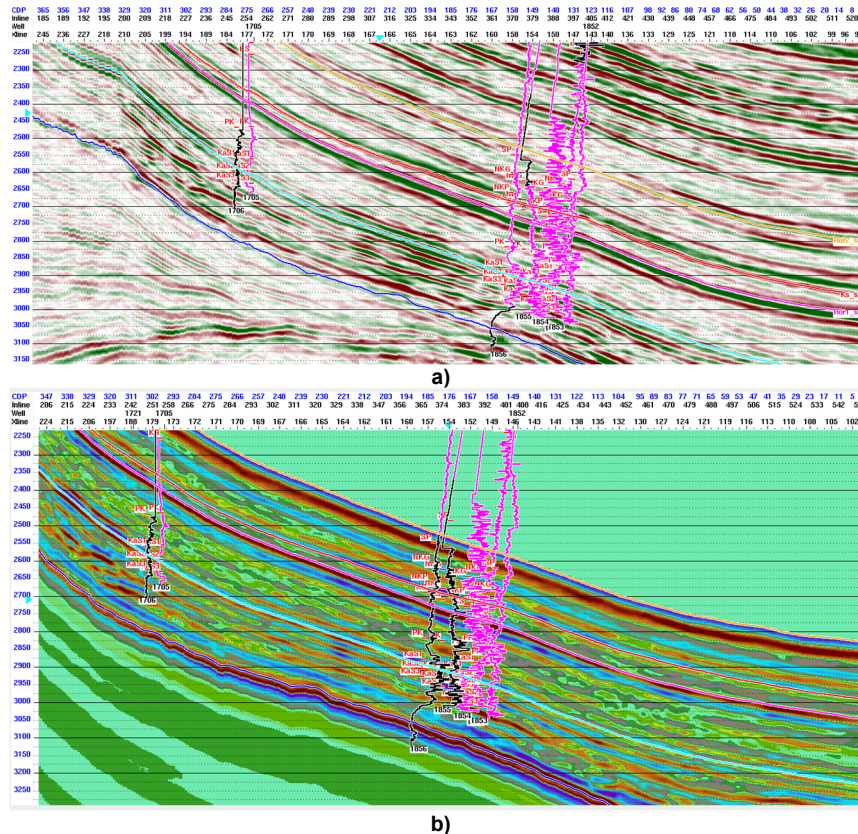


Fig. 7. Vertical time section (a) and the corresponding PAL section (b) in relative impedances along the traverse

The inversion was performed using the Hampson-Russell software suite in deterministic mode, which is based on the use of an a priori geological model. The key procedures in the inversion are the estimation of the "initial" signal and the construction of the a priori geological model. The signal estimation was carried out in two stages. In the first stage, seismic data were tied to the geological section. This tie was performed over a broad window encompassing the entire target interval. For the initial approximation, a zero-phase signal calculated from seismic data in the vicinity of Well 1856 using VSP data was used (Fig. 8). Signal estimation was performed only near Well 1856, where a complete set of well-log data required for accurate tying was available: VSP results, density, and acoustic logs. The final estimate of the "initial" impulse was taken as the signal shown in Fig. 8, characterized by a phase shift of 13° .

To construct the a priori geological model, the target interval is divided into thick layers with uniform layering characteristics (based on the pattern of filling reflections). This thick-layered model is used to transfer correlation across the inter-well space when building a 3D a priori model from well-log data. The resulting model serves as a framework for the actual inversion of seismic traces into pseudo-acoustic impedance. The degree to which the framework model influences the inversion is controlled by the corresponding parameters.

Figure 9 presents a comparison of vertical slices of the relative impedance cube along line 364 of the Govsan field. A detailed analysis of this cube slice shows that, in both sections, a pronounced decrease in acoustic impedance values is observed (Riahi, & Fakhari, 2022) at the level of the underlying PT deposits. This decrease is mainly associated with a sharp reduction in seismic wave velocities and densities, ranging from -110 to -2598 (m/s) $\times$ (g/cm³), within clayey deposits saturated with fluids, which is characteristic of zones with abnormally high formation pressures (AHFP (Riahi, & Fakhari, 2022; Sun et al., 2023). The existence of an AHFP zone is also confirmed by the results of vertical seismic profiling (VSP) conducted in two wells of the Govsan field (Ahmadov, 2019; Starostenko, Legostaeva, & Savchenko, 2014).

VSP (Vertical Seismic Profiling) surveys were successfully conducted in well 1856 in the summer of 2010 and in well 1867 in 2014 (Starostenko, Legostaeva, & Savchenko, 2014). The surveys were conducted in the cased Well 1856 (single and double casing) using impulsive sources, including a pneumatic chamber and the most advanced four-level VSP probe available at the time, the VSI-4. No significant problems were encountered during the field observations. The acquired data are of good quality and suitable for the objectives and tasks set for the VSP surveys.

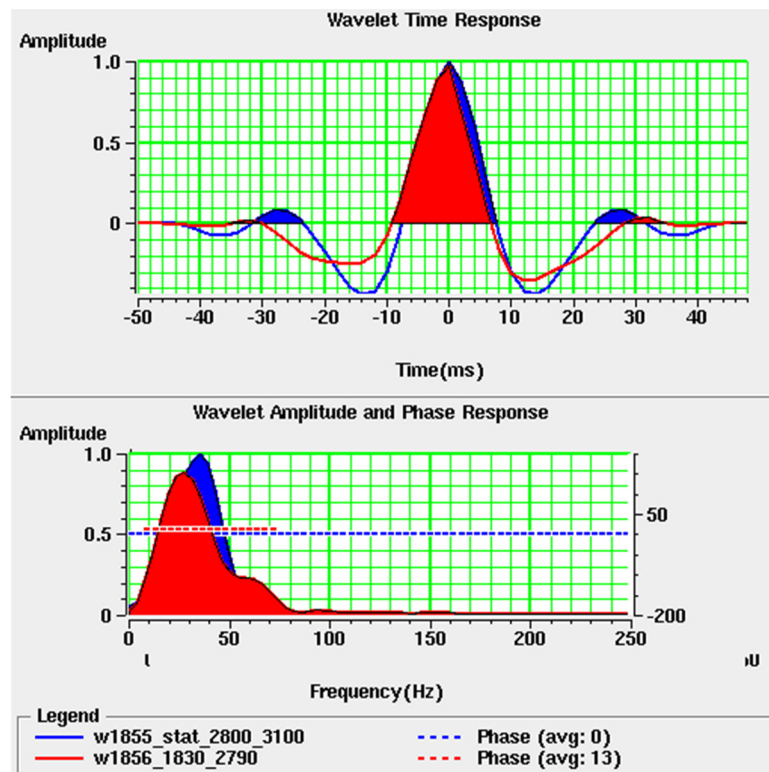


Fig. 8. Impulse estimates calculated near Well 1856: zero-phase (blue) and final (red)

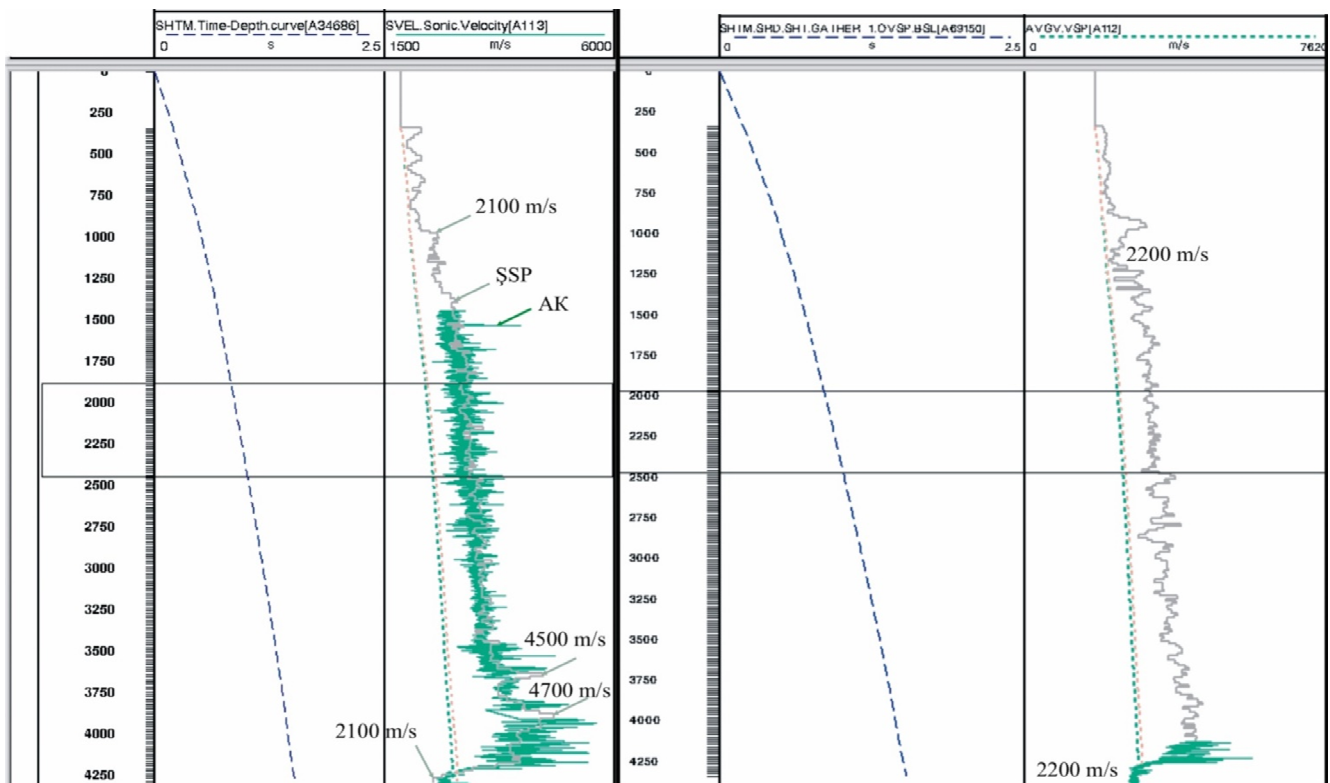


Fig. 9. Vertical hodograph (a) and interval velocity curve calculated from VSP data, compared with the well-log velocity curve (b)

During data processing, the most efficient multicomponent methodology was applied, which includes polarization analysis, calculation of projections, and parametric decomposition of wavefields. This approach enables simultaneous processing of all three recorded XYZ components, allowing the extraction of reflected scalar waves with the highest possible quality. The processed data were migrated, resulting in both time and depth

VSP sections. The constructed models were successfully validated for structural dip and acoustic properties using the complete set of recorded VSP data. Therefore, the reliability and accuracy of the VSP results can be considered well substantiated. A joint analysis of the VSP sections and surface seismic data demonstrated a good level of consistency between them.

To predict velocities below the well bottom and to extend the depth–time relationship for estimating the depths of the most interesting reflecting horizons, it was decided to perform Pseudo-Acoustic Logging (PAL), also known as acoustic impedance inversion. The PAL was calculated based on the corridor stack of reflected waves from the VSP data. Since any inversion is a highly non-trivial process, numerous iterations of PAL with different inversion parameters were analyzed. The presented results are stable and consistent with the a priori information. For the PAL inversion, the dominant frequency range of the VSP data 5–70 Hz was selected.

It should be noted that the theory of PAL (Pseudo-Acoustic Logging) is developed for a one-dimensional medium: flat-layered structure, vertical well, and a VSP observation configuration corresponding to a vertical profile. These assumptions are not entirely accurate for Well H1867, which does not allow for a guarantee of 100 % reliability of the obtained data. Nevertheless, the results appear to be correct rather than false-synthetic (i.e., they do not exhibit uncharacteristic behavior, doubtful values, or inversion instability).

In addition, the recorded VSP and well-log data show a significant decrease in velocities in the lower part of the section, which also confirms the PAL results. The predicted P-wave velocity below the well bottom was used to calculate a predictive depth–time relationship, which, in turn, can be used to estimate the expected depths of the most interesting reflecting horizons below the well bottoms.

Without going into the detailed processing and interpretation of the VSP data, we note several important results of the well seismic surveys (Salmanov et al., 2023; Starostenko, Legostaeva, & Savchenko, 2014). Analysis of the velocity curves obtained from VSP and well-log data below the bottoms of the studied wells shows that, after a significant increase in interval velocities, a sharp decrease to approximately 2000 m/s is observed at greater depths, corresponding to a depth of about 1000 m (Fig. 9). A similar pattern is observed in both wells. In our view, this clearly indicates the presence of an AHFP (abnormally high formation pressure) zone at this field, associated with fluid accumulations in the underlying PS deposits. In our opinion, this clearly indicates the presence of an abnormally high formation pressure (AHFP) zone within the studied field, associated with fluid accumulations (Riahi, & Fakhari, 2022; Sun et al., 2023). Such abnormally elevated pressures arise as a result of reservoir sealing during burial, when formation fluids lose the ability to escape from the reservoir and thus prevent rock compaction under the increasing load of the overlying strata, i.e., lithostatic pressure. In effect, only a portion of the overburden weight is transmitted by the rock framework to the pore-filling fluid. Consequently, the rock experiences differential (effective) pressure corresponding to a somewhat shallower depth, and the seismic velocity within it corresponds to that reduced depth.

A one-dimensional V_p – V_s velocity model was constructed as the first-approximation 1D V_p – V_s model for parametric decomposition based on VSP data from wells No. 1856 and 1867. The constructed models were compared with slices extracted from the seismic inversion cubes, which demonstrated their complete consistency with respect to the AHFP zone.

As noted above, the Hovsan field is located in the southeastern part of the Absheron Peninsula and extends into the offshore zone of the Caspian Sea. In 2017, well No. 1870 was drilled targeting the underlying PT formations, where an abnormally high formation pressure (AHFP) zone was anticipated based on VSP data. Indeed, the wellhead

pressure reached approximately ~800 atm, compared with the expected 400 atm. The well flowed uncontrollably for several days and was eventually suspended due to technical constraints.

Surface and well seismic studies made it possible to identify an AHFP (abnormally high formation pressure) zone in the Hovsan field section, which stratigraphically corresponds to the underlying PS deposits. Lithofacies-wise, these deposits consist of clay-rich formations with interbedded sands. These sand layers were not clearly visible on conventional seismic sections. However, seismic inversion of the 3D seismic data allowed these sand interbeds to be identified.

A key finding is that the AHFP zone is clearly distinguished in vertical sections of both absolute and relative pseudo-acoustic impedance. Thus, seismic inversion of 3D seismic data can be effectively used to predict the AHFP zone (Abdolahi et al., 2022).

A well drilled into Miocene deposits in 2015 confirmed these predictions, producing a flow of approximately 100 tons of oil per day, thereby further confirming the hydrocarbon potential of the underlying PS deposits within the studied field.

Authors' contribution: Tofik Ahmedov – conceptualization, methodology, writing (original draft), formal analysis; Amikishi Asadli – data curation, visualization, writing (review and editing); Goychek Tashviqi – investigation, validation, writing (review and editing).

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ПРОГНОЗУВАННЯ ЗОН АНОМАЛЬНО ВИСОКОГО ПЛАСТОВОГО ТИСКУ З ВИКОРИСТАННЯМ ДАНИХ 3D СЕЙСМІЧНОЇ ІНВЕРСІЇ

Вступ. У статті наведено відомості про розташування досліджуваного родовища Говсан, історію його вивчення різними геологічними та геофізичними методами, а також основні отримані результати. Зазначається, що дослідження цієї території розпочалося ще у XIX ст. із прилеглому району Сухани-Карачухур, де було пробурено першу розвідувальну свердловину (район Карачухур). У 1930–1940-х рр. у межах досліджуваної території також проводилися різні геофізичні дослідження, і в результаті електророзвідки було отримано перше уявлення про тектоніку Біна-Говсанської синклінали. Дані газозйомки згодом дали змогу виявити аномальні зони в межах родовища Говсан. Сейсмічні дослідження проводилися з 1930-х до середини 1950-х рр. методом відбитих хвиль (RM), а у 1977–1978 рр. – методом спільної глибинної точки (CDP). Окремі сейсмічні профілі було отримано у 1993 та 1999 рр. Детальні дослідження методом CDP виконувалися у 1996 та у 2003–2004 рр. У 1948 р. в свердловині №1308 у калінській світі продуктивної товщі було відкрито нафту, після чого родовище Говсан було введено в промислову експлуатацію. Нині родовище розробляється лише на суші, оскільки його морські межі залишаються невизначеними через недостатню вивченість.

Методи. У 2011–2012 рр. у районі Зих-Говсан було проведено 3D-сейсмічні дослідження методом CDP. Роботи виконувалися за різноманітних приповерхневих сейсмо-геологічних умов і охопили площу 70 км². Наведено інформацію щодо польових робіт: у цій зоні використовувалися чотири типи джерел сейсмічної енергії та три типи приймачів. Під час польових робіт не було належним чином виконано узгодження джерел, що спричинило труднощі при обробці даних. Крім того, калібрування приймачів було проведено лише частково, що також ускладнило обробку. Особливу увагу приділено застосуванню сейсмічної інверсії.

Вертикальне сейсмічне профілювання (VSP) було успішно проведено у двох свердловинах родовища Говсан: № 1856 та № 1867. Наведено коротку інформацію про свердловинні дослідження та обробку отриманих даних.

Результати. Отримано результати псевдоакустичної інверсії (PAC-інверсії), а також проведено порівняння вертикальних розрізів кубів абсолютного та відносного акустичного імпедансу вздовж одного з профілів 3D-зйомки родовища Говсан. Показано, що в обох розрізах на рівні підстильних відкладів продуктивної товщі (PS) спостерігається різке зниження значень акустичного імпедансу. Це зниження головним чином пов'язане з різким зменшенням швидкостей сейсмічних хвиль і густини – від 110 до 2598 (м/с)×(г/см³) – у глинистих, насичених флюїдом породах, характерних для зон аномально високого пластового тиску (АВПТ).

Наявність зони АВПТ також підтверджується результатами VSP, отриманими у двох свердловинах родовища.

Наземні та свердловинні сейсмічні дослідження дали змогу виявити зону АВПТ у розрізі родовища Говсан. Стратиграфічно інтервал АВПТ охоплює підстильні відклади продуктивної товщі, які літологічно представлені глинистими відкладами з прошарками пісків. Ці піщані прошарки не відображалися на традиційних сейсмічних розрізах. Однак інверсія 3D-сейсмічних даних дозволила їх виділити.

Висновки. Важливим висновком є те, що зона АВПТ чітко виділяється на вертикальних розрізах як абсолютного, так і відносного акустичного імпедансу. Отже, можна стверджувати, що сейсмічна інверсія 3D-сейсмічних даних може бути використана для прогнозування зон АВПТ.

Свердловина, пробурена у міоценових відкладах у 2015 р., підтвердила наші припущення та дала приплив близько 100 тонн нафти на добу, що додатково підтверджує нафтогазоносний потенціал підстильних відкладів продуктивної товщі в межах досліджуваної території.

Ключові слова: нафтогазоносність, сейсмічна інверсія, сейсмічний розріз, VSP, міоценові відклади, 3D-сейсмічна зйомка.

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