Reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control — A case study in the C block of lower Congo basin

Ling Liu, Dazhen Tang, Hao Xu, Lihui Liu

A School of Energy Resource, China University of Geosciences, Beijing 100083, PR China
B Rockstar Petroleum Science and Technology Limited Company, Beijing 100192, PR China

ABSTRACT

Currently, conventional forecasting methods of well-to-seismic integration are unable to identify turbidite channel sandstones due to scarcity of well data in deepwater areas, small geophysical differences between sandstones and mudstones of turbidite channels and strong sandstones heterogeneity. The reservoir prediction of deep-water turbidite channels is still a difficult issue in deep-water research. On the basis of previous studies, we propose a new technology named “reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control” in view of the characteristics of deep-water turbidite sandstones. This new technology improves the reservoir prediction of complex sedimentary systems after classifying seismic lithofacies and connecting lithofacies with rock-physics. Furthermore, it can accomplish the genetic classification statistics of rock-physics, improve conversion accuracy of seismic elastic parameters/reservoir parameters and achieve the quantitative reservoir prediction under the double control of seismic geomorphology and seismic lithofacies. The C block of Lower Congo Basin is characterized by few well data, complex lithology but high resolution seismic. We use the technology to predict the reservoirs of this area and have achieved excellent results. This has great significance for the later exploration.

1. Introduction

In recent 20 years, a lot of petroleum has been found in deep-water deposits. According to study, 90 percent of the oil and gas reserves discovered in deep-water basins come from deep-water turbidite deposits, and deep-water exploration has become an important and active field in international oil industry (Pang et al., 2005; Peng et al., 2005; Shanmugam, 2000; Stowa and Mayall, 2000; Pettingill and Paul, 2002). After the discoveries of giant oil-gas fields in Campos Basin of Brazil, such as Albacora, Marlim, deep-water petroleum exploration is heating up. Currently, more than 100 countries are engaging in offshore oil exploration and the countries which are engaging in deep-water exploration are more than 50 (Jia et al., 2005). There exist many hot spots of deep-water exploration in the world, including West Africa, Brazil Campos Basin and the Gulf of Mexico. The research on deep-water turbidite deposits and their related reservoir prediction will be maintained at least 25 years in the future (Stowa and Mayall, 2000).

Deep-water reservoirs are the key to deep-water petroleum exploration, but logging curves fail to distinguish hemi-pelagic mudstones from deepwater sediment-gravity flow deposits. And due to small geophysical differences between sandstones and mudstones of turbidite channels, conventional forecasting methods of well-to-seismic integration are unable to identify sandstones. Therefore, reservoir prediction of deep-water sandstones is more complex than that we thought, and it is still a difficult issue in deep-water study (Weimer et al., 2000; Liu, 2013). Previous researchers predicted deep-water turbidite sandstones according to seismic attributes, well data and seismic inversion, and did achieve some results. However, the prediction results are determined by interpreter experience and seismic quality and the accuracy is very low due to few well data in deep-water areas, and non-unique solutions of seismic attributes and seismic inversion (Han, 2013; Xie et al., 2015).

Seismic lithofacies (Avseth et al., 2009) refer to macroscopic depositional units at seismic scale, and not only refer to lithofacies, such as water or oil-filled sandstone, but also contain geofacies. More important, seismic lithofacies have seismic attribute characteristics (i.e. can be identified with seismic attributes). With the classification of seismic lithofacies, we can better understand...
seismic signals and improve reservoir prediction of complex sedimentary systems. Meanwhile, seismic lithofacies can connect lithofacies with rock-physics, so we can identify and predict lithofacies quantitatively by seismic elastic parameters. These improve the ability of reservoir prediction and description. To address the features of deep-water turbidite sandstones, we have designed a technology named “reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control” and used the method to predict reservoir in the C block of Lower Congo Basin. Reservoir studies confirm that the method is effective for quantifying reservoir lithology.

2. Geological setting

Lower Congo Basin is one of the middle basins on the West Africa coast. It is a continental rift basin superimposed on a passive continental margin, and is located in the southern part of the Niger Delta basin (Xiong et al., 2010). Its basement is Precambrian crystalline bedrock and is covered with Cretaceous and Tertiary formations, while Jurassic strata are developed locally. The basin contains salt rock of Aptain age, with a large thickness and stable distribution. Using the salt rock as a boundary, the basin fill can be divided into pre-salt formation, salt formation and post-salt formation, i.e. salt formation is Aptain; pre-salt formation is mainly fluvial and lacustrine deposits; while post-salt formation is the marine carbonate deposits of Ablian age, and becomes marine clastic deposits upward. Since Oligocene, the Congo River has rejuvenated again because of the rapid falling of sea level, the drastic uplift and subsidence of the strata. The terrigenous debris came from Congo River are brought into the deepwater fan system by the east-west Congo valley and formed Malembo Formation with a thickness of 6000m, the major production formation of giant oil and gas fields discovered in Angola in recent years. In addition, the fracture systems of the basin are complicated for the salt rocks activities and the tectonic stress action. In Neogene, these faults distribute in N–S direction and NNS-SSE direction, which intersect the turbidite channels extended along NWW-SEE direction and E–W direction (Fan et al., 2012). This provides a good condition for the forming of structural-stratigraphic traps.

The study area is located in C block, north central Lower Congo basin (Fig. 1). It is tectonically situated on the upper-middle continental slope where the Congo fan system develops into deepwater. UM8 of Malembo formation is the reservoir objective layer and is mainly composed of channel-levee deposits with turbidite sandstones and abyssal mudstones. Previous study indicated that the area has good source rocks and excellent trap conditions, but reservoirs are the major risk of exploration, because the study area does not include the major payload zone of Oligocene-Miocene sandstones as the water depth of this area is less than 2000m. Moreover, the turbidite channel sandstones have rapidly lateral changes.

3. Data and methods

3.1. Data

The study was based mainly on 3D post-stack seismic data, pre-stack seismic data and well logs. The dominant frequency of post-stack seismic is approximately 40Hz, and the frequency bandwidth is 10–80Hz. The available maximum offset angle is wide and approximately 50°. Moreover, near-trace gathers have the characteristics of high signal to noise ratio (SNR) and no multiples. Until now, three wells have been drilled, namely C-n1, C-SE3 and M-1. The first two wells have composite logs, while the last one has no well data. The approximate well locations are illustrated in Fig. 4.

Fig. 1. Tectonic map of the study area.

Fig. 2. Technique process.
3.2. Methods

Seismic attributes and seismic inversion are the major method of reservoir prediction (Liu, 2008; Guan et al., 2006), but the previous researchers proposed the technology of “reservoir prediction with facies control”, i.e. using sedimentary features to control seismic attributes and seismic inversion. This improved the accuracy of reservoir prediction to some extent, but for deep-water turbidite sandstones, it has become difficult since conventional forecasting methods of well-to-seismic integration are unable to identify them. In this study, in view of the features of deep-water turbidite sandstones and the meaning of seismic lithofacies, we try to use seismic lithofacies to predict reservoirs. At present, seismic lithofacies achieve mainly qualitative analysis according to geofacies, log facies and seismic facies (Zhang et al., 2011). Quantitative research has been rare, except for neural network learning which has certain randomness (Yang et al., 2004; Wang et al., 1996). On the basis of previous study and taking the idea of facies control into consideration, we have now designed a technology named “reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control” to accomplish quantitative reservoir prediction. This new technology calculates seismic lithofacies with sedimentary geomorphology control firstly, and then predicts reservoir thickness and porosity with seismic lithofacies control. This has achieved a quantitative prediction of reservoir with double facies control and improved reservoir prediction accuracy. This technology includes six steps: (1) seismic geomorphology analysis of turbidite channels; (2) Log identification of seismic lithofacies; (3) rock-physics analysis of seismic lithofacies; (4) seismic lithofacies calculation; (5) seismic lithofacies verification; (6) quantitative reservoir prediction. The process of this technique is as follows (Fig. 2).

4. Reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control

4.1. Seismic geomorphology of turbidite channels

It is very important to analyze seismic geomorphology and determine the distribution of sedimentary bodies before research.
in order to guide seismic lithofacies calculation, because seismic lithofacies represent the rocks or rock combinations of different sedimentary environments. The turbidite channels of the study area show the features of small-scale, unclear downcutting reflection and are hard to track laterally in the section. Therefore, we took advantage of seismic attributes to confirm the plane distribution of turbidite channels based on the theory that “the plane width of sedimentary system is far greater than its vertical thickness, and it is more possible to identify the sedimentary systems in plane rather than in section” (Zeng and Tucker, 2004; Galloway and Hobday, 1983; Wei et al., 2008).

Fig. 3 shows that the oil-filled sandstone of C-n1 well is high-amplitude. Below it is a mudstone, but the mudstone also shows the feature of bright spots, this means that high-amplitudes are not only the interface response of sandstones and surrounding rocks in the C block of Lower Congo basin, but also may be caused by mudstones internal impedance interface for other reasons (Li, 2012). How to identify whether the high-amplitudes are the reflection of turbidite sandstones? We can identify the high-amplitude reflection of the turbidite channels according to morphological characteristics, because the deep-water turbidite channels of the study area have the feature of low-sinuosity. For example, we can do some strata slices of seismic amplitude and observe them. If the high-seismic amplitudes of the stratal slices have obvious channel or fan shape, the probability of turbidite channels’ reflection is large and vice versa. In this study, we use geometric attributes to research. The coherence attribute develops three NWW-SEE turbidite channels which have “meandering” plan view and are cut by near NS trending faults. Sandstones extend along the length of the main channels, while levee deposits are distributed along the outside, parallel to the deep-water turbidite channels (Fig. 4a). The morphology of north turbidite channel is the most obvious, followed by the central and south area. In order to better depict turbidite channel morphology, we adopted the technology of RGB frequency mixing (Liu and Marfurt, 2005; Liu et al., 2004; Cao, 2010). Using the technology of wavelet transform (Zhu et al., 2009), we divided seismic into low-frequency seismic data, middle-frequency seismic data and high-frequency seismic data, and then formed a series of stratal slices, finally displayed them with RGB technology. On RGB slice, the morphologies of the three NE–SW turbidite channels are obvious and the boundaries of the faults are also clearly. This improves the prediction accuracy to a great extent (Fig. 4b).

4.2. Log identification of seismic lithofacies

Logs act as the bridge between rock parameters and seismic data. Log identification of seismic lithofacies is the basis of seismic lithofacies analysis. We often do the log identification of seismic lithofacies based on different kinds of data, such as rock cores, thin sections and logs. In this study, we only use logs for lacking other data in the early exploration stage. Taking C-n1 well as an example, we use gamma curve, combining with density, P-wave velocity and S-wave velocity to identify seismic lithofacies based on the seismic lithofacies classification scheme of deep-sea clastic systems (Avseth et al., 2009). We distinguished three types of seismic lithofacies, namely seismic lithofacies I, seismic lithofacies II and seismic lithofacies III. Seismic lithofacies I refers to sandy conglomerate and conglomerate formed in turbidite channels, its GR < 40 and is box-shaped; Seismic lithofacies II refers to sand shale interbedding and forms in levees, its 40 < GR ≤ 70 and is zigzag-shaped; Seismic lithofacies III refers to pure mudstones, mostly formed as deep-water hemi-pelagic mudstone, and rarely in turbidite channels, its GR > 70 and is nearly a straight line (Fig. 5).

4.3. Rock-physics analysis of seismic lithofacies

The purpose of rock-physics analysis of seismic lithofacies is to connect lithofacies with rock-physics and then improve the reservoir prediction ability of complex sedimentary systems with...
seismic amplitude. The steps are as follows: Firstly, choose wells which have complete information; Secondly, use different symbols to represent different types of seismic lithofacies in the cross-plots (in this study, circle represents seismic lithofacies I, square represents seismic lithofacies II and triangle represents seismic lithofacies III); Finally, do cross-plot analysis of different parameters. Fig. 6 indicates that the P-wave impedances of different types of seismic lithofacies have serious overlaps, therefore, it cannot identify seismic lithofacies. VP/VS can distinguish different types of seismic lithofacies (Fig. 7), but it is not the optimal parameter because we need to do elastic parameter inversion on the basis of elastic impedance (Li et al., 2009) and multiple inversions will produce cumulative errors. Furthermore, identification errors are greater due to the small magnitude of VP/VS and the little classification threshold difference (the classification threshold of VP/VS between seismic lithofacies I and seismic lithofacies II is 1.8, while the classification threshold of VP/VS between seismic lithofacies II and seismic lithofacies III is 2.2). Near-angle stack impedance approximates P-wave impedance, while far-angle stack impedance contains VP/VS information. Compared to P-wave impedance and S-wave impedance, the elastic impedances of near-angle stack impedance or far-angle stack impedance can more easily identify seismic lithofacies, and the success rate is 73% when we use both near and far angle stack impedance, while using only near-angle stack impedance, the success rate is just 49% (Avseth et al., 2009). Therefore, we tried to use both near and far angle stack impedance to identify different kinds of seismic lithofacies.

Before the elastic impedance inversions, we need to do angle stack. AVO characteristics are directly affected by the division precision of stack angle. In view of the SNR of pre-stack seismic and computer memory, we did four angle stacks, including 0°–14°, 12°–26°, 24°–38° and 36°–50°. Considering that the wider the angle, the more abundant the S-wave information, we chose 0°–14° and 36°–50° as the basic seismic data. Finally, the elastic impedances were calculated with modified elastic impedance (Liu and Wang, 2011). The method not only maintains the advantage of elastic impedance (Ma and Morozov, 2010), but also has strong anti-noise ability.

Fig. 8 shows that using only far-angle ray elastic impedance or only near-angle ray elastic impedance we are unable to distinguish different types of seismic lithofacies, but use of both far and near angle stack impedance is more successful, and their boundaries are nearly parallel to the various types of seismic lithofacies. In order to better identify the boundaries of different types of seismic lithofacies, we proposed the concept of extended ray elastic impedance (EREIMP) according to Poisson impedance (Quakenbush et al.,...
EREIMP is the new impedance formed by rotating a right angle according to the cross-plot of near-far angle ray elastic impedance and is expressed by the following formula: 
\[ \text{EREIMP} = A \cdot \text{REI}_{\text{near}} + B \cdot \text{REI}_{\text{far}} + C. \]
Where EREIMP is extended ray elastic impedance and its unit is \( g/cm^3 \cdot m/s \); REIfar and REInear are far-angle ray elastic impedance and near-angle ray elastic impedance, respectively, and their units are both \( g/cm^3 \cdot m/s \); A, B and C are the controlling parameters of optimal discrimination obtained from mathematics coordinate rotation. The steps are as follows: Firstly, find a suitable trend line between seismic lithofacies \( \text{III} \) and seismic lithofacies \( \text{II} \); And then rotate an optimal angle along this trend line and form a new coordinate system to better identify different types of seismic lithofacies. It is worth noting that the two parameters participated in mathematics coordinate rotation must have the same order of magnitudes.

In the new coordinate system, the new Y-axis is the primary X-axis named REI7, while the new X-axis is EREIMP calculated by near-far angle ray elastic impedance, and the formula between EREIMP and near-far angle ray elastic impedance is as the following:
\[ \text{EREIMP} = 0.54 \cdot \text{REI7} - 0.84 \cdot \text{REI43} + 1078.88 \]
Different values of EREIMP referred to different types of seismic lithofacies: seismic lithofacies I (EREIMP > 600), seismic lithofacies II (0 < EREIMP ≤ 600); seismic lithofacies III (EREIMP ≤ 0).

### 4.4. Seismic lithofacies calculation

The inversion of near and far angle ray elastic impedance is the key of seismic lithofacies classification, because we divide seismic lithofacies into different types according to the classification threshold of EREIMP obtained from rock-physics analysis. EREIMP is obtained from the calculation of near and far angle ray elastic impedance. As previously mentioned, we adopt the modified elastic impedance and its formula is as follows (Liu and Wang, 2011):

\[ \text{REI}_i = \frac{A_{li}}{\cos \theta_i} \left( 1 - 4 \frac{\text{SI}_i^2 \sin^2 \theta_i}{A_{li}^2} \right) = \frac{\rho_i c_i}{\sqrt{1 - \alpha_i^2 p^2}} \left( 1 - 4 \alpha_i^2 p^2 \right) \]

Where \( p \) is ray parameter.

Fig. 10 shows that high impedances occur mainly in turbidite channels and match well with the oil layer. Therefore, the results of
Ray elastic impedance inversion are reliable and can be used to calculate seismic lithofacies. On the basis of ray elastic impedance calculation, we calculated the EREIMP with near and far angle ray elastic impedance according to the EREIMP formula and got the seismic lithofacies with the calibration of rock-physics classification threshold. Fig. 11 indicates that seismic lithofacies I and seismic lithofacies II are mainly developed in turbidite channels, and the former mainly develops in the center of turbidite channel. This matches with C-n1 well whose oil thickness is 33m (Fig. 11), and the section position is illustrated in Fig. 12. In the seismic lithofacies plane, seismic lithofacies I and seismic lithofacies II are mainly distributed along NW–SE direction, and seismic lithofacies II are parallel to seismic lithofacies I (Fig. 12). This indicates that the results of seismic lithofacies, well data and geological setting are consistent, and seismic lithofacies can be used to predict reservoirs.

4.5. Seismic lithofacies verification

Seismic lithofacies verification includes point verification and plane verification. Point verification refers to a comparison of the seismic lithofacies obtained from logging interpretation with that obtained from seismic inversion and a determination as to their consistency. If they are not, return to logging identification of seismic lithofacies to calculate again. The specific steps are as follows: Firstly, transform the seismic lithofacies interpreted by well from depth domain to time domain; Secondly, extract near-far angle elastic impedance curve from seismic trace near wells; Thirdly, compare the seismic lithofacies interpreted by well with that calculated by near-far angle elastic impedance and examine the consistency of them. Fig. 13 shows that the resolutions of seismic lithofacies calculated by seismic are lower than that interpreted by well due to low-resolution seismic, but both of the trends are consistent.
uniform, and the consistency is greater than 80%. Plane verification refers to a comparison of the seismic lithofacies plane with seismic geomorphology and checking the consistency of them. As the analysis in 2.3.3, the consistency of seismic lithofacies and seismic geomorphology is also greater than 85%. Point verification and plane verification show that the results of seismic lithofacies are reliable and can be used to predict reservoir quantitatively.

4.6. Quantitative reservoir prediction

4.6.1. Reservoir thickness prediction

Currently, the calculation methods of reservoir thickness include tuning curve, integrating amplitude-frequency information (Hu et al., 1995), neural network (Yin et al., 1999), co-Kriging multivariate statistical analysis (Ji et al., 2000), and impedance characteristics analysis (Xu and Duan, 2001). In this study, the reservoirs vary rapidly laterally, which results in a low coincident rate and less reliability of reservoir thickness prediction. But seismic lithofacies are directly related to lithology and different seismic lithofacies represent different lithologies, therefore, we can indirectly calculate reservoir thickness with seismic lithofacies. The steps are as follows: Firstly, calculate the cumulative time thickness of the seismic lithofacies I and seismic lithofacies II during the objective layer; and then obtain the reservoir thickness plane of depth domain by velocity transformation. The reservoirs of the study area extend NE–SW with a thickness of 5–35m. The reservoirs thicker than 17.5m occur mainly in turbidite channels, and the thickness of the levees is about 7.5–17.5m, while the area between turbidite channels was mainly deep-water mudstones, reservoirs are few and they are mostly less than 7.5m thick (Fig. 14). The prediction of thickness of C-n1 well and C-SE3 well is 35m and 13m, respectively, while the actual thicknesses are 33m and 11.5m, respectively, and both are oil layers. This indicates that the calculated thickness and actual thickness are consistent.

**Fig. 11.** Seismic lithofacies section.

**Fig. 12.** Seismic lithofacies plane.
4.6.2. Reservoir porosity prediction

Generally, porosity is calculated by using the mapped relationships with other elastic parameters due to lack of direct relationship between porosity and seismic parameters. For example, some researchers used seismic velocity to calculate porosity on the basis of Wyllie equation (Wyllie et al., 1956); Philips et al. (1994) used the linear regression relationship between porosity and P-wave velocity to predict porosity, Hampson et al. (2001) proposed that we can calculate porosity by building a multiple linear and nonlinear relationship between seismic attribute and well porosity, Cadeton and Castagna (2007) predict porosity by combining rock-physics and seismic attribute. None of the methods paid any attention to the sedimentary factors, so the calculation accuracy is low. The porosity prediction based on seismic facies analysis is established on the basis of the facies classification (Liu et al., 2010). This method provides a reliable basis for the lateral prediction of porosity, but it...
is uncertain because this method is using neural network to qualitatively classify seismic lithofacies. On the basis of the quantitative calculation of seismic lithofacies with seismic elastic parameters, the technology of “reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control” analyzes the relations between P-wave impedance and porosity of different types of seismic lithofacies and converts the P-wave impedance into porosity with these relations. Compared to the porosity predicted from only the relationship of P-wave impedance and porosity, the porosity predicted with seismic lithofacies control can better display the lateral distribution of porosity and makes more geological sense. Fig. 15 shows that the relation between porosity and P-wave impedance is not obvious when we do not classify the seismic lithofacies. After eliminating seismic lithofacies III, the porosities of seismic lithofacies I and seismic lithofacies II have a certain linear relationship with their P-wave impedances. For the prediction accuracy, we adopted the idea of facies control and analyzed the relations between porosity and P-wave impedance according to the types of seismic lithofacies. The relations of porosity and acoustic impedance in seismic lithofacies I and seismic lithofacies II are as the following: \[ \text{POR}_I = -7.37 \times 10^{-5} \text{IMP} + 0.69; \]
\[ \text{POR}_{II} = -8.86 \times 10^{-5} \text{IMP} + 0.65. \]
Finally, with seismic lithofacies control, we eliminated seismic lithofacies III and predicted the reservoir porosity with different relations only in seismic lithofacies I and seismic lithofacies II. The horizon distribution law of porosity matched with that of seismic geomorphology, seismic lithofacies and reservoir thickness. Furthermore, high porosity zones were mainly distributed along turbidite channels (Fig. 16). The predicted porosities of C-n1 well and C-SE3 well are 0.14 and 0.11, respectively, and the actual porosities of C-n1 well and C-SE3 well are 0.13 and 0.12, respectively. Therefore, the prediction accuracy of reservoir porosity is high and reliable.

**Fig. 15.** The cross-plot of porosity and P-wave impedance with seismic lithofacies control.

**Fig. 16.** Reservoir porosity.
5. Conclusions

(1) We propose a new technology named “reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control” based on a geological view of deep-water turbidite sandstone. Compared to conventional methods, this technology can do genetic classification statistics of rock-physics and improve the conversion accuracy of seismic elastic parameters to reservoir parameters under the double control of seismic geomorphology and seismic lithofacies. Moreover, it achieves quantitative reservoir prediction and solves the difficult problem of identifying turbidite channel sandstones that conventional forecasting methods of well-to-seismic integration are unable to do;

(2) This technology has been used in the prediction of turbidite channel sandstones in C block of Lower Congo Basin. By comparing the prediction results with well data, the reliability and effectiveness of the technology have been verified and the prediction results are significant for later exploration;

(3) The precision of seismic lithofacies division and reservoir prediction is strongly dependent on seismic resolution and elastic parameter sensitivity. The higher the seismic resolution and the more sensitive the elastic parameters, the higher is the prediction accuracy of turbidite channels with the technology of “reservoir prediction of deep-water turbidite sandstones with seismic lithofacies control”.

Acknowledgments

The research was supported by the Fundamental Research Funds for the Central Universities (Grant No.2652015330). The author would like to take this opportunity to express our appreciation and thanks to Liu Xuyia, Zhang Lingling for their hard work on this study. In addition, we also want to thank Ron J Steel, Phd, the associate editor of Marine and Petroleum Geology for his help in English language modification and the two reviewers for their helpful suggestion.

References