



# AVO Modeling and Its Application to Hydrocarbon Detection

## A Case Study in BH3 Structure, Kazakhstan

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**Abstract.** Relationships between reservoir properties and elastic parameters are established using log data. Based on rock physics modeling, seismic responses and AVO features of rocks and fluids are analyzed using AVO forward modeling. The oil-bearing sandstone thickness is estimated using forward modeling of a 2D wedge, which has geologically meaningful model for geophysical interpretation. The markov-Chain Monte Carlo lithology simulation and geostatistical inversion are used to predict oil-bearing sandstone thickness and distribution in the Upper Jurassic reservoir and an effective workflow of hydrocarbon detection is established.

**Keywords:** AVO effect · Petrophysical modeling · Forward modeling · Hydrocarbon detection

## 1 Problems in BH3 Structure

BH3 structure in the south Turgay Basin, Kazakhstan is a typical faulted anticlinal structure (see Fig. 1) which has been confirmed. Well P-3 was drilled with 3 oil layers of 9.9 m thick at the depth 1117–1131 m in the Upper Jurassic Akshabulak Formation; this led to the discovery of Upper Jurassic reservoir in BH3 structure. Well blowout occurred at P-3; thus, another well, P-3B, was drilled in the vicinity. This well was drilled with 5 oil layers of 12.9 m thick at the depth 1101–1125 m in the Akshabulak

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Formation. Logging interpretation denoted large lateral variation of reservoirs between these two wells 100 m apart. Centered around P-3, two wells, P-2 and P-4 with the interval of 400–500 m, were drilled in the major axis direction of BH3 structure; but both of them failed. As per the study, reservoir properties at P-2 and P-4 are deteriorated. These three wells may be drilled with different sedimentary facies. Thus, how to predict reservoir properties is crucial to the deployment of exploratory wells and appraisal wells.

Reservoir prediction in this prospect is challenging. (1) It is hard to predict quickly changed reservoir properties. (2) The dependency of hydrocarbon on rock types makes it difficult for hydrocarbon detection.

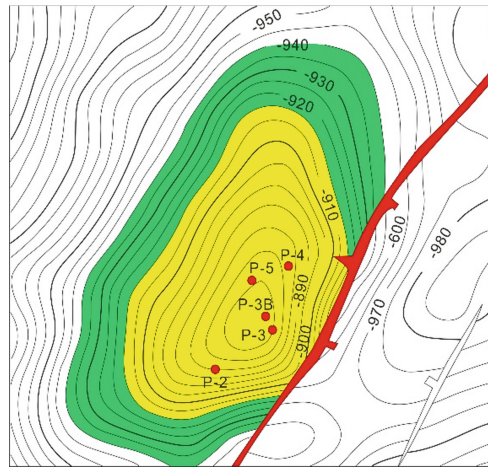


Fig. 1. Structure map of the top of the Akshabulak Formation in BH3 structure

## 2 Methodology

### 2.1 Normalization and Standardization of Logging Curves

In view of observed data and Jason inversion workflow, the procedure of inversion was divided into two steps.

The first step was deterministic inversion. Seismic waveform data is transformed into reflection coefficient and subsequent P-impedance with petrophysical meaning [1]. Using Jason inversion, seismic data could be translated into elastic parameters in accordance with the customized workflow. The workflow could be strictly controlled, and the inversion result is unique. P-impedance derived from inversion is of petrophysical meaning.

Well data of P-3, P-3B, and P-4 and the latest migration data will be involved in seismic inversion. The data of P-2 will be used for blind test and threshold definition. The inversion result will be used for a new well design of P-5.

The tasks in this step include:

- (1) Multi-well consistency processing of log data and lithologic classification[2];
- (2) Forward modeling and inversion feasibility study to optimize workflow and major parameters;
- (3) Constrained sparse spike inversion;
- (4) Inversion interpretation at seismic resolution;
- (5) Blind test and new well site feasibility study.

The second step was geostatistical inversion, which is model-based inversion with high precision and resolution. There are a number of geostatistical parameters and assumptions to constrain the inversion, which depend on the model [3]. Through geostatistical inversion, we may conduct feasibility study of lithologic simulation. The result of inversion will also be analyzed to support geologic study and exploratory deployment.

The tasks in this step include:

- (1) Geologic modeling;
- (2) Geostatistical parameters test and definition;
- (3) Markov-Chain Monte Carlo lithologic simulation and geostatistical inversion;
- (4) Interpretation of inversion results.

### 3. Deterministic inversion

- (1) Multi-well log consistency processing

Log data could be used to calibrate seismic data which contain reservoir information. High-quality log data are the base of quantitative reservoir characterization [4]. Log data quality has to be controlled before joint application with seismic data in view of poor quality, multi-well inconsistency, or data missing (see Figs. 2 and 3). Density curves were distorted at the intervals with borehole collapse; this cannot be amended using environmental correction. We employed multi-variate linear fitting to formulate a multi-variate linear equation at the intervals with similar rock types and fluids. The equation is shown as follows.

$$\text{LOG rec} = f(\text{Rt}, \text{Rs}, \text{Dt}, \text{GR}) \quad (1)$$

Such a linear fitting equation was derived at the interval with similar rock types and oil saturation and good data quality [3]. Then we used this relationship between the log to be fitted and reference logs to reconstruct the log, e.g. density, at the interval with borehole collapse. After log correction, we obtained the relationships between reservoir properties and elastic parameters (see Fig. 4). These relationships may then be used to interpret reservoir properties with elastic parameters derived from seismic inversion.

Gamma, sonic, and density logs of major wells were corrected, followed by multi-well consistency check and normalization to obtain log curves with good quality and consistency.

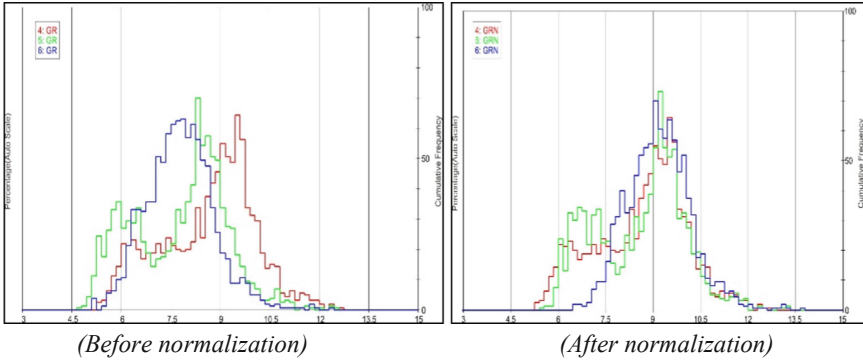


Fig. 2. Deterministic inversion (upper) and geostatistical inversion (lower)

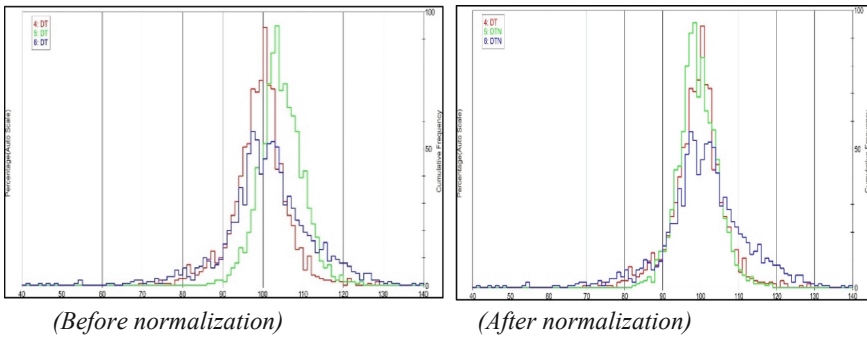


Fig. 3. Sonic histograms before and after multi-well normalization at the Akshabulak Formation

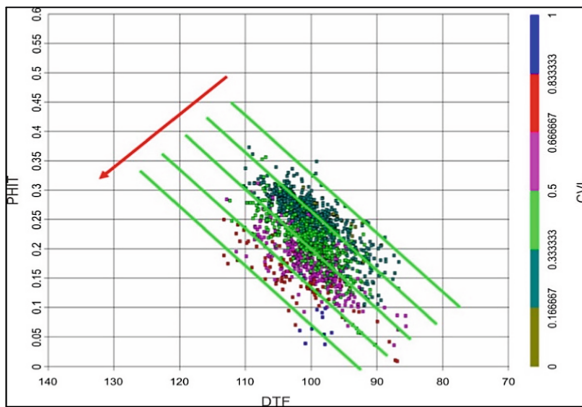


Fig. 4. Crossplot of acoustic time and porosity after multi-well normalization

### 2.2 Rock Physics Modeling

Log data of Well P-3 were used as the constraints of rock physics modeling. The parameters of fluids and rock matrix are shown as follows.

In view of high porosity of sandstone in the zone of interest, the self-consistent model was used for modeling. Void pores will be included in the matrix, followed by hybrid fluids.

The microstructure of pore space (Alpha) is an important parameter in velocity modeling. As per the analysis, Alpha of sandstone in the zone of interest (water-bearing sandstone in the Akshabulak Formation) is 0.14. P-velocity of water-bearing sandstone could be accurately modeled using this value.

Saline water and in situ light oil were mixed in accordance with saturation. The brie index of hybrid fluids was set to be 2. P-velocity of oil-bearing sandstone agreed well with measured P-velocity (Tables 1 and 2).

**Table 1.** Parameters of Upper Jurassic rock matrix in BH3 structure

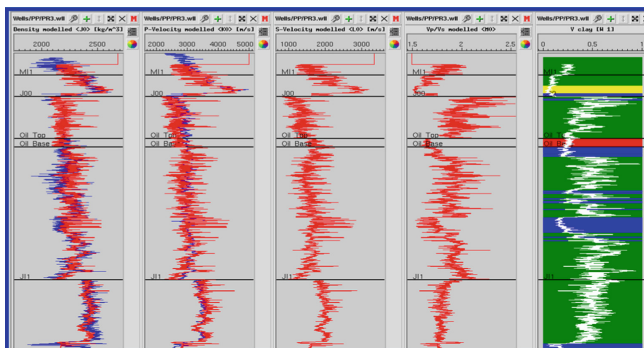
Matrix density	Matrix P-velocity	Matrix S-velocity
Mudstone: 2450 kg/m <sup>3</sup>	Mudstone: 3890 m/s	Mudstone: 1770 m/s
Quartz: 2650 kg/m <sup>3</sup>	Quartz: 5000 m/s	Quartz: 3345 m/s

**Table 2.** Parameters of Upper Jurassic reservoirs in BH3 structure

Fluid	Density g/cm <sup>3</sup>	Viscosity mPa.s	Volume factor m <sup>3</sup> /m <sup>3</sup>	Total compressibility X10 <sup>-4</sup> 1/Mpa	Saturation pressure Mpa
Oil	0.73	1.373	1.084	15.96	4.2289

Oil reservoir temperature 46.33, pressure 11.99 Mpa and gas-oil ratio 32 m<sup>3</sup>/m<sup>3</sup>

S-velocity was estimated under the assumptions of similar Alpha for S-wave modulus to that for P-wave and Vp/Vs 2.2 for dry mudstone matrix. Estimated S-velocity was then used for AVO modeling (see Fig. 5).



**Fig. 5.** Measured (blue) and modeled (red) P-velocity and S-velocity at Well P-3

As indicated by rock physics modeling, Akshabulak sandstone and mudstone have similar P-impedance. It is hard to differentiate between sandstone and mudstone by using P-impedance or S-impedance.  $V_p/V_s$  is lithologically sensitive and could be used to identify sandstone and mudstone [5]. Due to light oil property (in situ density 0.73 g/cc), oil-bearing sandstone has lower  $V_p/V_s$  than water-bearing sandstone; this may lead to type-II AVO at the oil-water contact [6].

### 2.3 AVO Modeling and Wedge Modeling Analysis

Well P-3 was selected for AVO modeling. Using the wavelet extracted and time-depth relation from well-tie calibration, the Knott-Zoeppritz was employed to calculate the reflection coefficient at each offset [3].

Synthetic gather (see Fig. 6) shows that the critical incidence angle at the tight bottom Cretaceous conglomerate was reached at the offset 2200 m; such reflections were muted in the real gathers because they were superimposed by direct waves. At the silty mudstone interval at 0.9 s, due to thin-bed tuning, there is AVO effect from near offsets to far offsets. Phase rotation occurs at far offsets. There are no reflections at near offsets at 0.95 s with oil-bearing sandstone and water-bearing sandstone; but a weak peak occurs at the oil-water contact at far offsets. This is residual AVO effect. There is also AVO effect at the sandstone-mudstone interface below 1.02 s.

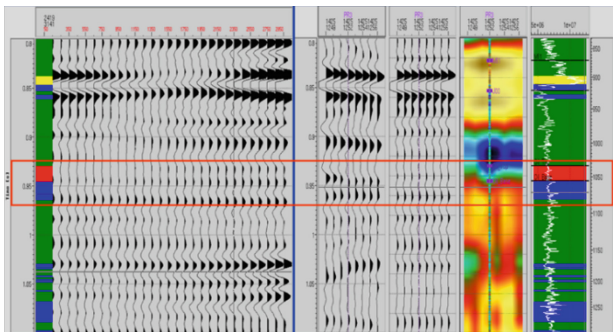


Fig. 6. Synthetic gather and well-tie calibration at Well P-3

As per well-tie calibration, strong reflections at the bottom of the Cretaceous System and the bottom of the Upper Jurassic Akshabulak Formation correlate well with synthetic seismogram. Real amplitude at 0.9 s with silty mudstone and 0.945 s with oil-water contact is far larger than synthetic amplitude. In view of phase rotation and amplitude increase at far offsets at 0.9 s in synthetic seismogram, it was inferred that more far-offset strong amplitude was preserved in stacked data for some reasons (surface waves at near offset or low signal-to-noise ratio at near offsets). This is why synthetic seismogram is inconsistent with real gather. Due to such residual AVO information, impedance inverted may be close to elastic impedance or virtual impedance; this may facilitate the identification and tracking of oil-water contact.

A 2D wedge-like model was build which corresponds to CDP1200-CDP1300 at inline 1420 (see Fig. 7). Oil-bearing sandstone thickness increases from 0 to 30 ms. A seismic wavelet was generated for convolution, and the reflection amplitude at sandstone bottom was extracted. As indicated by the tuning curve, the tuning thickness is 14 ms. The interval velocity of oil-bearing sandstone is 2800 m/s; so, we took the half of the tuning thickness as the lower limit of thickness interpretation in time domain. This means oil-bearing sandstone thicker than 7 ms (or 10 m) maybe predicted using deterministic inversion.

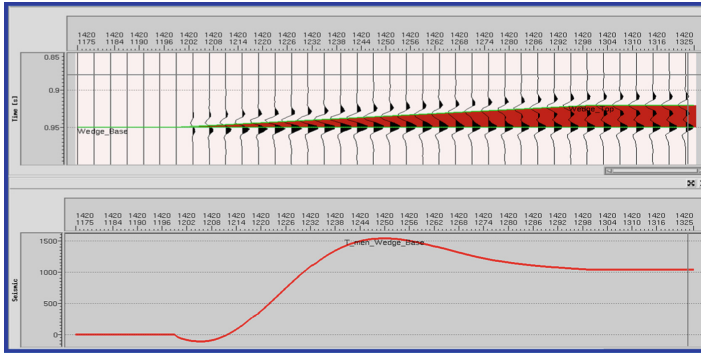


Fig. 7. Synthetic seismogram of a wedge-like model and tuning thickness curve

### 3 Constrained Sparse Spike Inversion

Constrained sparse spike inversion may expand the effective band width of seismic data through adjusting the sparsity of reflection coefficient sequence; the output is an elastic parameter model [3]. Figure 8 shows the amplitude spectrum at the zone of interest and the wavelet extracted using seismic data. There is a key parameter  $\lambda$  in the inversion, which determines the sparsity of reflection coefficient sequence and correlation between synthetic seismogram and real data. A small  $\lambda$  will make the reflection coefficient sequence sparser, and a large  $\lambda$  will increase well-seismic correlation. On the other hand, a large  $\lambda$  will lead to high-frequency noises in the inversion, and a small  $\lambda$  will yield a result with less geologic details corresponding to weak reflection.

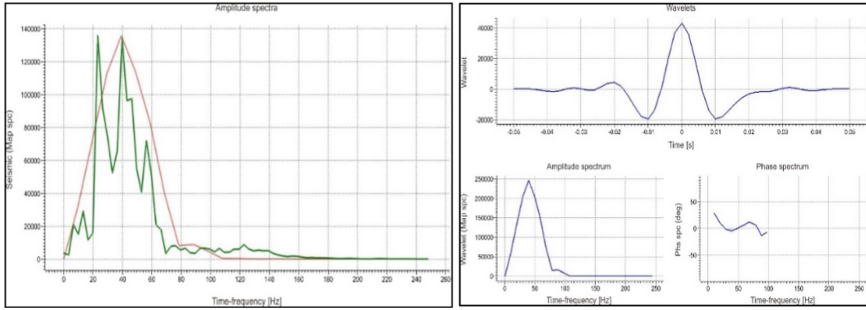


Fig. 8. Amplitude spectra and extracted seismic wavelet

Constrained sparse spike inversion generates an absolute impedance model. Low frequencies missing in seismic data has to be complemented (see Fig. 9).

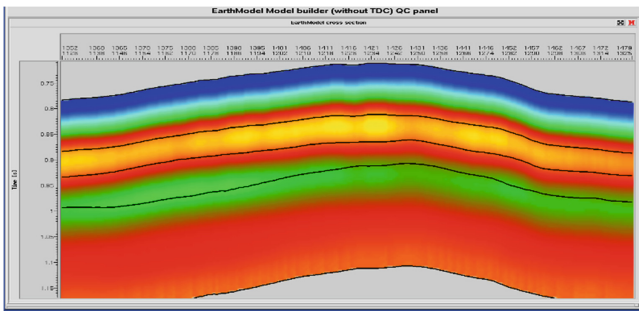


Fig. 9. Low-frequency P-impedance model at 0–8 Hz

An arbitrary line was set from SW to NE to cross P-2, P-3, P-3B, and P-4 (see Fig. 10). P-impedance is plotted using a linear color bar. Oil-bearing sandstone, water-bearing sandstone, and mudstone are plotted in red, blue, and green, respectively.

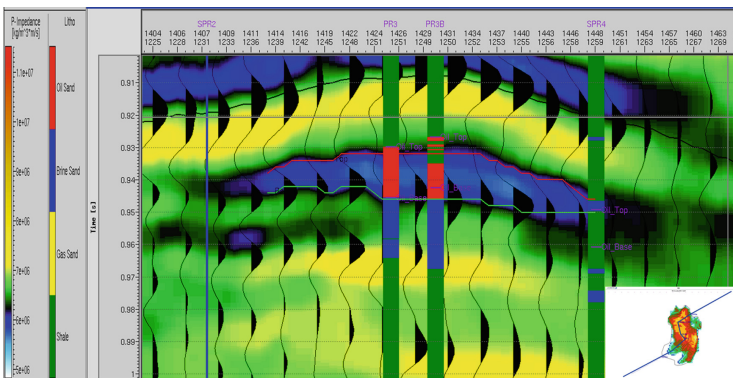


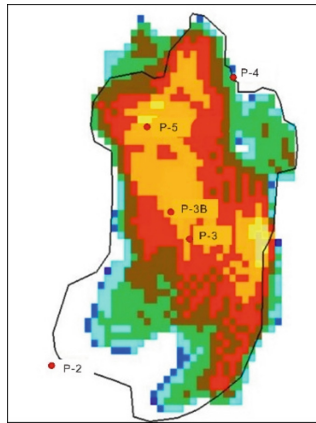
Fig. 10. Cross-well P-impedance inversion



After tuning the color bar, we could see a lenticular body with a nearly horizontal bottom in time domain. The bottom agrees with the bottom of the oil layer drilled in Wells P-3 and P-3B.

For three wells for well-tie calibration, P-3 and P-3B were drilled with oil-bearing sandstone of 10 m thick, and P-4 was not drilled with oil-bearing sandstone. Thus, a threshold of P-impedance was determined to check the geologic anomaly and its distribution.

In accordance with deterministic inversion, we predicted the distribution of Akshabulak oil-bearing sandstone (see Fig. 11).

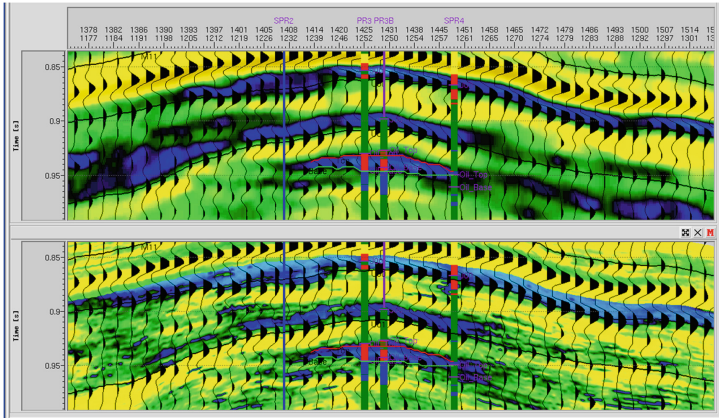


**Fig. 11.** Oil-bearing sandstone distribution of BH3

The oil-water contact of the Akshabulak Formation is at 0.945–0.950 s. The area of the Akshabulak oil-bearing sandstone is about 1 km<sup>2</sup> at the current seismic resolution and its time thickness is generally smaller than 14 ms.

## 4 Geostatistical Inversion

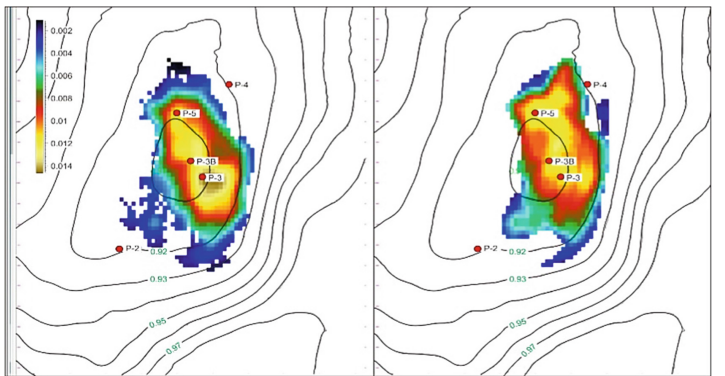
Geostatistical inversion is a model-based inversion which uses log data and geologic data to match seismic data; the output is laterally continuous high-resolution impedance and lithologies (see Fig. 12). The samples for lithologic simulation were not generated randomly; it was constrained by seismic data [4]. In addition to the inclusion of high frequencies, the inversion engine also requires high correlation between synthetic seismogram and real data.



**Fig. 12.** Deterministic inversion (upper) and geostatistical inversion (lower)

Geostatistical inversion combines well data and geostatistical information with seismic data. It is the best solution to the prediction of lithologic reservoirs with strong heterogeneity.

Geostatistical inversion (see Fig. 13) and deterministic inversion generated similar results of Akshabulak oil-bearing sandstone area and thickness.



*(Geostatistical inversion)*      *(Constrained sparse spike inversion)*

**Fig. 13.** Time thickness maps of oil-bearing sandstone

In accordance with the results of geostatistical inversion and deterministic inversion, well drilling of P-5 was deployed and finished on November 22. Oil layers were drilled in the Lower Cretaceous Series, and an equivalent oil flow of 126 m<sup>3</sup>/d was yielded in oil testing using 8 mm choke. Oil layers of 12 m were drilled in the Upper Jurassic Series, and oil-saturated cores of 8.14 m were acquired.

## 5 Conclusions

- (1) The relationships between reservoir properties and elastic parameters, which were established using log data, determined the feasibility of inversion. These relationships also functioned as the criteria for quantitative interpretation of inversion result.
- (2) Forward modeling and AVO analysis revealed seismic responses of lithologies and oil-water contact. Forward modeling using a wedge-like model could be used to interpret oil-bearing sandstone thickness and build a geophysical model with geologic meaning.
- (3) Geostatistical inversion combines well data and geostatistical information with seismic data. It is the most appropriate solution to the prediction of lithologic reservoirs with strong heterogeneity.

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