WELL-LOG CONSTRAINED INVERSION FOR LITHOLOGY CHARACTERIZATION: A CASE STUDY AT THE JZ25-1 OIL FIELD, CHINA

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(Received July 18, 2015; revised version accepted December 4, 2015)

ABSTRACT

Zhang, Q., Chen, Y., Guan, H. and Wen, J., 2016. Well-log constrained inversion for lithology characterization: a case study at the JZ25-1 oil field, China. *Journal of Seismic Exploration*, 25: 121-129.

With an estimated total reserve of over 800 million barrels of oil equivalent (BBOE), JZ25-1 field is the largest light oil field in the Bohai Bay Basin, Eastern China. The reservoir rocks are mainly sandstones in the Paleocene Shahejie Formation (Es). Thus, a deep understanding of sand distribution is crucial to the efficient development of the field. In this paper, we performed lithology characterization using the well-log constrained inversion. Through seismic-well tie, initial modeling and simulated annealing, we obtained an acceptable inversion result. Using the wave impedance model as a constraint, we created sand thickness map with Kriging interpolation. The result indicates that sand bodies in the lower Es3 were thicker than those in the upper formation, and the thickness of sandstones varies laterally in the study area.

KEY WORDS: well-log constrained inversion, lithology characterization, seismic-well tie, simulated annealing, Kriging interpolation, case study, Bohai Bay Basin.

INTRODUCTION

The JZ25-1 oil field in China is the first field holding hundreds of millions of tons of light oil in the Bohai Sea that has been discovered in recent years (Xu et al., 2010). It is located along the central Liaoxi low uplift, Liaodong Bay depression within the Bohai Bay Basin of eastern China (Fig. 1a). The No.1 Liaoxi Fault acts as the boundary and confines the study area to the thrown side, in the Liaoxi sag (Fig. 1b).

0963-0651/16/$5.00

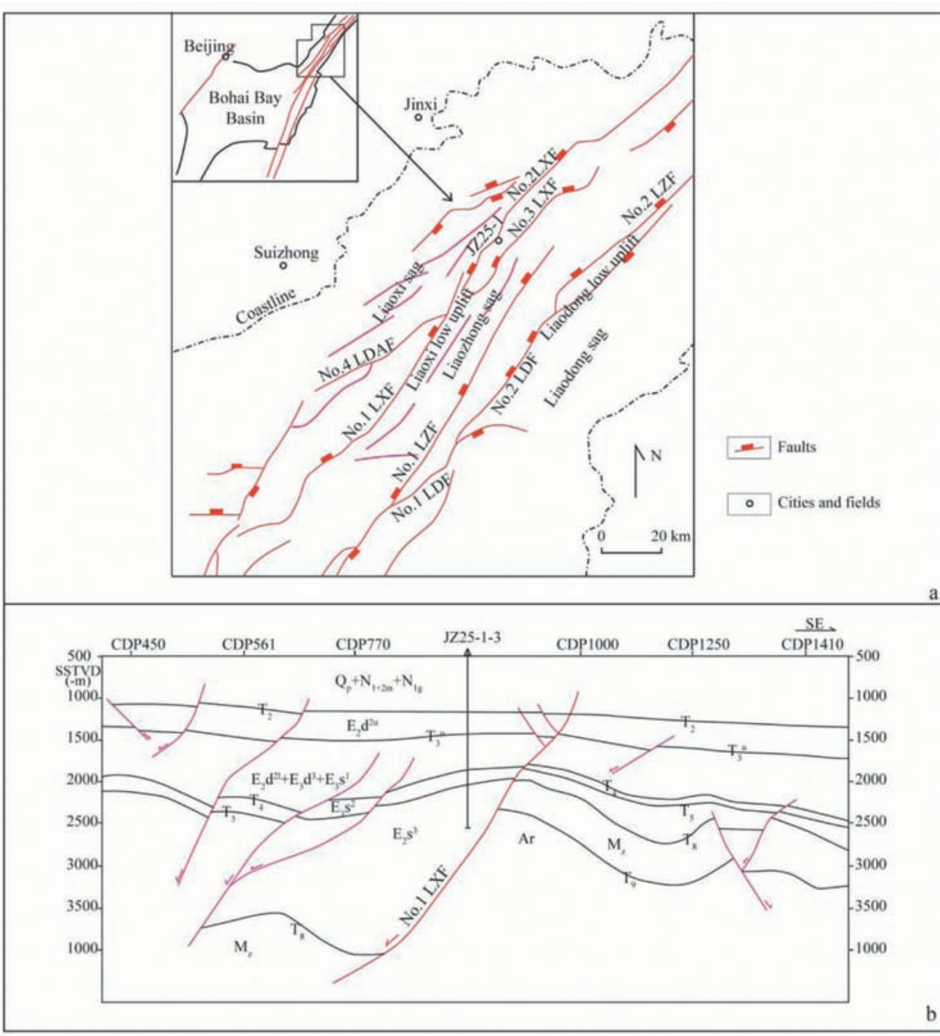


Fig. 1. (a) Simplified structural map of Liaodong Bay depression and JZ25-1 field. LXF, LZF, LDF, and LDAF indicate Liaoxi fault, Liaozhong fault, Liaodong fault, and Luda fault, respectively. (b) A SE-NW trending structural and stratigraphic profile through Well JZ25-1-3.

The lithostratigraphy in the JZ25-1 field consists of the Pingyuan Formation (Quaternary), the Minghuazhen and Guantao Formation (Neogene) and the Dongying and Shahejie Formation (Paleocene). The field produces from the Shahejie Formation which is divided into three members, among which the third member was developed in a fan-delta environment with the thickness ranging between 380 to 746 meters. The lithology is mainly light grey and brown-grey mudstones, with a layer of sandstones 54 to 74 meters thick in the middle. The field was discovered in 2007 and production began in 2009. During the initial stage of oil production, strata pressure dropped rapidly and field output decreased fast. Hence lithology characterization that is fundamental for studying sand body distribution has a significant impact on optimizing injection-production pattern, controlling strata pressure and improving oil field development efficiency.

It has been a common way to interpret lithology using a combination of log characteristics and rock cores. Though the vertical resolution of well logs is good, the horizontal resolution is poor. Meanwhile, although at a lower vertical resolution, seismic data is the most laterally continuous information available. Thus, the integration of seismic and well-log data can add great value in reservoir characterization by providing a high-resolution three-dimensional description of the reservoir. The combination of seismic and well-log data is possible using seismic inversion, which can convert seismic information into petrophysical properties, such as acoustic impedance and shear impedance (e.g., Srivastava and Sen, 2010). Well-log constrained inversion is a model-based method which uses a forward model to calculate synthetic seismic data as part of the inversion algorithm.

METHOD

In this paper, we apply a well-log constrained inversion method that aims to find an optimum geophysical model with a minimum difference between the response of the model and the observed data (seismic traces) in the least-squares sense. The objective function can be expressed as follows:

$$J = \|\mathbf{D} - \mathbf{F}\|_P + \mathbf{W}_I \|\mathbf{M}_I - \mathbf{M}_I^{pri}\|_P + \mathbf{W}_C \|\nabla_x \mathbf{M}_I - \nabla_x \mathbf{M}_I^{pri}\|_P \ , \quad (1)$$

where $\mathbf{D}$ and $\mathbf{F}$ indicate the observed seismic data and the synthetic data, respectively. $\mathbf{M}_I$ indicates the impedance model parameter, $\mathbf{M}_I^{pri}$ indicates the prior value of the impedance I model parameter, ∇_x indicates the lateral gradient, $\mathbf{W}_I$ and $\mathbf{W}_C$ indicate weight coefficient of the prior value of the impedance model and the controlling factor of lateral continuity, respectively, and $\|\cdot\|_P$ indicates the L_P norm.

The expression of the objective function includes three parts. The first requires the response of the model (F) to approach the observed record (D) as much as possible. The second requires that the inversion result cannot deviate from the prior value too far. And the last requires that the inversion result reveals some degree of lateral continuity. We apply the simulated annealing method to solve these constrained optimization problems to obtain a high-resolution inversion result. The detailed well-log constrained lithology characterization workflow is shown in Fig. 2. In the following context, we will provide some extra descriptions about some key steps.

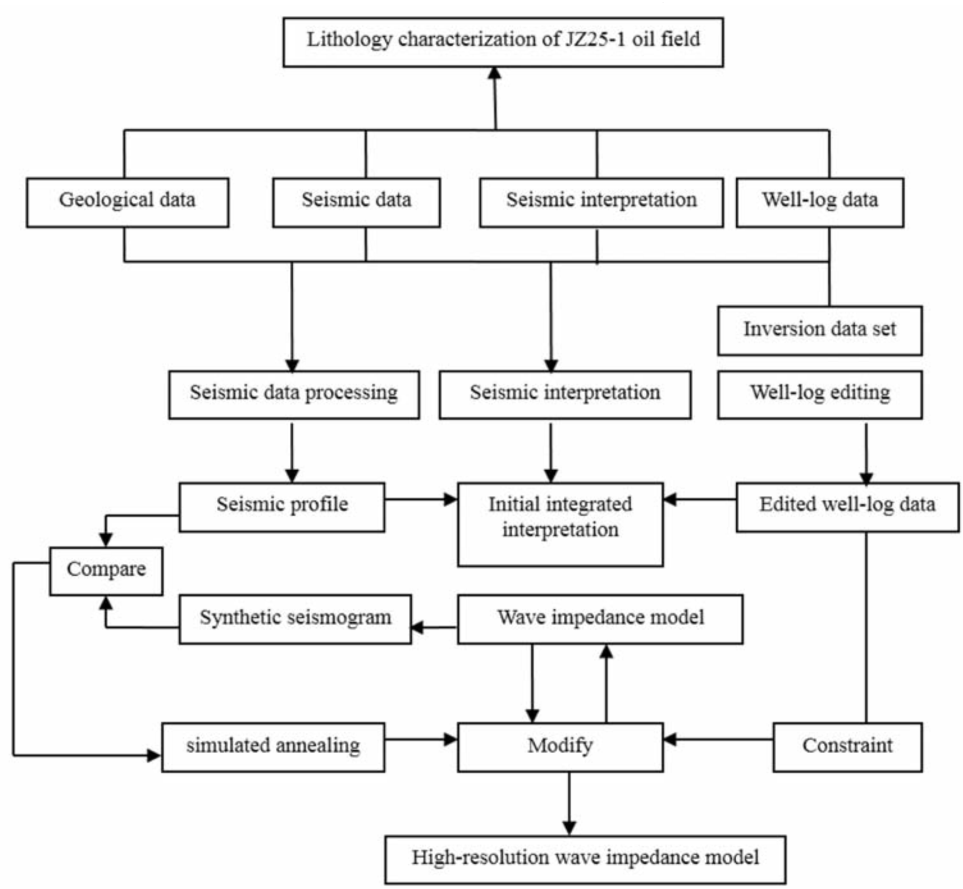


Fig. 2. Workflow of well-log constrained inversion.

Seismic-well tie

The integration of well data with the corresponding 3D seismic data can be obtained based on seismic forward modeling through synthetic seismogram generation. The synthetic seismogram is constructed from well logs (density and sonic to be specific). The idealized five-step workflow in the seismic-well tie (as adapted from Roy, 1997) is as follows:

- Step 1: Edit and calibrate well logs

  Well logs are a result of physical measurement of the earth's properties. However, the measurements are affected by multiple factors such as borehole irregularities and mud filtrate invasion. Therefore, the primary goal in well-log data editing is to rid the data of measurement related errors. In addition, there is a need to synthesize logs that are not available from other existing logs.

- Step 2: Review and assess the seismic data

  It is important that the seismic data is as close as possible to a true representation of the real stratigraphy and rock properties. This can be achieved by implementing the right processing flow, especially by improving the signal-to-noise ratio (SNR) of seismic data (Chen and Ma, 2014; Chen and Fomel, 2015; Gan et al., 2015).

- Step 3: Construct the well log synthetic sequences required

  The easiest and commonest type of forward modeling is based on the convolution model, which assumes vertical ray paths and a horizontally layered earth. According to the convolution model, the seismic signal, S, is a convolution of the earth's reflectivity series or response, R, the seismic wavelet, W, and a compensation factor accounting for wavelet attenuation Q, i.e.:

$$\begin{aligned} S(t) &= R(t) * W(t) * Q(t) \ , \\ S(f) &= R(f)W(f)Q(f) \ , \end{aligned} \tag{2}$$

  where S(f), R(f) and Q(f) are the frequency-domain Fourier transforms of the time-domain responses of S(t), R(t), and Q(t), respectively. The reflectivity series is calculated from acoustic/seismic impedance, I. The impedance, I, of an elastic medium is the ratio of the stress to the particle velocity Aki and Richards (2002) and is given by the product of sonic velocity, V, and density, ρ, i.e.: $I = \rho V$.

The reflectivity at every interface is calculated to generate the so called reflectivity time series; this is convolved with the seismic wavelet to generate the synthetic seismogram.

- Step 4: Run pilot analysis of the well tie

  The first step in making a perfect well-tie is to run pilot analyses to establish the parameters for estimating the wavelet, key among which is a scan of time gates and traces around the well for the best match location (Roy, 1997).

- Step 5: Estimate the wavelet, with diagnostic checks on its accuracy

  The single link existing between well data and seismic data is the wavelet; therefore, it should be carefully estimated.

Initial modeling

The low-frequency information in seismic impedance inversion can be complemented by interpolating laterally the impedance information from the multiple wells, using seismic horizons as trends.

Wave impedance inversion

Using the simulated annealing method and under the constraint of noise and covariance estimates of the model and well-log data, we iteratively modify the model to get an acceptable residual error. The obtained model then can be taken as the inversion result.

DISCUSSIONS

From the case study, we can obtain several general conclusions about the sand distribution rule. The sand distribution is controlled by both deposition and structural movement. The deposition of the third member of Shahejie Formation was generated during the first rapid Liaodong Bay depression period. The sedimentary system mainly contains the alluvial fan-fan delta deposition. The second member of Shahejie Formation is generated during the first stationary Liaodong Bay thermal depression period. Because of the structural movement became less intense, the basin topography becomes smoother. The Liaodong Bay depression originated from the fan-fan delta deposition system and the braided river delta system in the west-east sides of the basin.

Vertical sand distribution

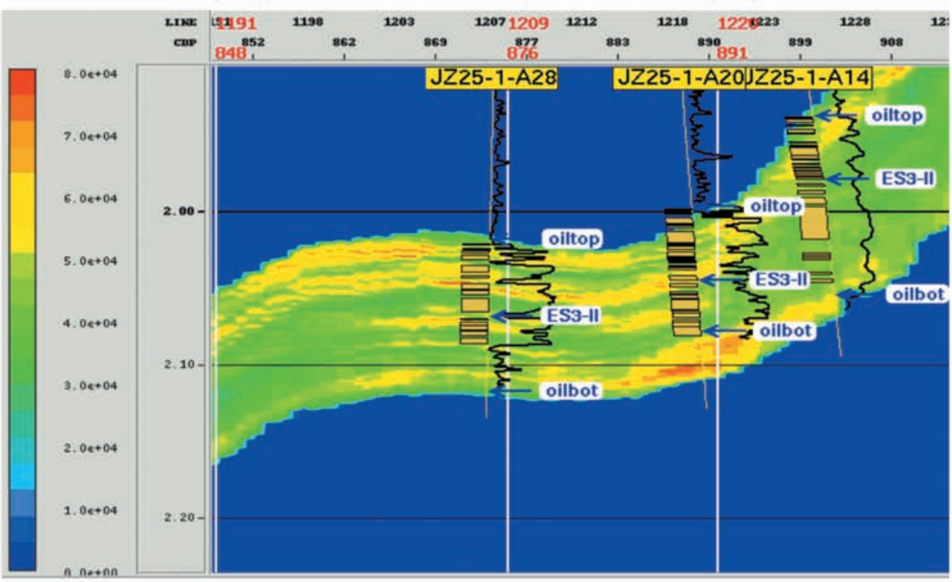
In this case study, we evaluate the vertical sand distribution rule of the JZ25-1 oil field based on a comprehensive investigation of the seismic, well-log, drilling, cores information based on the well-log constrained impedance inversion from 3D seismic data. We divided the Shahejie Formation reservoir into two key strata: the oil-strata in the third member of Shahejie Formation and the second member of Shahejie Formation. The sand distribution of different strata are different according to the spatial locations (here we emphasize the vertical distribution rule). The sand distribution of J25-1 oil field has an obvious layered property. The third member of Shahejie Formation has an obvious massive structure and the second member of Shahejie Formation has an obvious bedded structure. The sand distribution is generally controlled by the structure movement, while it is also affected by the sedimentary facies. From Fig. 3a we can see that the depth of the sand layers decrease from the bottom to the top. There is a big reservoir at the well A-20 position. The sand of different strata are connected well from the vertical inversion result.

Horizontal sand distribution

Based on the well logs, and a comprehensive analysis of the seismic attributes, we can predict the spatial sand distribution of the Shahejie Formation in the Liaodong Bay depression area. The spatial sand distribution is shown in Fig. 3b. In the first and third members of the Shahejie Formation, the long axis of the alluvial sand lays on the similar direction as that of the water flows. The source direction is on the east side of study area. The average thickness of the sand strata is about 40 meters for the third member of Shahejie Formation. The thickness of the sand strata in the southern part is relatively thinner, and is about 20 meters. The sand thickness in the northern part is relative larger, and reaches about 60 meters. The first and third members of the Shahejie Formation originated from the same source. However, during the deposition period the water layers increased a lot, which made the source decrease a lot, and the thickness of the sand strata becomes thinner.

CONCLUSIONS

We have performed lithology characterization using the well-log constrained inversion on the JZ25-1 oil field, China. The distribution of sand bodies can be inferred from the inversion. Sand bodies of the third member of Shahejie Formation are stacked vertically and bodies in the lower part are thicker than those in the upper part (Fig. 3a). Using the wave impedance model as constraint, sand thickness map can be created by kriging interpolation, thus



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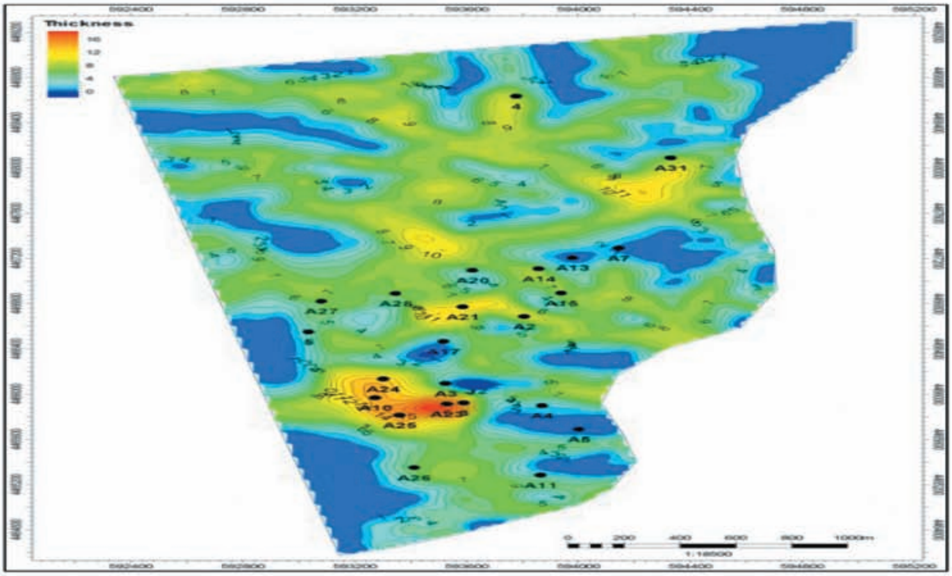

b

Fig. 3. (a) Inversion profile of a section through Well JZ25-1-A28, Well JZ25-1-A20 and Well JZ25-1-A14. The strata is in the third member of Shahejie Formation. Yellow indicates sand. (b) The sand thickness map of Es3 II-2.

the horizontal distribution of sand bodies can be inferred. The average sand thickness of Es3 II-2 is 10 meters and sand thickness reaches its maximum in the southern part of the study area (Fig. 3b).

ACKNOWLEDGMENTS

We thank CNOOC (China) Ltd. Tianjin for the authorization to present this work.

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