

Tofik AHMADOV, DSc (Geol. & Mineral.), Prof.

ORCID ID: 0000-0003-0634-5600

e-mail: akhmedov.tofik@bk.ru

Azerbaijan State Oil and Industry University, Baku, Azerbaijan

Amikishi ASADLI, Doctoral student

ORCID ID: 0009-0003-0711-8028

e-mail: amikishiasadli@gmail.com

Azerbaijan State Oil and Industry University, Baku, Azerbaijan

Goychak TASHVIGI, Doctoral student

e-mail: goycektesviqi@gmail.com

Institute of Geology and Geophysics, Baku, Azerbaijan

Seismic Inversion of VSP Data from the Govsany Field in Azerbaijan and Depth Estimation of Key Seismic Horizons Below the Kalin Suite of the Productive Series

Abstract

This paper presents a comprehensive study of Vertical Seismic Profiling (VSP) data and Pseudo-Acoustic Logging (PAL) inversion applied to well H1856 at the Govsany hydrocarbon field located on the Absheron Peninsula, Azerbaijan. The primary focus is on the analysis and prediction of seismic velocities below the well bottom to establish a reliable depth-time relationship, which in turn was used to forecast the depths of key seismic reflecting horizons, particularly those lying beneath the Kalin Suite — the main productive formation of the field. The VSP observations, conducted with multi-component processing, demonstrated high-quality data that correlate well with acoustic logging measurements, enabling the construction of robust one-dimensional and two-dimensional velocity models to characterize the acoustic properties of subsurface formations.

PAL inversion was successfully implemented using a dominant frequency range of 5 to 70 Hz, resulting in stable and adequate velocity profiles that reveal a significant velocity decrease below the well bottom. The derived depth-time model facilitated the prediction of depths for important seismic horizons, information that was crucial in guiding the drilling of the deep production well 1870. This well discovered productive reservoirs within an abnormal high-pressure zone (AHPZ) and was operated successfully before being decommissioned for technical reasons.

The study underscores the importance of integrating VSP and acoustic logging data to improve the accuracy of seismic interpretation and reservoir characterization. Furthermore, it highlights the limitations of conventional inversion theories when applied to deviated wells such as H1856, emphasizing the inherent uncertainties that must be considered. For future seismic acquisition efforts, the use of vibrational seismic sources is recommended due to their stable frequency spectra across all depths, which would significantly enhance data resolution compared to impulsive sources like pneumatic chambers. Overall, the research provides valuable insights into seismic velocity modeling and horizon depth prediction in complex geological settings, contributing to optimized well placement and resource development strategies.

Introduction

The vertical seismic profiling (VSP) observations under consideration represent the first borehole seismic survey project conducted by Schlumberger in the world's oldest oil- and gas-bearing region — the Absheron Peninsula of Azerbaijan. The work was carried out in Well No. 1856 of the Govsany field, which is currently one of the most actively developed onshore oil fields in Azerbaijan.

Let us briefly describe the studied Govsany field. It is located in the Surakhani district of Baku, Republic of Azerbaijan, in the southwestern part of the Absheron Peninsula (Fig. 1).

The terrain is characterized by a coastal plain mainly covered with ancient Caspian deposits. From the northwest and west, the area is bordered by a plateau-like elevation, extending nearly in a meridional direction, formed of Absheron limestones.

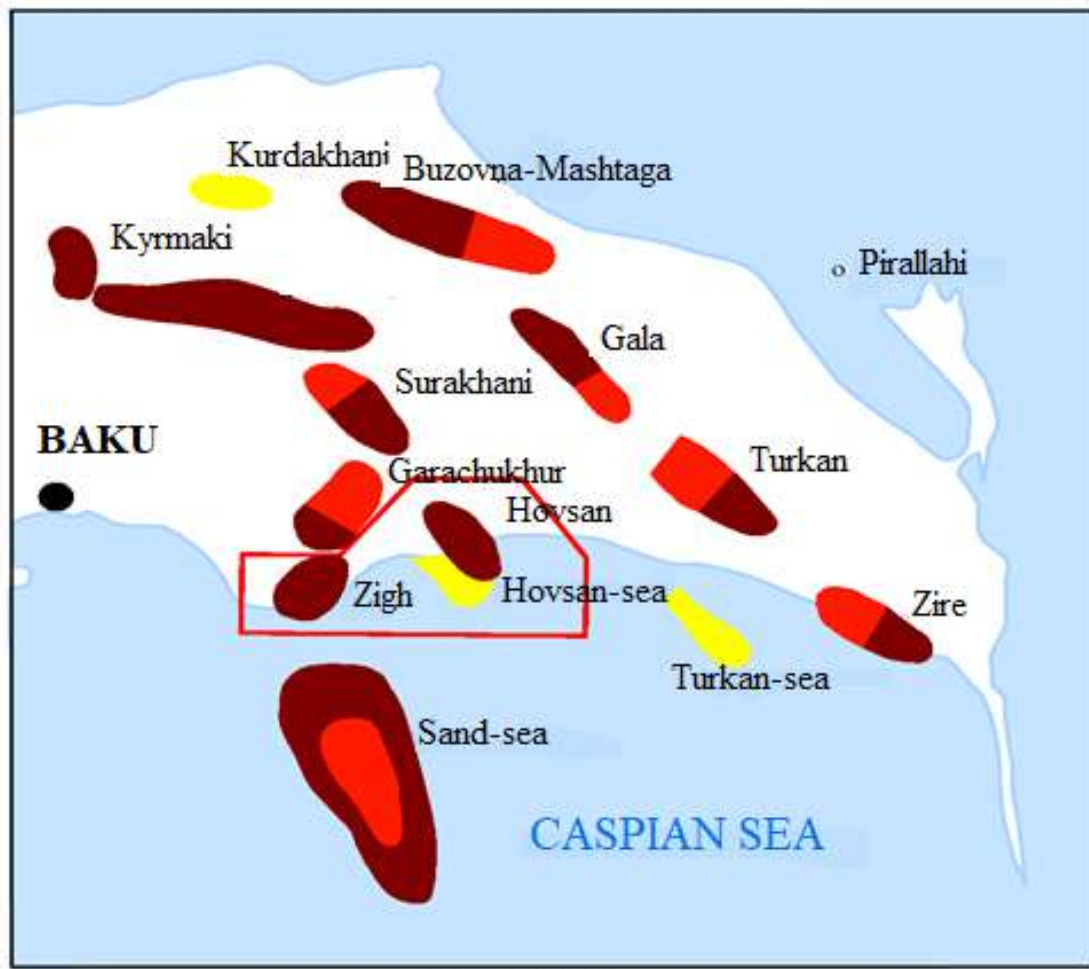
The work area contains numerous industrial facilities, including small plants, an electrical grid, auto repair shops, garages, water pumping stations, oil and water settling structures, and others. These industrial facilities are scattered throughout the territory, with a higher concentration in the central part of the field.

Between 1932 and 1935, a large number of exploratory-structural wells were drilled in the Govsany area by the Azneftarazvedka trust. Based on the obtained data and seismic surveys, a monoclinical bedding of the formations was established (Fig. 2). In 1948, Well No. 1308 within the Kalin suite of the productive series of the Lower Pliocene was discovered and brought into industrial development as the Govsany oil field.

In total, approximately one hundred exploratory and production wells have been drilled in the field: 3 exploratory, 20 appraisal, and 45 production wells. Currently, 45 wells have been decommissioned, including 24 due to geological reasons and 21 due to technical causes. During the 1990s, 11 wells were drilled at the field.

The field is exploited solely onshore, as its offshore boundaries remain undefined due to insufficient study. The main oil-bearing deposits are those of the Kalin suite of the productive series. The productive series, associated with Middle Pliocene deposits, contains the richest oil and gas reserves across all fields of the Absheron Peninsula. The series has a thickness exceeding 3500 meters and is primarily composed of alternating sandy and clayey formations.

Thanks to years of comprehensive litho-facies, petrographic, microfaunal, and other studies, the productive series is well researched.



M. 1: 230 000

SYMBOLS:






-  - oil fields
-  - oil and gas fields
-  - promising deposits
-  - coastline
-  - outline of works of the MOGT-3D

Fig. 1. Map of the hydrocarbon-bearing area of Govsany (excerpt)

The Lower Pliocene formations lie unconformably on Pontian clays and are widespread. The productive series of the Lower Pliocene is subdivided into upper and lower sections due to an erosional unconformity between them.

The lower section of the productive series consists of the Kalin (KaS), Podkirmakin (PK), Kirmakin (KS), Upper Kirmakin Sandy (UKS), and Upper Kirmakin Clayey (UKG) suites.

The Kalin Suite (KaS) is the basal suite of the productive series and occupies only the southern and southeastern parts of the Absheron Peninsula. Its thickness increases southward, following the dip of the formations, from 0 to 385 meters, reaching a maximum within the Bina-Govsany depression.

Geological exploration and appraisal works here have established a decrease in thickness and, in some places, the pinch-out of the Kalin Suite upwards along the structural rise. These formations lie unconformably on an eroded surface of Pontian deposits, characterized by a sharply expressed angular unconformity. North of the saddle that separates the Surakhani uplift from the Balakhani-Ramani area, deposits of the Kalin Suite are absent across the entire Absheron Peninsula. They are also missing in the uplifted parts of the folds.

The increase in thickness of the Kalin Suite occurs due to a stratigraphic thickening of its section, resulting from the appearance of new layers at the base of the suite.

At the Govsany field, only the Kalin Suite is oil-bearing. In the northeastern and eastern parts of the field, wells 1810 and 1820 have penetrated the entire thickness of the Kalin Suite, measuring 250 m and 280 m respectively. The depth to the top of the Kalin Suite at the Govsany field ranges from 3,327 m (well 1410) to 4,245 m (well 1829).

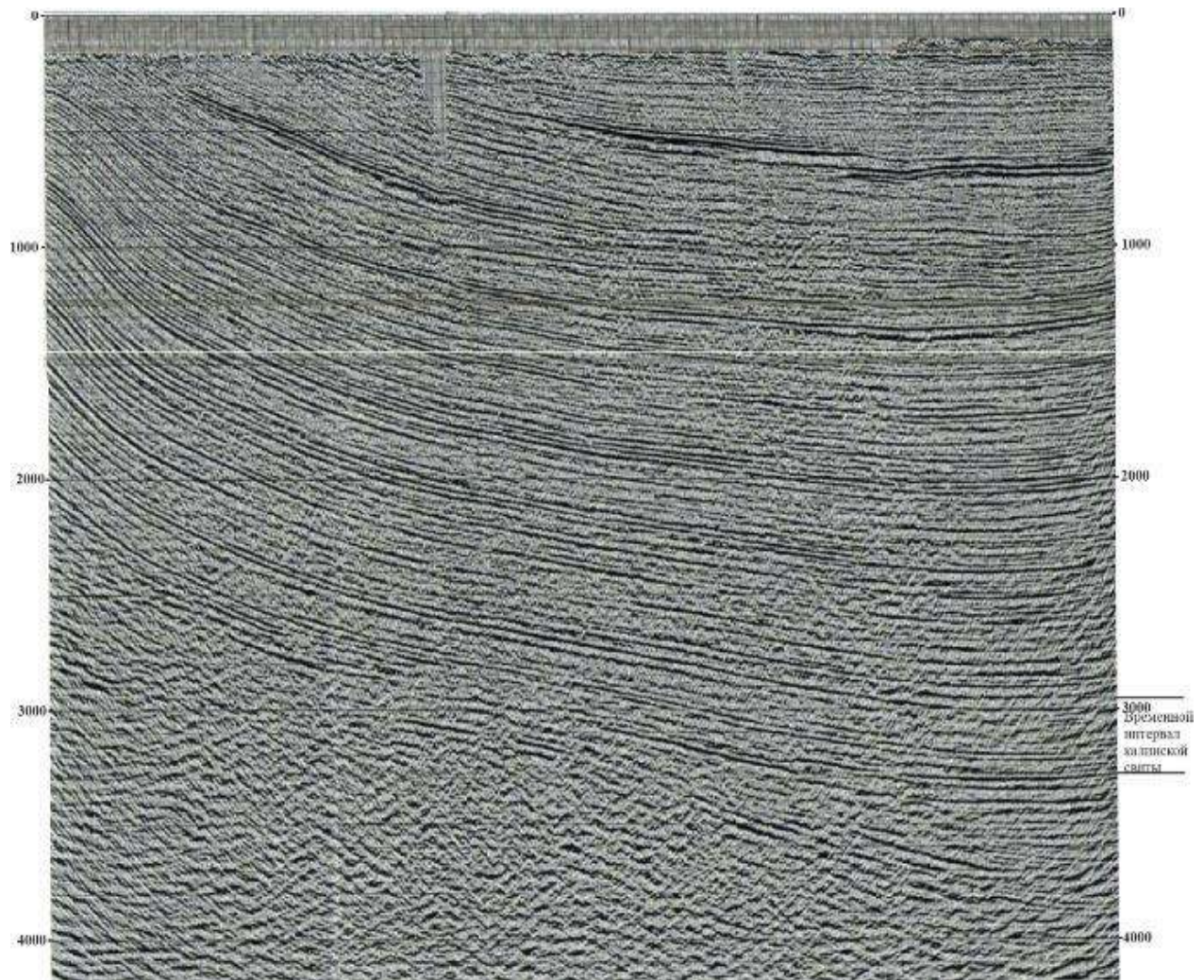


Fig. 2. 2D Seismic Section along Profile 030808

Lithologically, the Kalin Suite is characterized by alternating interlayers of clayey and sandy rocks. The sandy and aleuritic rocks appear as gray, light gray, locally dark gray, and yellowish varieties. Granulometric analysis indicates that the sand-aleurite rocks of the Kalin Suite are poorly sorted. The clayey rocks are well sorted and contain only a minor admixture of aleuritic material; they are mainly gray, dark gray, and finely laminated. The lower part of the suite is relatively more clayey.

The deposits of the suite are divided from top to bottom into three sand-aleurite packages: KaS-1, KaS-2, KaS-3, with a fourth horizon, KaS-4, identified in recent years. This division was possible due to differences in both lithology and oil-bearing properties of the delineated packages. Each of the identified layers is further subdivided into several thinner sublayers.

At the top of the KaS-3 layer is the SG-IIIa horizon, which is only traced within the Bina-Govsany syncline (Govsany field). According to seismic data, this horizon is bounded by fault disruptions to the west and east. The SG-III horizon, corresponding to the top of the Kalin Suite, is traced throughout the entire area.

The Govsany field was discovered in 1948 by well 1308, which yielded a flowing oil influx from intervals 3697–3694 m and 3709–3706 m (KaS-2 layer) with a production rate of 56 tons/day of oil and 118 tons/day of water. As noted earlier, hydrocarbon presence in the field has been established solely in the Kalin Suite layers.

Four layers are distinguished within the Kalin Suite deposits: KaS-1, KaS-2, KaS-3, and KaS-4, which currently serve as production units. The reservoir layers are divided into blocks I, II, III, IV, and V by tectonic faults.

The VSP studies were conducted in well 1856 of the Govsany field, which is located within the Absheron oil and gas-bearing region. The location of well 1856 is shown in Fig. 3.

The selected VSP setup represented a combination of longitudinal (VSP) and non-longitudinal (NVSP) profiles. The primary objectives of the study were:

- построение точной глубинно-временной зависимости ВСП и получение надежной информации о скоростях;
- калибровка Акустического Каротажа, расчет синтетических сейсмограмм и таблиц для глубинно-временных преобразований в масштабе калиброванного АК;
- обработка, записанных волновых картин ВСП, с выделением отраженных Р-волн;

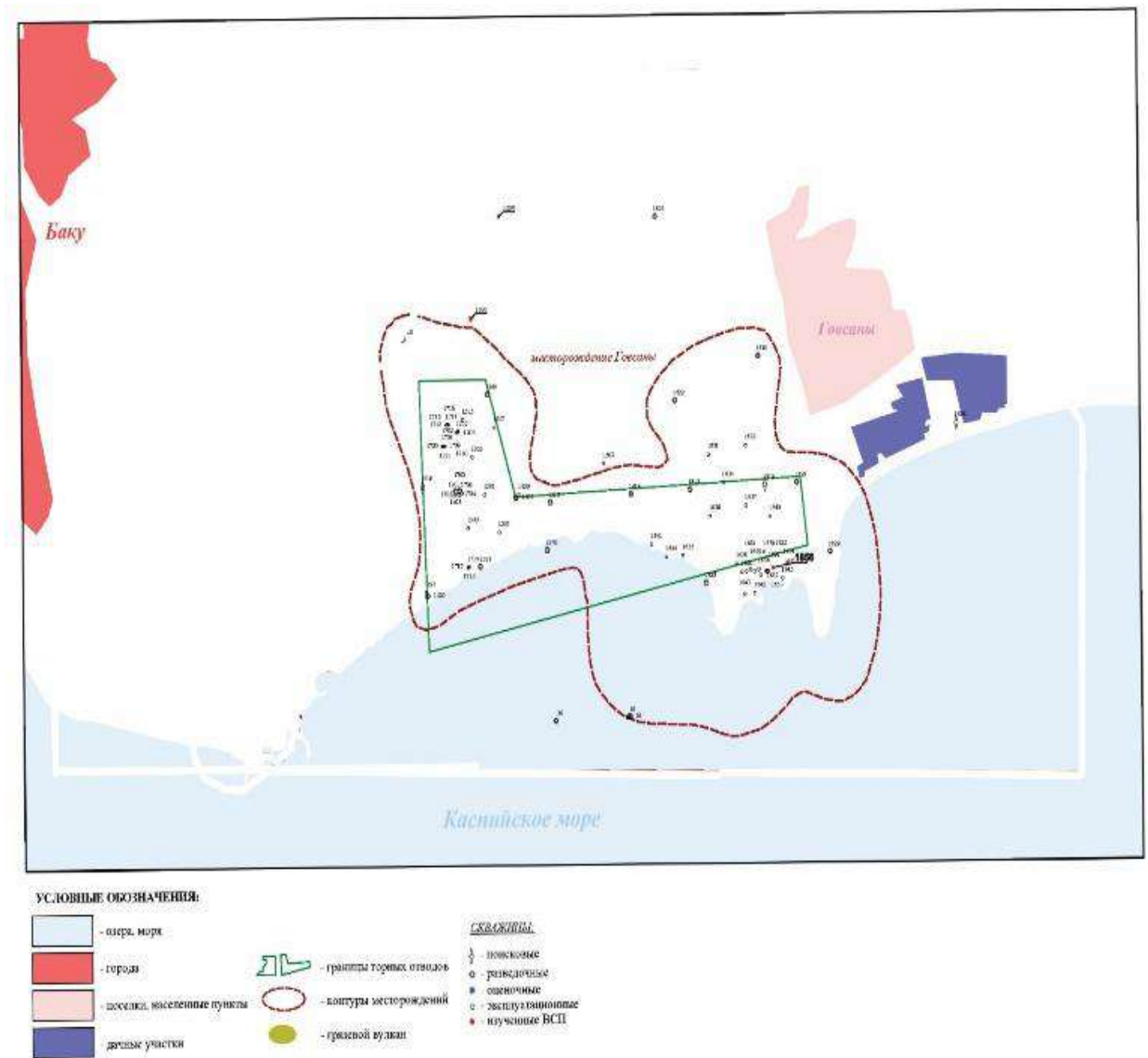


Fig. 3. Deep Drilling Study Scheme of the Govsany Area

Research method

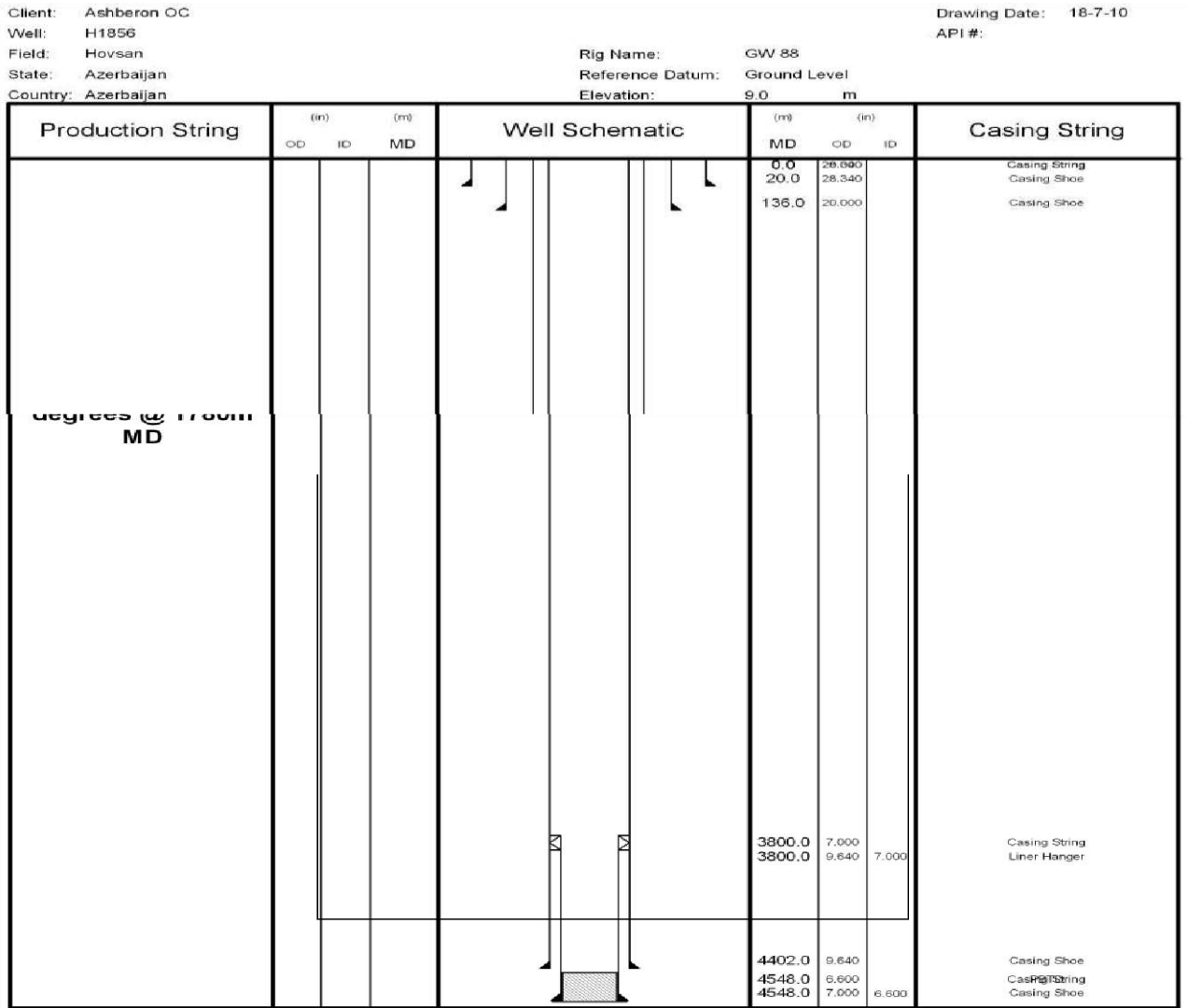
Field observations of VSP and NVSP (non-vertical seismic profiling) were conducted using a four-point VSI-4 probe. This instrument is equipped with a three-component accelerometer-type seismic receiver. A pneumatic chamber with a volume of 250 cubic inches and a shot pressure of 2000 psi was used as the source. The source depth was set at 2 meters below ground level for both VSP and NVSP measurements.

The monitoring hydrophone was suspended 1 meter above the source in both setups. The source-controller offset for the VSP was 87.1 meters, and for the NVSP, it was 1304.7 meters; the azimuth of the VSP offset was 189°, and for NVSP, 287.2°. The most important altitudes were as follows: rotor table at -17.44 m; ground level at -26.44 m; reference level — Baltic Sea level.

The observed intervals included 275 levels of the longitudinal VSP profile (between 4500 m and 324.2 m measured depth) and 270 levels of the non-longitudinal NVSP profile (between 4499.93 m and 400.46 m measured depth). The chosen depth sampling interval was approximately 15.12 m for both setups.

VSP data were recorded in the cased well using both single and double casing strings (Fig. 4). The well deviation reached up to approximately 37.15° (Fig. 5). VSP data were recorded in the cased well using both single and double casing strings (Fig. 4). The well deviation reached up to approximately 37.15° (Fig. 5).

The shot pressure of the pneumatic chamber remained sufficiently stable during both VSP and NVSP observations. The acquired data are logically consistent and of good quality, with clearly defined first arrivals. The last several levels of the VSP were complicated by tube waves and head wave refraction (only in NVSP). Polarization analysis and frequency-band filtering helped to recover accurate first arrival times in these zones affected by the mentioned interferences (Fig. 6).



ALL DEPTHS ARE DRILLERS DEPTHS

Fig. 4. Well Construction

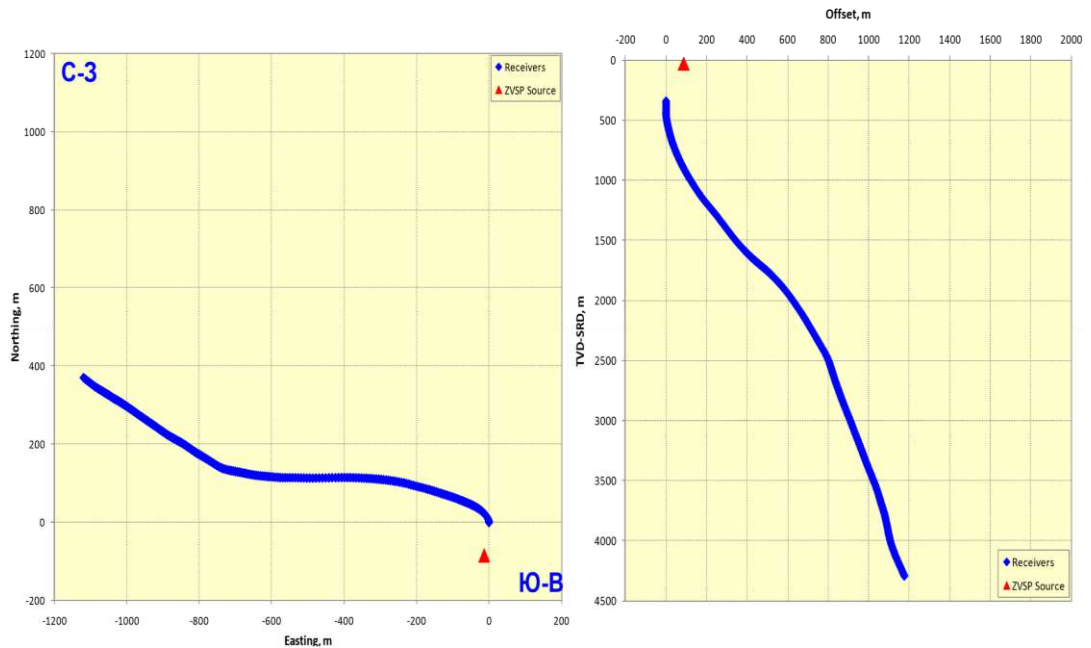


Fig. 5. VSP Layout Geometry: side plan view; red — sources; blue — receivers; the well is taken as the reference point (0,0)

The frequency content of the reflected P-waves is limited to 80 Hz, and that of the shear S-waves to up to 70 Hz, which is adequate. The effect of aliasing of reflected frequencies is observed above approximately 80–90 Hz for P-waves and around 30 Hz for S-waves, related to the medium-velocity formation and the depth sampling interval of approximately 15.12 m (Fig. 7).

Overall, there is a pronounced attenuation of frequencies with depth, which is characteristic of impulsive sources such as pneumatic chambers, especially when their number or volume is small. To mitigate this issue, the use of vibrational seismic sources is recommended, as they generate a more stable frequency spectrum across all depths.

To avoid the problem of aliasing, we recommend reducing the depth sampling interval in future surveys by half—to 7.5 m. Along with increasing the energy of the excitation source, this would extend the recorded seismic frequency spectrum.

In general, the observed data exhibit good and conditioned quality, meeting the objectives and goals set for the VSP study.

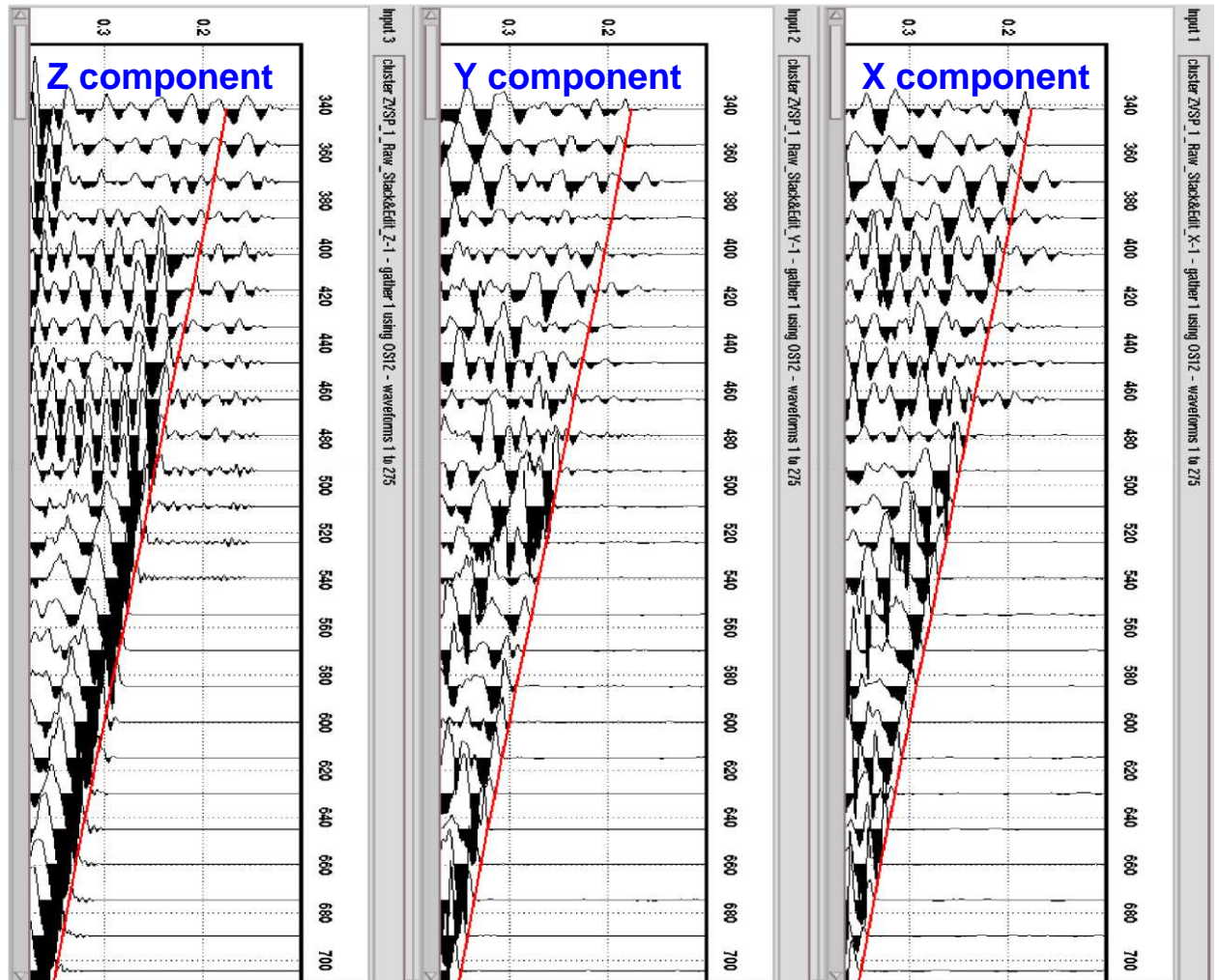


Fig. 6. Polarization analysis and band-pass filtering helped restore accurate first arrival times

No serious issues were encountered during the field observations. The acquired data are of good and conditioned quality, meeting the objectives and tasks set for the VSP study.

VSP observations were conducted at the MAXIS logging station (Schlumberger Multitask Acquisition and Imaging System) using VSI Workbench software for VSI-type VSP probes. The main parameters of the field observations and equipment used are presented in Table 1.

The most effective multicomponent processing methodology was applied during data processing, incorporating polarization analysis, projection calculation, and parametric field decomposition. This approach enables the simultaneous processing of all three recorded components (X, Y, Z), extracting high-quality scalar reflected waves

The constructed models successfully passed verification for structural dip and acoustic properties using all recorded VSP data. Therefore, the reliability and accuracy of the VSP sections can be considered well established.

Joint analysis of the VSP sections and surface seismic data revealed both a strong correspondence and the added value of VSP data in subsequent integrated interpretation of the field. Since one of the outcomes of multicomponent field decomposition includes reflected shear waves (UpS), the analysis of S-wave sections becomes especially significant. Given the different nature of P- and S-waves, their images of subsurface structure (OGT) often

complement each other and allow for the extraction of both qualitatively and quantitatively richer information during integrated interpretation.

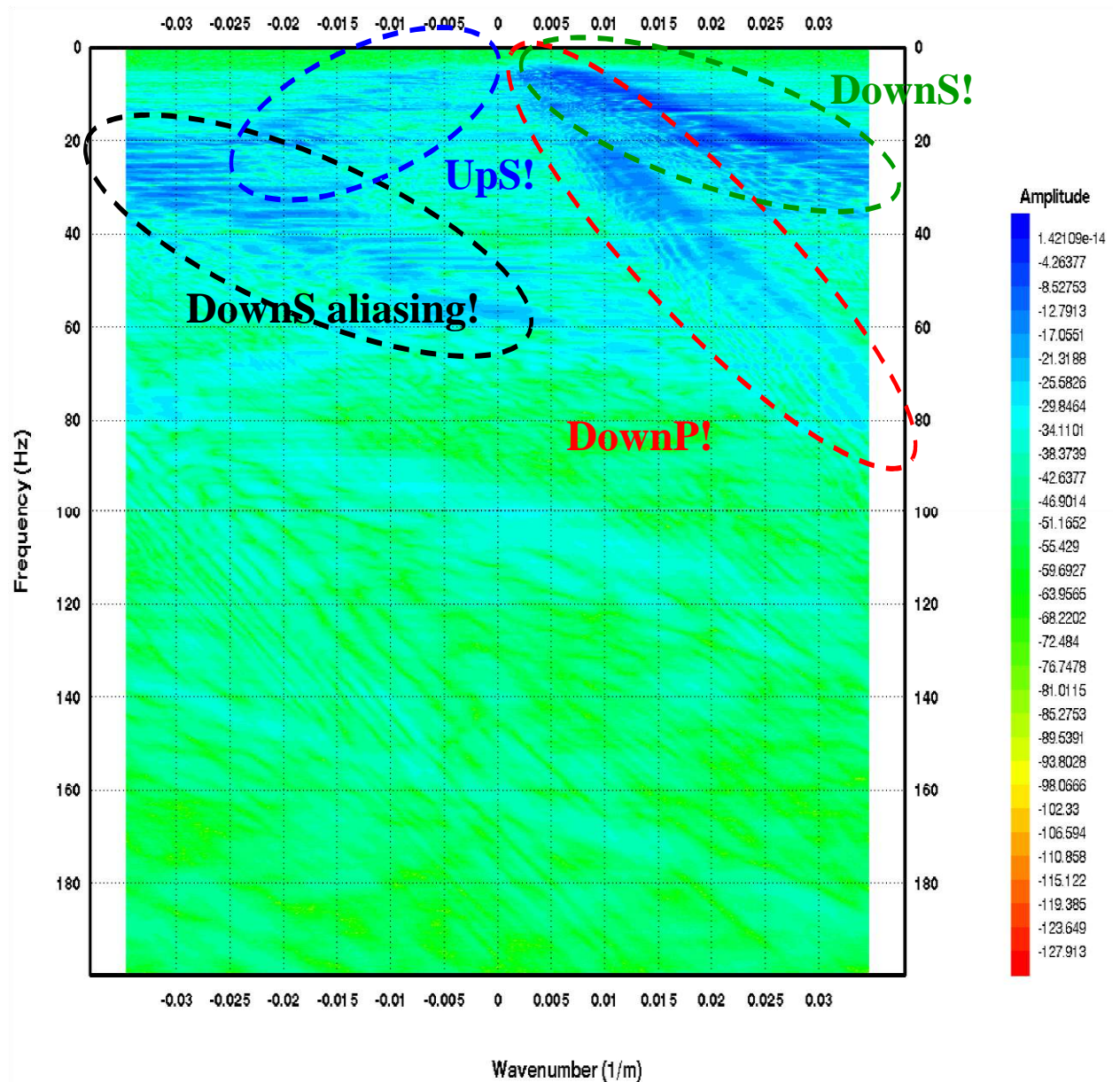


Fig. 7. Frequency content of reflected P-waves is limited to 80 Hz, and shear S-waves up to 70 Hz

It is important to note that S-waves, which propagate only through solid media, are unaffected by fluids and gaseous phases. This property makes them especially useful for mapping complex geological areas such as mud volcanoes, gas caps and pockets, and salt dome tectonics with strong head-wave refraction, where studying P-wave time and depth sections alone is insufficient or ineffective.

A strong correlation was observed between the P- and S-wave sections and the surface seismic data, further confirming the reliability of the processing.

To forecast velocities below the total depth of the well and to extend the time–depth curve for predicting the depths of the most significant reflecting horizons beneath the Pliocene deposits, a Pseudo-Acoustic Log (PAL) was performed — also known as acoustic impedance inversion. The results obtained are stable and consistent.

The predicted P-wave velocity below the well bottom was used to calculate a forecasted time–depth relationship, which in turn was used to predict the expected depths of the most significant Miocene-age reflecting horizons in Well H1856.

The VSP processing described here was performed using the BorSeis 5.0 package, included in the commercial implementation of GeoFrame (Austin Systems Center), version GF 4.0.3, and Q-BorSeis Omega-2, version 2.6.1.

VSP Layout Type	Longitudinal and Non-Longitudinal Profiles VSP; 16.07.2010
1	2
Well Name	H1856
Reference Level (SRD)	0 m (Baltic Sea level)
1	2
Rotor Table Altitude (KB)	-17.44m
Ground Level (GL)	-26.44m
Maximum Well Deviation	~37.15°
Number of VSP Levels	VSP – 275; NVSP – 270
VSP Interval	VSP: 4500–324.2 m measured depth (~15.12 m step) NVSP: 4499.93–400.46 m measured depth (~15.12 m step)
Observation Time, Sampling Interval	5 s; 1 ms
Source Type	Pneumatic chamber (volume – 250 in ³ , pressure – 2000 psi)
Controller Type	Monitoring hydrophone in pit
Source/Controller Offset	VSP: ~87.1 m NVSP: ~1304.7 m
Source/Controller Azimuth	VSP: ~189°. NVSP: ~287.2°
Source Depth	VSP: 2 m below ground level NVSP: 2 m below ground level

Table 1: Field Observation Parameters and Equipment

Review of the results

To forecast velocities below the well bottom and to extend the depth-time relationship for predicting the depths of the most significant reflecting horizons, it was decided to perform a Pseudo-Acoustic Log (PAL), also known as acoustic impedance inversion.

The PAL was calculated based on the corridor stack of reflected waves from the longitudinal VSP profile. Since any inversion is an inherently non-trivial process, multiple iterations of PAL were performed and analyzed using various inversion parameters before selecting the version presented here.

The final results are stable and adequate. For the PAL inversion, the dominant frequency range of the longitudinal VSP profile — 5 to 70 Hz — was selected (Fig. 8).

It is important to note that the theory behind PAL is developed for a one-dimensional medium: a horizontally layered structure, a vertical wellbore, and a longitudinal VSP acquisition geometry. These assumptions do not fully apply to Well H1856, which prevents absolute confidence in the accuracy of the derived data.

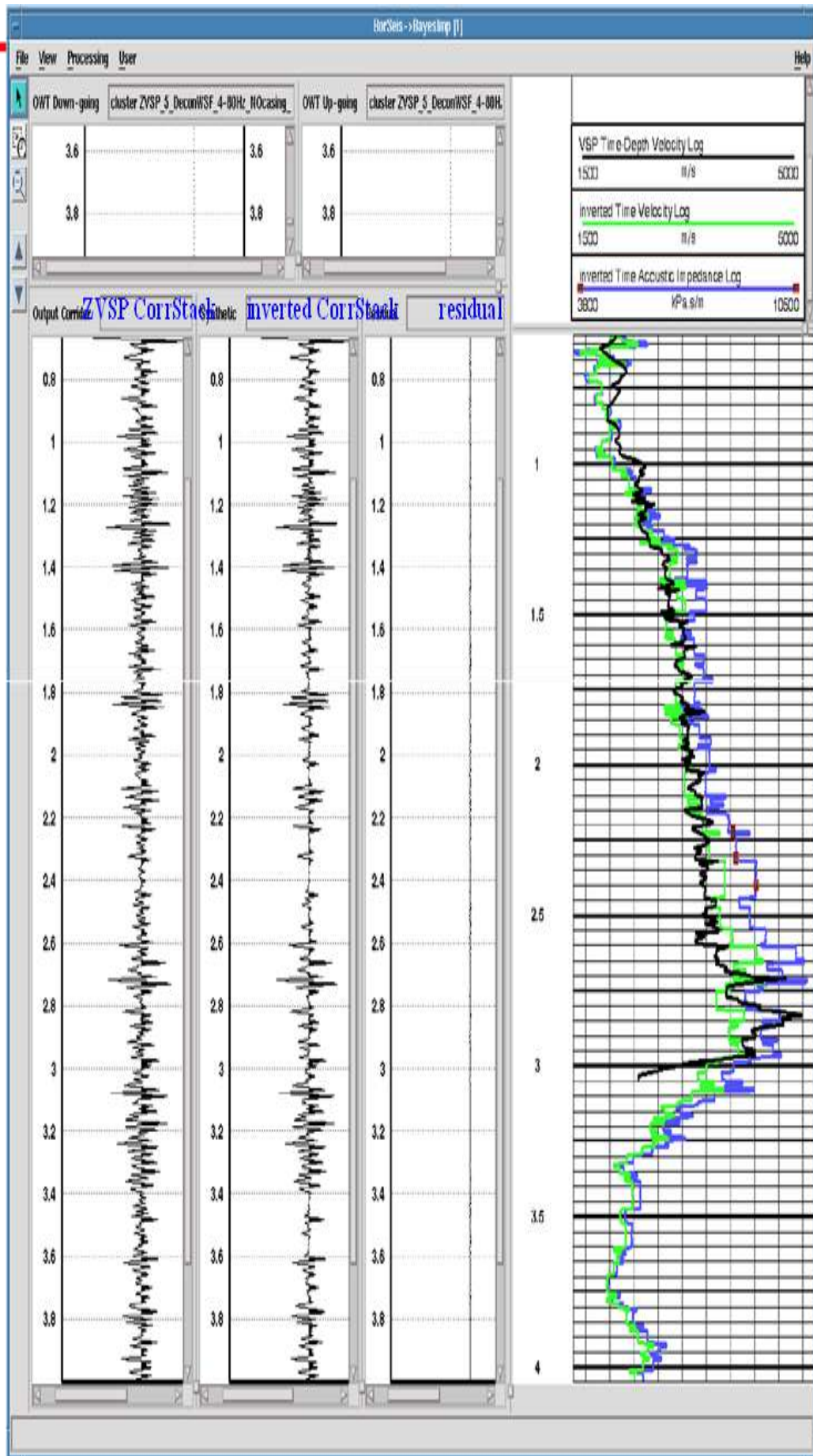


Fig. 8. PAL Inversion: 60 ms corridor stack from VSP with a frequency range of 5–70 Hz; results are stable

and adequate

Nevertheless, the results appear adequate rather than artificially synthetic — they do not exhibit uncharacteristic behavior, implausible values, or inversion instability. Moreover, the recorded VSP and acoustic logging (AL) data confirm a significant velocity drop in the lower section of the interval, which further supports the PAL outcome (Fig. 9).

In any case, when using the obtained data, one must keep in mind that such inversions and forecasts carry a considerable degree of uncertainty and risk, which cannot be quantitatively evaluated without verification through drilling followed by well logging

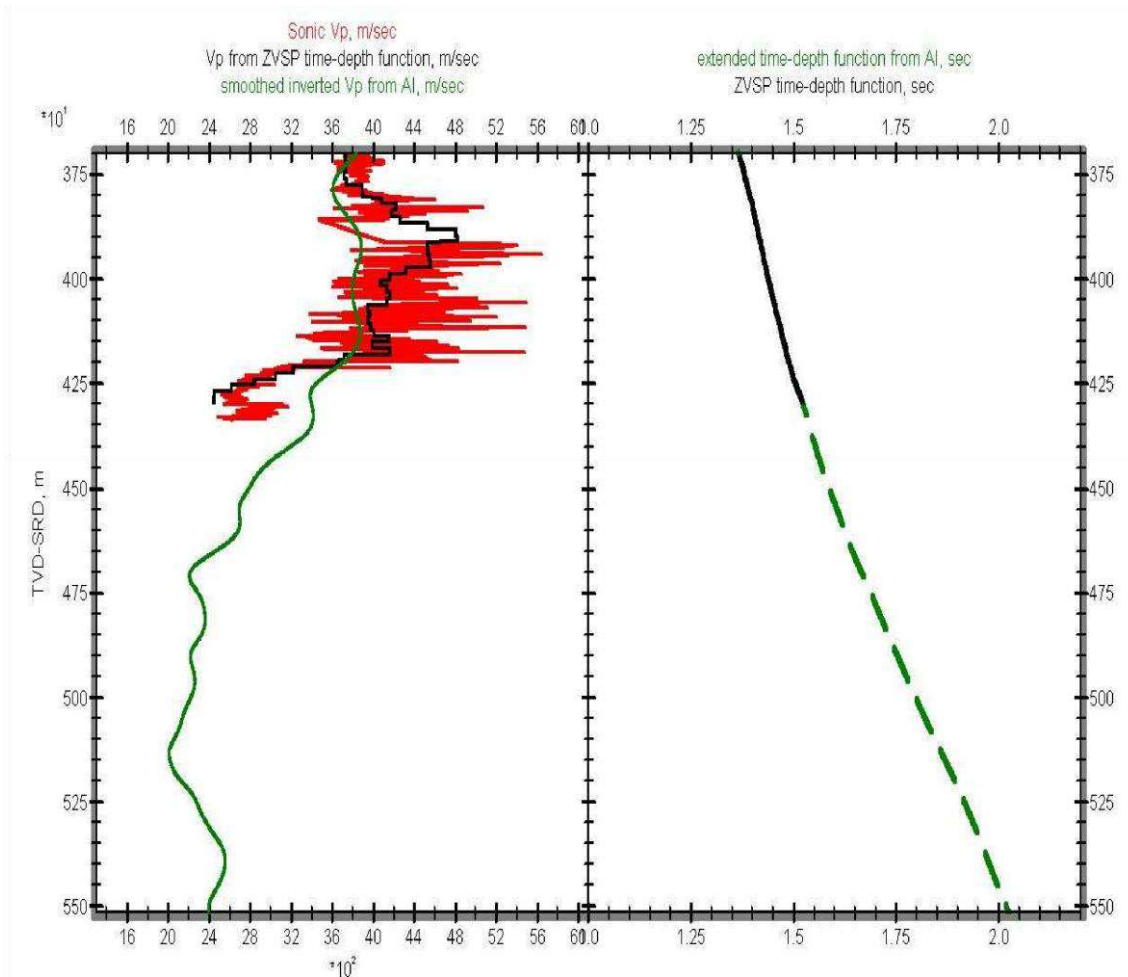


Fig. 9. PAL inversion shows a decrease in velocities to approximately 2100 m/s below the well bottom

The predicted P-wave velocity below the well bottom was used to compute the forecasted depth-time relationship, which in turn was employed to estimate the expected depths of the most significant reflecting horizons in Well H1856 (Fig. 10).

These horizons are mainly located beneath the Kalin Suite, which is the primary productive unit of this field. The formations underlying the Kalin Suite of the productive series also hold considerable practical (i.e., industrial) interest. Therefore, determining the depths of seismic horizons that reflect the structure of formations below the Kalin Suite was a key objective of this study.

Below is a table showing the predicted depths of the most significant horizons beneath the well bottom. The depth markers correspond to the intersections of the yellow lines with the green vertical line. The depth forecasts are based on the depth-time relationship derived from the PAL.

Horizon Numbers / No.	Time (s)	Depth (m)
Horizon 1	3.005	4244
Horizon 2	3.069	4335
Horizon 3	3.112	4407
Horizon 4	3.139	4448
Horizon 5	3.197	4529
Horizon 7	3.301	4665
Horizon 8	3.399	4775

Table 2. Depths of the Most Significant Seismic Horizons

Using the predicted depths of the key seismic reflecting horizons, deep production well 1870 was drilled, which revealed productive reservoirs within the abnormal high-pressure zone (AHPZ) with a daily production rate of approximately 100 tons. This well was operated for some time before being decommissioned due to technical reasons.

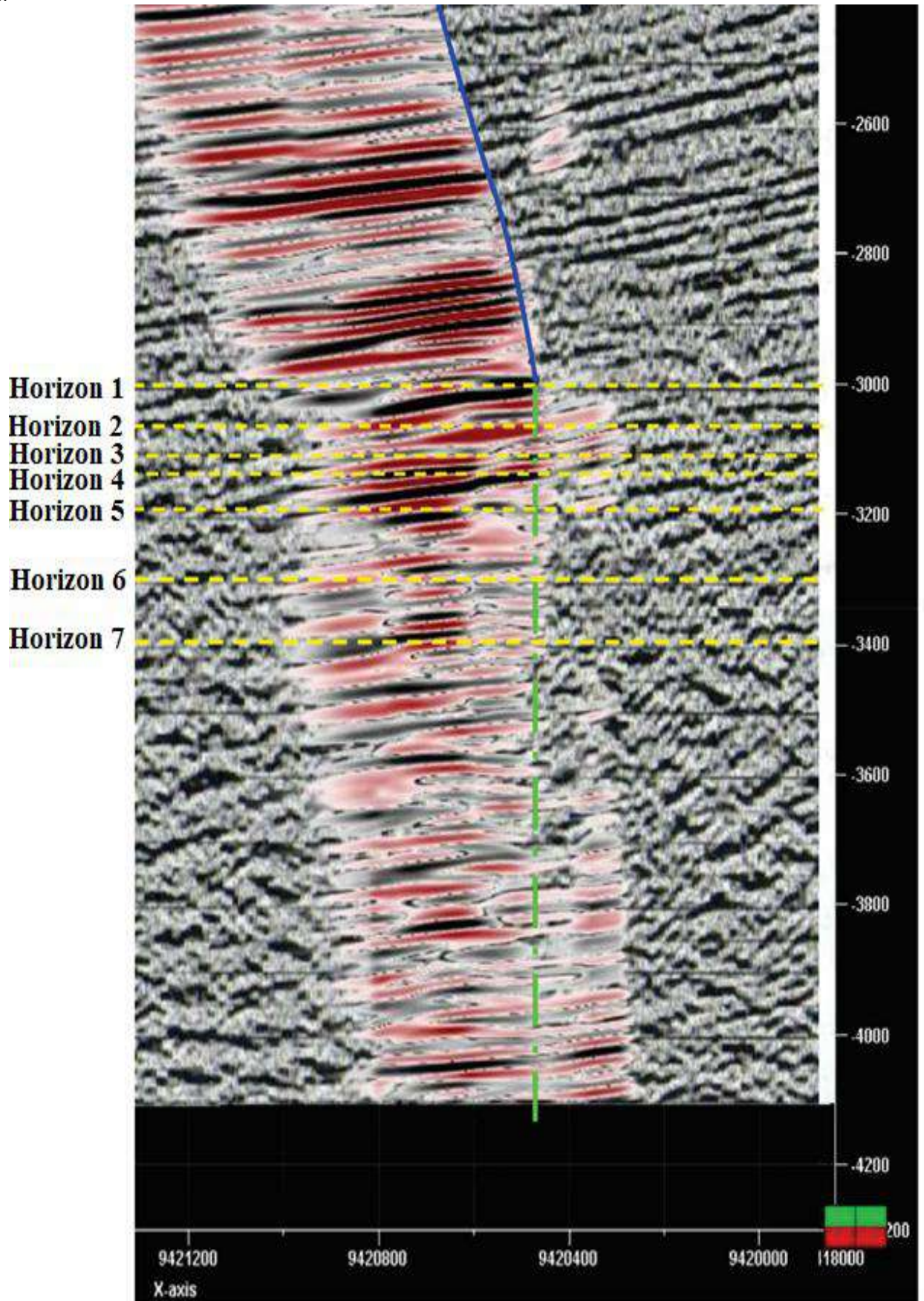


Fig. 10. Predicted P-wave velocity below the well bottom was used to estimate the expected depths of the most significant reflecting horizons in Well H1856

Conclusion

As a result, an accurate depth-time relationship was obtained from the VSP data. Interval velocities from VSP correlate well with acoustic logging (AL) data. One-dimensional and two-dimensional velocity models were constructed, effectively describing the acoustic properties of the formations within the study area. Calibration of AL data and the calculation of synthetic seismograms also proceeded without significant difficulties.

To achieve the highest possible quality results, multi-component VSP processing was selected, allowing extraction of the full useful energy distributed across all axes.

Mapping using the VSP method was conducted independently from surface seismic survey results. This provided an additional source of geological and geophysical information valuable for the integrated interpretation of the field. Moreover, the VSP confirmed that the structural interpretation within well H1856 is accurate, at least within the VSP-mapped interval.

PAL was successfully computed for this well, enabling velocity prediction below the well bottom and generation of a depth-time relationship to estimate depths of key seismic horizons. A depth forecast for the most significant reflecting boundaries was completed.

For future studies, the use of vibrational seismic sources is recommended, as they generate a relatively stable frequency spectrum at all depths, enabling acquisition of high-resolution data without the significant frequency losses typical of impulsive sources like pneumatic chambers.

References

1. Al Ahmedov T.R. et al. Some results of surface and borehole seismic surveys at the Govsany hydrocarbon field // Karotazhnik. Scientific and Technical Bulletin. Issue 6 (216), 2012. Tver, Russia.
2. Ahmedov T.R. et al. The role of guided waves in the formation of the wavefield of borehole seismic surveying: the case of the Govsan area // Azerbaijan Oil Industry, Baku, 2013, No. 2, pp. 9-14.
3. Ahmedov T.R. On the geological effectiveness of seismic surveys in studying non-anticlinal traps of various types in Azerbaijan // Proceedings of the Ural State Mining University, Issue 3 (43), 2016, pp. 41-45.
4. Dobrynin V.M., Serebryakov V.A. Geological and geophysical methods for predicting abnormal formation pressures // Moscow: Nedra, 1989.
5. Esipko O.A., Moskalenko V.N. Information support for determining and forecasting fluid pressure based on well logging and drilling data // Karotazhnik, Issue 11 (176), Tver, 2008, pp. 44-58.
6. Kuliyeu G.G., Agayev Kh.B., Shirinov N.M. Study of the influence of pressure on elastic parameters of geological media based on seismic and well data // Proceedings of the IX International Scientific Conference "Monitoring of Geological Processes", Kyiv: Kyiv National University Press, 2009, pp. 17-18.
7. Mamedov P.Z. On the causes of rapid subsidence of the Earth's crust in the South Caspian Basin // Azerbaijan Oil Industry, Baku, 2008, No. 1, pp. 9-15.

INFORMATION ABOUT THE AUTHOR

Tofiq R. Ahmadov, Dr. Sc., Professor, Azerbaijan State University of Oil and Industry, 20, Azadliq avenue, Baku, 1020, Azerbaijan;

akhmedov.tofik@bk.ru;

Amikishi Ch. Asadli, Doctoral student, Azerbaijan State University of Oil and Industry, 20, Azadliq avenue, Baku, 1020, Azerbaijan;

amikishiasadli@gmail.com

Goychak M. Tashvigi, Doctoral student, Institute of Geology and Geophysics, 119 H. Javid Avenue, AZ1143, Baku, Republic of Azerbaijan

goycektesviqi@gmail.com