



### Integration of 3D Seismic and Reservoir Simulation for Exploitation of Remaining Oil in a Heavy Oil Field: A Case Study

Guo Xiangyu\*, Ling Yun, Huang Xuri, Cai Yintao, BGP, CNPC

#### Summary

Based on a full azimuth 3D seismic (cell size 6.25 m × 6.25 m and coverage area 14 km<sup>2</sup>) and reservoir simulation on one well group (40 vertical wells and 5 horizontal wells in an area of 600 m × 400 m), an integrated research on a SAGD (Steam Assisted Gravity Drainage) production was carried out in an oilfield in Northeast China. The results indicate that the configuration of steam chambers caused by steam flooding could be estimated from high precision 3D seismic data, and it is more accurate than the reservoir simulation model with locally varying descriptions of the chambers (the accuracy of the simulation model is influenced by density, porosity and permeability data). But with only seismic data, it is difficult to differentiate the influence of geological sedimentation or small sized fractures from the steam chambers, and further to predict the distribution of remaining oil. Integrating the 3D seismic data with the reservoir simulation model (thus forming a 3.5D seismic method), we were able to predict the remaining oil. This approach is free from many technical difficulties facing time-lapse applications such as no baseline survey and non-repeatable noise.

#### Introduction

It was observed in the lab that a large velocity change can occur in rocks with heavy oil if the oil is replaced by steam (Nur et al., 1984). From the late 1980s, the application of time-lapse seismic was investigated (Robert and Terrance, 1987). The Duri heavy oilfield with steam injection is well known for its application of time-lapse seismic in production monitoring (Jenkins. et al., 1997). By 2001, more than one hundred time-lapse seismic projects have

been conducted around the world (Lumley, 2001). But the effectiveness and reliability of the method depends on the quality and repeatability of the surveys. The technique of 3D exploration for the remaining oil with historical production data (called a 3.5D seismic) could avoid the non-repeatability problem commonly associated with time-lapse seismics, and reduce the cost of exploration for the remaining oil at the same time (Ling et al., 2008). The application of 3.5D (integrating 3D seismics with reservoir simulation) seismic techniques to a heavy oilfield in Northeast China will be discussed through a case study in this paper.

#### Geological and geophysical background

The main producing reservoir, Ng, is on a monoclinial structure (Figure 1a) covering 1.95 km<sup>2</sup> (white oval in Figure 1b). The reservoir has a maximum thickness of 145 m, and is located at depths between 540 m and 800 m. Both the porosity and permeability of the reservoir are high, with edge, top and bottom water. Production of this heavy oilfield started in 1997 and 10 to 12 cycles of steam stimulation have been implemented with well intervals of 70 m, oil recovery rate reached 20–25%. Starting in 2005, five SAGD well pairs have been utilized. These well were still in production when the high density 3D seismic data were acquired in February, 2009.

The SAGD process raised the oil recovery by 5–10%. The steam chambers inside the reservoir are quite complicated due to the two stages of steam flooding. Figure 2 is a seismic section across the reservoir; a discontinuity in the reflection signal inside the steam chambers can be observed. Under the Ng layer, reflection time slows and the reflection amplitude



## Integration of 3D Seismic and Reservoir Simulation for Exploitation of Remaining Oil in a Heavy Oil Field: A Case Study

becomes weak.

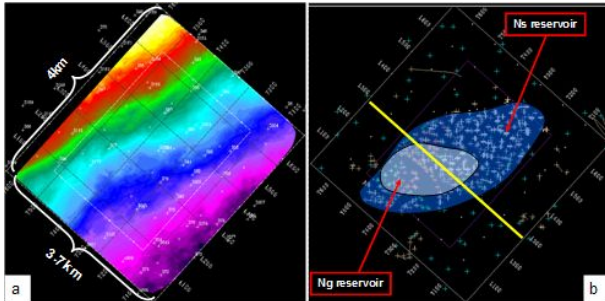


Figure 1: (a) Structure of the top of reservoir and (b) the spatial distribution of Ng (small white oval, 700 wells in this 1.95 km<sup>2</sup> area), Ns (large blue oval, 5.6 km<sup>2</sup>, not discussed in this paper) reservoirs

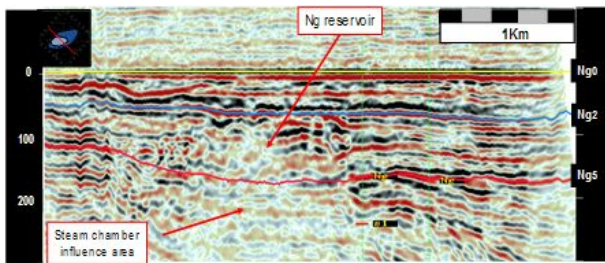


Figure 2; Inline seismic section across the reservoir.

The 3D seismic survey is of wide azimuth with a reservoir layer aspect ratio equal to 1. The survey has a full fold area of 6 km<sup>2</sup>, with a 6.25 m × 6.25 m bin size and 90 fold. We employed a processing procedure that both enhances the vertical resolution and relatively preserves the information of the reservoir. The processing flow includes: time – frequency domain spherical spreading and absorption compensation (Gao et al., 2004) for the near–surface and earth absorption effect, two –step statistical deconvolution on both shot and receiver gathers (Ling et al., 1998) aimed at land reverberation suppression and removal of the spatial wavelet difference. A geophysical QC procedure (Gao et al., 2009) was implemented in all major processing steps. Also, high precision velocity picking, statics and NMO+DMO+

post–stack migration were included in the processing work flow.

### Integrated interpretation of reservoir simulation and seismic data

Figure 3 are the amplitude slices of Ng2 and 80 ms below Ng2, respectively. The local amplitude difference can be observed in the Ng2 reservoir (white oval in Figure 3a); the zoomed view (Figure 3c) shows the clear amplitude difference. In Figure 3b, there is a weak amplitude area which correspondences well with the Ng2 reservoir. The weak amplitude in the seismic reflection is caused by the steam injection, which indicates that the seismic amplitude does reflect the steam flooding effect. In addition, the local amplitude variation may indicate the distribution of steam chambers and remaining oil.

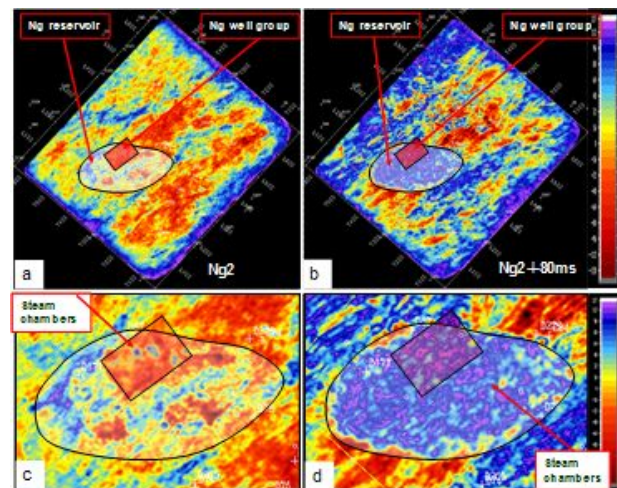


Figure 3: Amplitude slices (a: Ng2, b: 80 ms below Ng2) and zoomed view (c: Ng2, d: 80 ms below Ng2).

Based on the geological interpretation, some overall understanding of the steam chambers could be reached, and the local amplitude variation could also be observed. However, it is difficult to differentiate



## Integration of 3D Seismic and Reservoir Simulation for Exploitation of Remaining Oil in a Heavy Oil Field: A Case Study

the influence of geological sedimentation or small sized fractures from steam chambers, and to further predict the distribution of the remaining oil.

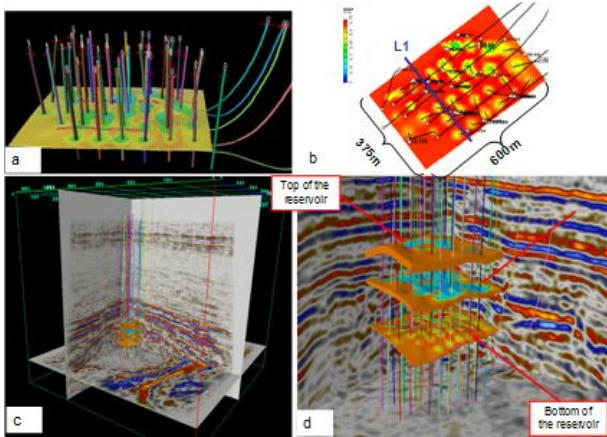


Figure 4: (a and b) Distribution of the production well group and (c and d) integrated display of both the seismic and reservoir simulation models (three slices of the model show the oil saturation attributes).

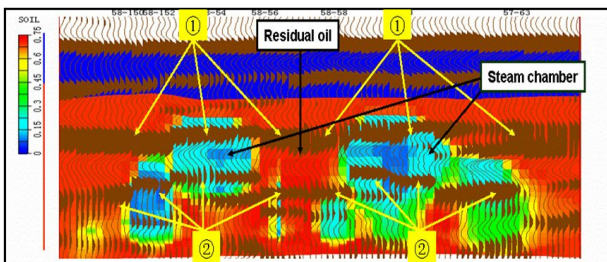


Figure 5: Integrated display of seismic (traces) and reservoir simulation result (color contours) on L1 (indicated in Figure 4b). The events marked as '1' are related to the top of the steam chambers, and those marked '2' correspond to reflection inside the steam chambers. The areas with low oil saturation (colored blue) are the steam chambers, the high saturation areas (colored red) indicates presence of remaining oil.

We have carried out integrated research to solve the above mentioned problems. We use one well group in the area for the reservoir simulation study. This well group consists of 40 vertical and five horizontal wells (Figure 4a). It covers an area of 600 m × 375 m (Figure 4b). Two kinds of steam flooding methods

were applied in the production: the Cyclic Steam Stimulation using vertical wells in the early stage, and SAGD with vertical wells as injector and horizontal ones as producers later on. The complicated injection pattern gave rise to the complex steam chambers, which could be observed in the steam simulation results (Figures 4c and 4d). The reservoir simulation model was obtained through the history match of production data with the initial geologic model. At the bottom of the simulation model, the steam chambers have good correspondence with the locations of injection wells. Inside the reservoir, the steam chambers appear to have a complicated connectivity and configuration. At the top of the reservoir, the steam chambers cover only a small area. In the cross section of the reservoir simulation model (colour display in Figure 5), one can observe the complexity of the steam chambers in the vertical direction as well as the distribution of the remaining oil. Although the reservoir simulation technique could do a fairly good job in the overall prediction, the prediction accuracy is affected by the density, porosity and permeability fields, which are applied in the heat conduction equation. Hopefully, the integrated interpretation of the high precision 3D seismic and reservoir simulation will help to enhance the ability of remaining oil prediction.

Figure 5 is the integrated display of the reservoir simulation and the seismic section. It is clear that: 1) at the top of the steam chambers the waveform becomes narrower (frequency increases) and the reflection time shorter. In the areas without the influence of steam, the waveform is relatively fatter (frequency decreases) and the reflection time is longer. These phenomena are caused by the steam and heavy oil replacement driven by steam injection,



## Integration of 3D Seismic and Reservoir Simulation for Exploitation of Remaining Oil in a Heavy Oil Field: A Case Study

so the overlying formation moves upwards, and the reflection coefficient varies. 2) Inside the steam chambers, frequency increases and reflection time decreases, while outside the steam chambers, one can observe a decrease in frequency and increase in reflection time. This is also caused by the replacement of the injected steam and the heavy oil.

If we were only using the seismic data, the regions marked '1' or '2' (Figure 5) could be interpreted as small faults or variation in sedimentation. From integrated interpretation of the reservoir simulation and seismic data, however, it can be concluded that these regions are actually the reflection of the steam chambers, and one could further confirm the spatial distribution of the remaining oil, thus achieving the goal of remaining oil exploration.

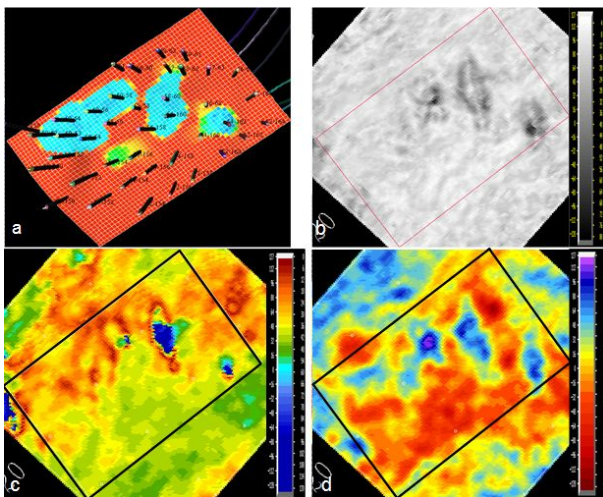


Figure 6: Reservoir simulation and seismic attribute slices at the top of Ng reservoir (a: simulation model; b: coherence; c: frequency; d: amplitude)

From the comparison between the reservoir simulation model (Figure 6a) and the various seismic attributes (Figures 6b, 6c, 6d) at the top of the Ng reservoir, one can observe a good correlation. In the

coherence slice (Figure 6b), there is clear incoherency in the areas of the steam chambers. From the frequency slice (Figure 6c), we can clearly see the frequency increases in the steam chambers. Also we can observe weak amplitude in the steam chambers in the amplitude slice (Figure 6d). In summary, at the top of the steam chambers, one can observe incoherency, high frequency and low amplitude features in the seismic attribute slices.

Some differences exist in both the spatial location and the shape of the steam chambers between the slices of the reservoir simulation and the seismic attributes. This is an indication of the difference between the reservoir simulation model and the seismic measurements. The reason for this is that the accuracy of the reservoir simulation is influenced by the accuracy in density, porosity and permeability, while the seismic attributes are the result of the measured seismic wavefields. It is expected that the local variations in seismic attributes are more realistic. In other words, seismic attributes are more accurate than the reservoir simulation in describing the local variation. The integrated interpretation of reservoir simulation and seismic data can better describe the shape of the steam chambers and thus predict the location of remaining oil.

### Conclusions

We have demonstrated that, based on the processing for a wide azimuth 3D seismic data that preserves reservoir information (amplitude, frequency, phase and waveform), the steam chambers caused by steam flooding can be estimated by seismic data. However, with only seismic information, the differentiation between the influence of sedimentation



## Integration of 3D Seismic and Reservoir Simulation for Exploitation of Remaining Oil in a Heavy Oil Field: A Case Study

variation or small-sized fractures from the steam chambers is rather difficult. On the other hand, the inaccuracy in the estimation of density, porosity and permeability will result in errors in reservoir simulations. It is especially true for complicated reservoirs. With the integration of 3D seismic data and reservoir simulation, uncertainty caused by single type of information can be reduced. From our study, we have found that the reservoir simulation can provide overall prediction of steam chambers, while seismic attributes are effective for interpretation of local variations.

### Acknowledgements

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