PARIS 2017

Tu D1 06

Reservoir Characterization through Geostatistical and Azimuthal Inversion Techniques – A Case Study for Carbonate Reservoir

H.L. Gao (Institute of Petrochina Tarim Oilfield Company), G.H. Li (Institute of Petrochina Tarim Oilfield Company), Y.L. Lu (CGG), J. Ting (CGG), X.W. He (CGG), B. Liu (CGG), G.Y. Yu* (CGG)

Summary

Karstic carbonate reservoirs commonly have multiple media of hydrocarbon storage including caves, vugs and fractures. It is often a big challenge for quantitative reservoir characterization in karstic carbonate because of the very complex seismic reflection, particularly when seismic resolution is limited. This paper aims to develop a workflow integrating geostatistical and azimuthal inversion techniques to accurately predict reservoir distribution characteristics including caves, vugs, strike and density of fractures in karstic carbonate reservoirs. The success of this workflow would provide tremendous support to the design of new development wells and dramatically increase drilling success.

Introduction

Karstic carbonate reservoirs commonly have multiple media of hydrocarbon storage including caves, vugs and fractures. It is often a big challenge for quantitative reservior characterization because of the very complex seismic reflection, particularly when seismic resolution is limited. Considering the significant amount of oil and gas reserves in carbonate rocks, if the reservoir distribution characteristics including caves, vugs, the density and strike of fractures could be predicted accurately, it would provide tremendous support to the design of new development wells and dramatically increase drilling success.

Key Technology

Based on the carbonate reservoir geological characteristics and technical challenges, key technologies and workflows employed in this seismic reservoir characterization study include:

- Seismic petrophysics and rock physics modeling
- Full-azimuth pre-stack geostatistical inversion
- Deterministic azimuthal inversion

Firstly, an integrated and iterative seismic petrophysics and rock physics modeling workflow was carried out to investigate and understand the relationship between the elastic parameters, and the characteristics of caves and vugs. Secondly, a pre-stack geostatistical inversion technology (Contreras, et al., 2005 and Contreras, et al., 2014) using full-azimuth data was conducted to characterize cave and vug facies. Thirdly, a deterministic pre-stack simultaneous inversion using isotropic modeling and inversion algorithm was performed to obtain individually-inverted azimuthal-sectored elastic properties, and followed by an advanced regression application modeling HTI (Horizontal Transverse Isotropic) anisotropy using the inverted elastic properties from all azimuth sectors in concert to analyze and predict the anisotropy magnitude and orientation of the fractures (Mesdag, 2016). These key technologies coupled with extensive quality controls produce accurate and robust prediction results that have been proven by newly drilled wells.

Case Study

The dataset used for this case study is the Yijianfang (O2y) carbonate formation located in the Tarim basin of western China (Figure 1). The main oil-bearing reservoir is of Ordovician age, buried to a depth of 7000m and overlaid by a thick clastic sequence.

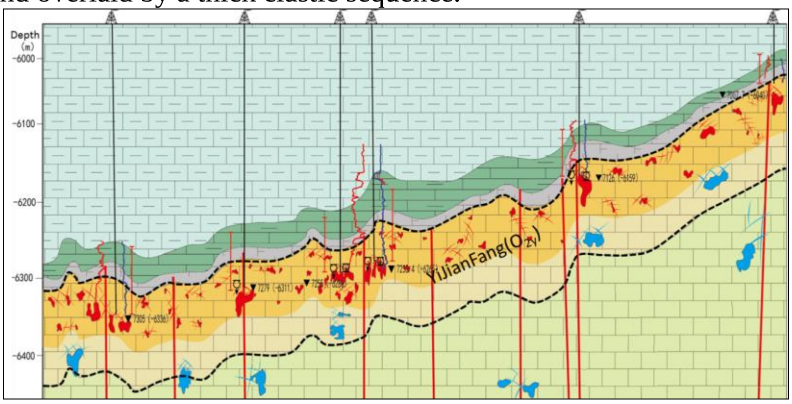

Figure 1 *Schematic geological cross section. The main target reservoir, YiJianFang (O2y) carbonate formation has developed a large number of caves, vugs and fractures.*

This formation was originally deposited as grain banks with a sub-phase of carbonate mud mounds. After a long geological history of diagenesis, all primary porosities were lost. But, because of the late multi-stage tectonic movements and karstification, a large number of caves, vugs and fractures were developed. All existing wells exhibit oil and gas shows with most of them experiencing mud loss during drilling which indicate the development of caves, vugs and/or fractures. According to the core and FMI data analysis, the fractures are mainly high angle from 75-90 degrees which approximate a HTI medium.

Seismic petrophysics and rock physics modeling

The petrophysical and elastic properties within the caves and vugs of the carbonate formation are very difficult to characterize. Nevertheless, based on the integrated and iterative seismic petrophysics and rock physics modeling through the Xu and Payne method (2009), the relationship between the elastic parameters, petrophysical (reservoir) properties and the cave and vug facies was established (Figure 2). The caves show highest porosity (>5.2%), lowest P-Impedance and lowest Vp/Vs; The vugs show average porosity (1.8%-5.2%), average P-Impedance and average Vp/Vs; Shale shows low porosity, average P-Impedance and high Vp/Vs; Other matrix shows lowest porosity, highest P-Impedance and highest Vp/Vs. Besides, there are considerable overlaps between the different facies. Therefore, pre-stack geostatistical inversion technology that attempts to predict reservoir heterogeneity and with multiple plausible realizations to capture uncertainty (or probability) was recommended to distinguish caves and vugs from the rest of the facies.

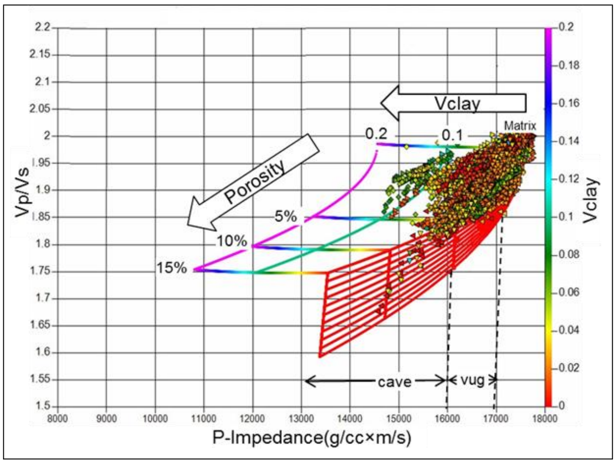

Figure 2 *Rock physics modeling results and rock physics template for facies and fluids interpretation.*

Full-azimuth pre-stack geostatistical inversion

Caves and vugs are the main containers for hydrocarbons in the Yijianfang carbonate reservoir. They exhibit significant seismic response and unique reflection characteristic known as "string" based on their physical appearance on the seismic section (Figure 3a and Figure 4c). In order to get more accurate and reliable reservoir details, full-azimuth pre-stack geostatistical inversion that conceptually combines geostatistical modeling and AVO/AVA simultaneous inversion was conducted using the full azimuth seismic data. The input parameters of facies proportions and probability trends were analysed from well logs, seismic facies analysis and deterministic inversion results.

Figure 3 shows a successful example of the application of pre-stack geostatistical inversion in this study area. The seismic trough of the characteristic "string" reflection was often used to identify the top of the caves or vugs in this study area. Sometimes, it is correct in non-shaly limestone area but not always. For the case example in Figure 3, when the well was drilled to the depth as indicated by the seismic trough (6800m), there was no reservoir where caves or vugs were expected. Pre-stack geostatistical inversion was then conducted and it predicted that the best reservoir with the lowest P-Impedance and lowest Vp/Vs was located below 6800m. The well trajectory was re-designed and the well was drilled deeper. Finally, mud loss occurred and good reservoir was found. This successful example proves that pre-stack geostatistical inversion provides more accurate prediction for caves and vugs in this study area.

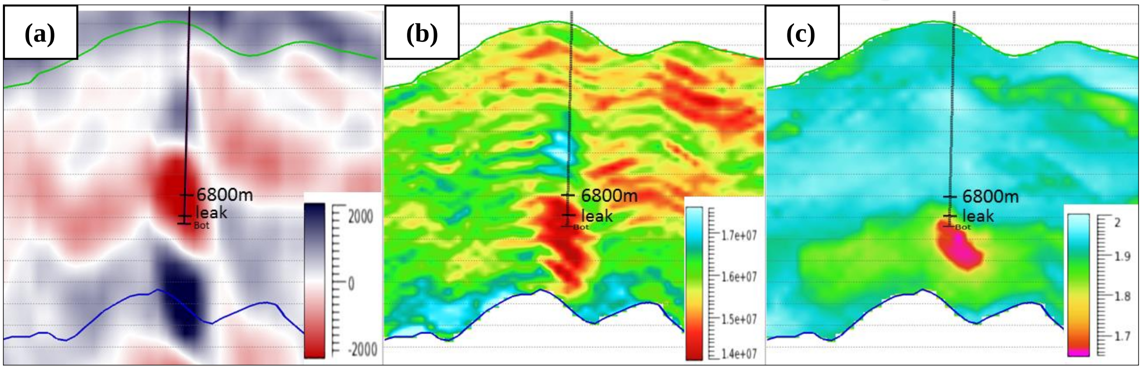

Figure 3 *(a) Seismic amplitude; (b) inverted P-Impedance; (c) inverted Vp/Vs.*

Deterministic azimuthal inversion

Fractures are another key factor that controls production in carbonate reservoir especially when the matrix porosity is low. They improve connectivity and permeability of the reservoir. The common approches in prediction of fractures are normally qualitative including coherence cube and curvature analysis. Recently, pre-stack seismic attributes including velocity or amplitude variation with angle and azimuth of incidence have been used to analyze fracture strike and density, but their solutions could be unstable and unreliable. Besides, full-azimuth pre-stack geostatistical inversion is not able to provide fracture information quantitatively. In this study, the layer properties-based anisotropy characterization using a two-step approach presented by Mesdag (2016) was found to be the most successful in providing a quantitative prediction for fracture strike and density.

A new wide-azimuth seismic dataset with an acquisition aspect ratio of 0.75 was acquired over the study area. The range of seismic frequency is 7Hz-45Hz, the fold is 179 and the offset range is 566m-7448m. A good seismic imaging has been performed prior to this reservoir characterization study. The input seismic data have been aligned in offset, angle and azimuth directions. The wide-azimuth seismic dataset was processed in 6 azimuthal sectors: 0-30°, 30-60°, 60-90°, 90-120°, 120-150° and 150-180°. Feasibility and pilot test studies were conducted to investigate the lateral consistency of seismic amplitudes and verify that significant differences in the seismic amplitudes among the azimuthal sectors were available. Then, pre-stack simultaneous inversion was performed on the wide-azimuth data for each azimuth sector separately to obtain elastic parameters such as Vp/Vs. With the six Vp/Vs volumes, an advanced regression application tool was used to analyze the magnitude (amplitude) and orientation (azimuth) of anisotropy. Finally, fracture strike and density were characterized through the use of magnitude and orientation volumes in the study area.

Reservoir information from a newly drilled (blind) well was available to validate the prediction of caves, vugs and fractures in this study (Figure 4). The predicted caves, vugs, fracture strike and density are well matched with the interpretation results at the blind well location. This well has produced 4.5×10^{4}T of oil so far.

Conclusions

This case study shows that the combination use of pre-stack geostatistical inversion and deterministic azimuthal inversion to quantitatively characterize carbonate reservoir is a reliable approach. It not only delineates the distribution of caves, vugs and fractures, but also provides prediction for the strike and density of fractures. It overcomes the limitations of the conventional methods and improves the precision of carbonate reservoir prediction. The prediction results are well matched against the drilling results from a new well. Effectively, it is able to characterize all reservoir types in carbonate formation (matrix, caves, vugs and fractures) and reduces risk in their exploration, development and production.

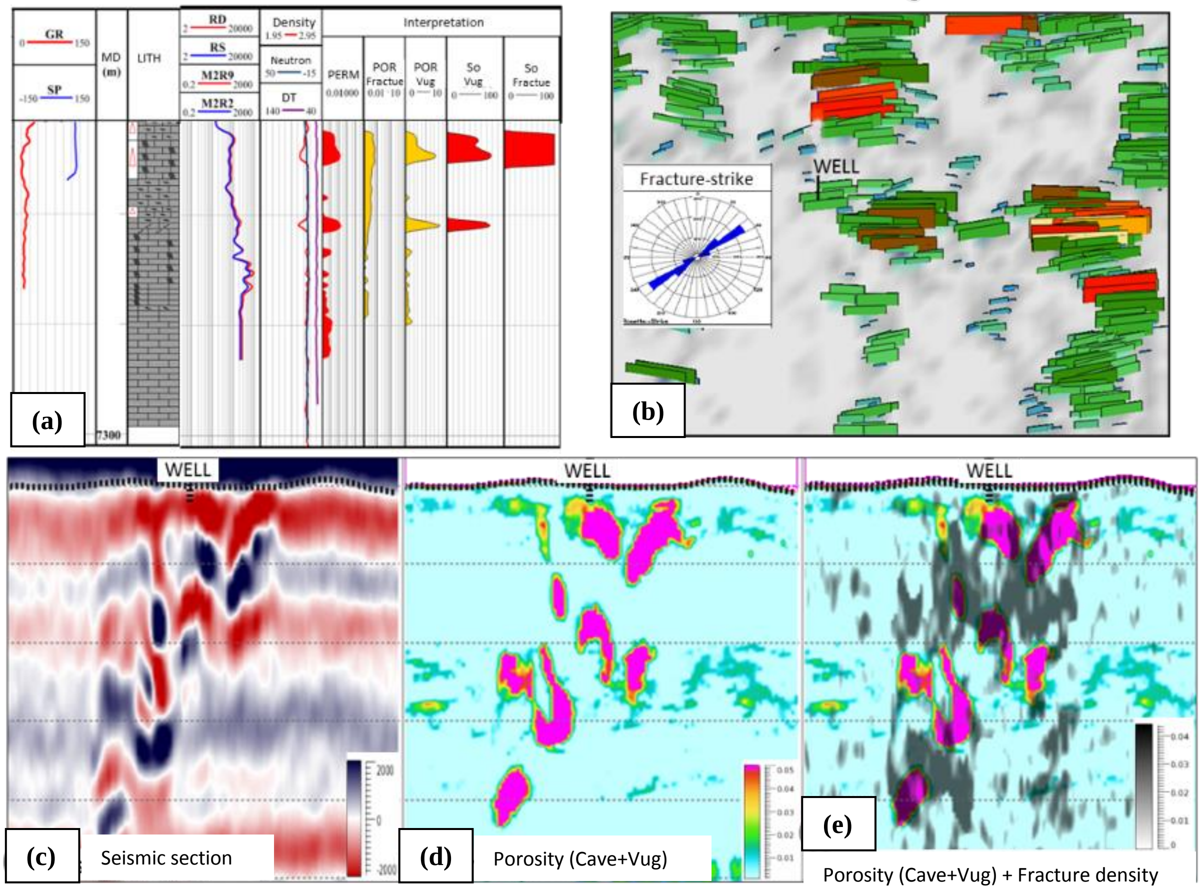

Figure 4 *(a) Well interpretation results; (b) Fracture strike from well FMI data (inset rose plot) is consistent with the azimuthal inversion results; (c) Seismic amplitude section; (d) The predicted reservoir porosity from pre-stack geostatistical inversion (warm colors show presence of caves and vugs); (e) Composite reservoir characterization analysis showing reservoir distribution (warm colors show presence of caves and vugs) and connectivity (black color shows magnitude of anisotropy which indicates fracture distribution).*

Acknowledgements

The authors express their thanks to Tarim Oilfield Institute of Exploration and Development of PetroChina and CGG for the permission to publish this paper.

References

Contreras, A., Torres-Verdin, C., Chesters, W., Kvien, K. and Fasnacht, T., [2005]. Joint stochastic inversion of 3D pre-stack seismic data and well logs for high-resolution reservoir characterization and petrophysical modeling: application to deepwater hydrocarbon reservoirs in the central Gulf of Mexico. SEG, Expanded Abstracts, 1343-1346.

Contreras, A., Torres-Verdin, C., Fasnacht, T., Chesters, W. and Kvien, K., [2014]. Joint stochastic inversion of 3D prestack seismic-amplitude data and well logs for high-resolution reservoir characterization of deepwater hydrocarbon reservoirs. The Leading Edge, May, 520-525.

Mesdag, P., [2016]. A new approach to quantitative azimuthal inversion for stress and fracture detection. SEG International Exposition and 86th Annual Meeting, 357-360.

Xu, S. and Payne, M. A., [2009]. Modeling elastic properties in carbonate rocks. The Leading Edge, January, 66-74.