B038

Fracture Prediction, Actual 2010 Drilling Results, and Full Wave Forward Modeling - An Integrated Technologies Approach

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SUMMARY

Over the last few years Lukoil has published the results of two exhaustive studies into the problem of fracture detection. Fracture prediction methods based on reflection amplitude, reflection curvature and its derivatives, coherency cube, spectral decomposition, ant-tracking technology, azimuthal anisotropy of P-wave velocity, and DWM amplitude cube analysis. We concluded that the DWM technique was the most reliable method for fracture permeability detection (Khromova et al., 2011). Lukoil planned a 2010 drilling program for horizontal wells based on DWM technology and this paper will report on the results of that 2010 drilling program. Two horizontal wells were drilled into a limestone interval and extensive well log measurements were taken. The well results illustrate that the location of the fracture systems as predicted by DWM were accurate to within 25 metres. The DWM amplitude maps and well log results will be shown to illustrate the success of this fracture prediction technique. Also, the ability to use these actual well results, along with full wave forward modelling, and DWM technology to push the boundaries of reservoir characterization prediction using an integrated seismic-based methodology is investigated.

Introduction

Three years ago an oil field in the Timano-Pechersky basin in Russia was the site of a specialized study into a productive fractured carbonate reservoir of Early Permian age. The study entailed the use of several conventional fracture detection methods and a new technique called duplex wave migration (DWM). Extensive well test results were used to compute well productivity coefficients and these actual results correlated strongly with the DWM amplitude cubes (Khromova *et al.*, 2008, Khromova *et al.*, 2009).

We studied fracture prediction methods based on reflection amplitude, reflection curvature and its derivatives, coherency cube, spectral decomposition, ant-tracking technology, azimuthal anisotropy of P-wave velocity, and DWM amplitude cube analysis. We concluded that the DWM technique was the most reliable method for fracture permeability detection (Khromova et al., 2011). Lukoil planned a 2010 drilling program for horizontal wells based on DWM technology and this paper will report on the results of that 2010 drilling program.

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Method

Duplex wave – is a wave that is reflected twice: first time from the sub-horizontal layer, then from a sub-vertical layer (or in the opposite order) and then it is recorded at the surface. Until recently, the imaging of sub-vertical boundaries using surface seismic was assumed to be impossible because in most cases the reflections from those surfaces never reached the surface. Duplex wave energy properties were studied in earlier publications (Kostyukevych *et al.,* 2001, Marmalevskyy *et al.,* 2005, Marmalevskyy *et al.,* 2006, Gornyak *et al.,* 2008) where it was shown that duplex wave energy is strong enough to be used in the exploration of geological targets. The DWM technology is well described in a January, 2011 First Break paper (Khromova et al., 2011) and others given in the reference list.

Example

During 2010 Lukoil drilled two horizontal wells, A and B, into this fractured carbonate interval targeting macro fracture swarms, the intensity and location of which, were predicted using DWM amplitude maps. In some cases these highly fractured zones produce high production rates of pure oil for up to three years. In other cases we encounter a reservoir just above the OWC and oil production waters out in a few months. The DWM amplitude maps enabled the drilling engineers to develop a detailed horizontal well drilling plan for 2010.

Drillers and oil engineers know that fractured zones can be hazardous due to the potential for accidents such as the loss of mud pressure and the drill bit itself. But, "being forewarned – is to be forearmed." A bore hole path was planned in such a way as to enter the top of the reservoir 70-100 m horizontal distance in front of the first predicted fractured zone, thereby enabling the well bore to become horizontal prior to entering the three predicted fracture zones. At exactly the predicted location the rate of penetration increased dramatically from 3-4 to 18 meters per hour, and drilling fluid absorption occurred at bore hole length of 1970 m (Figure 1). The next predicted fractured zone was encountered after passing through 180 m of limestone country rock at well bore length 2150 m. The third predicted fracture zone was encountered 100 meters later at well bore length 2250 m. An Advanced LOG suite shows that dense country rock (porosity 3-4%) is separating two porous layers. In the fracture zones the full-wave sonic log amplitude of the acoustic waves (P-waves, S-waves and tube Lamba-Stoneley waves) drop to zero. Since the horizontal wells penetrated normal to the sub-vertical fractured zones we can accurately measure the thickness of these zones. They vary from 5 to 8 meters in width.

The well log results for Well A are shown in Figure 1. Note the clear indication of three major fracture swarms.

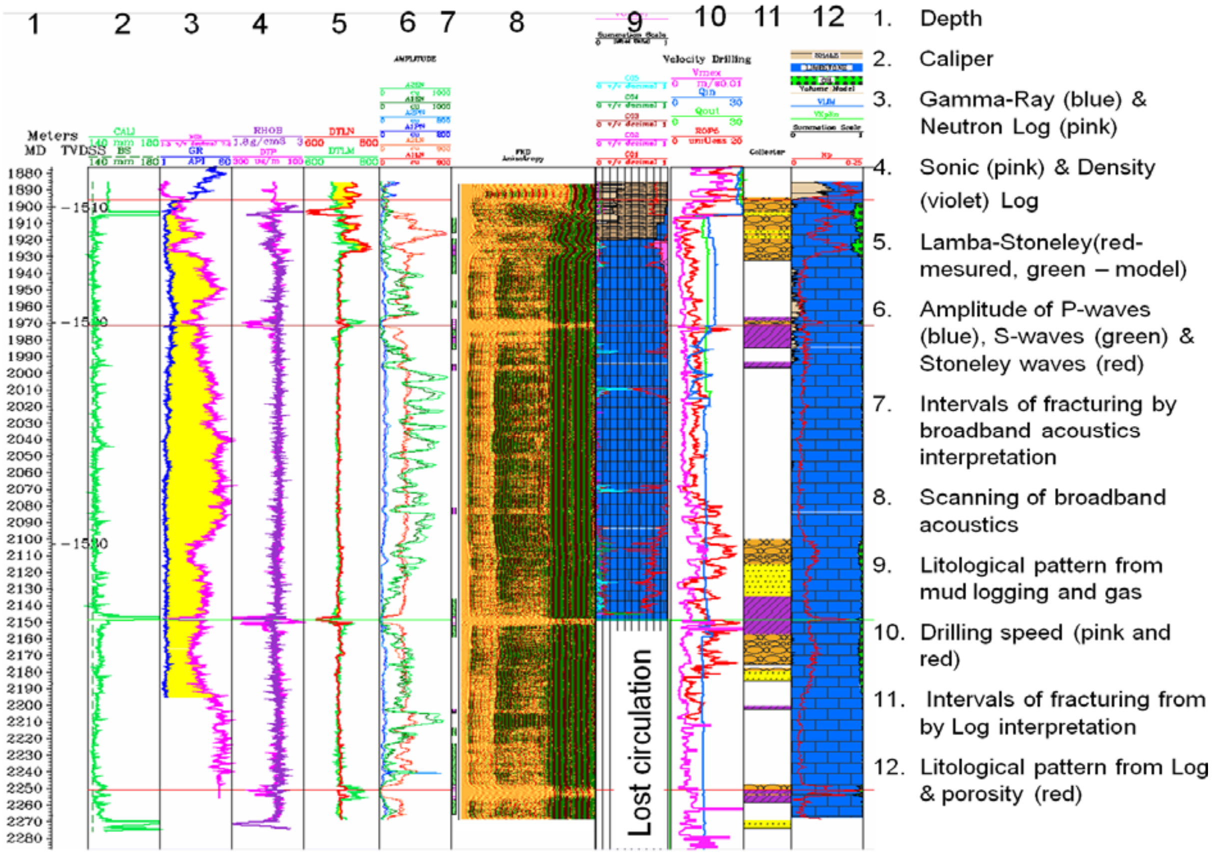

Figure 1: *Well log results from horizontal well A. Note that the actual depth of the horizontal well bore within the limestone interval is indicated to the right of the well bore length measurement.*

Figure 2 shows a vertical slice of the DWM amplitude cube in depth and the Well A trajectory is shown along with the amplitude measurements of the recorded Lamba-Stoneley waves. Well A results confirm the accuracy of horizontal location prediction of the fractures to be within the receiver interval which was 25 m. However, during the drilling of the horizontal section, mud loss occurred (in this case, it was decided to drill in the industrial water density 1.01 g/cm^3) and 100 m^3 per day of water was pumped into this zone.

The experience of drilling Well A taught the drillers and engineers that the increased complexity caused by drilling through three fracture zones was not an efficient reservoir exploitation policy. Therefore, the plan for drilling Well B called for the drilling to stop after entering the first predicted fracture zone as shown in Figure 3. Once again, at exactly the predicted location borehole B encountered a zone of intense fracturing. Production of pure oil from this well continued for two months with a rate of 124 m^3 per day and then began a gradual watering.

The process of drilling these two horizontal wells has greatly increased the confidence drillers and engineers have in the ability of the seismic method to predict the location and intensity of fracture zones. The accuracy of the predicted location is within 25 m. As a result of this process the drillers and engineers have changed their approach to exploiting this type of fractured reservoir.

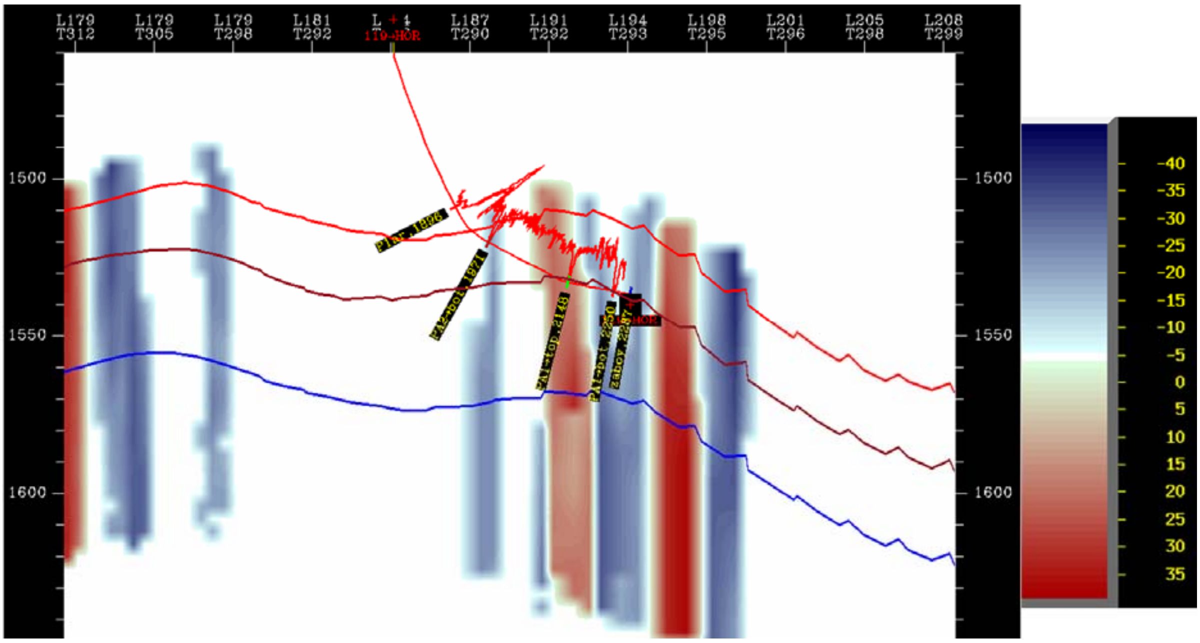

Figure 2 *Amplitude of Lamba-Stoneley Wave (red log) plotted along the trajectory of horizontal Well A plotted over a vertical slice of the DWM amplitude cube.*

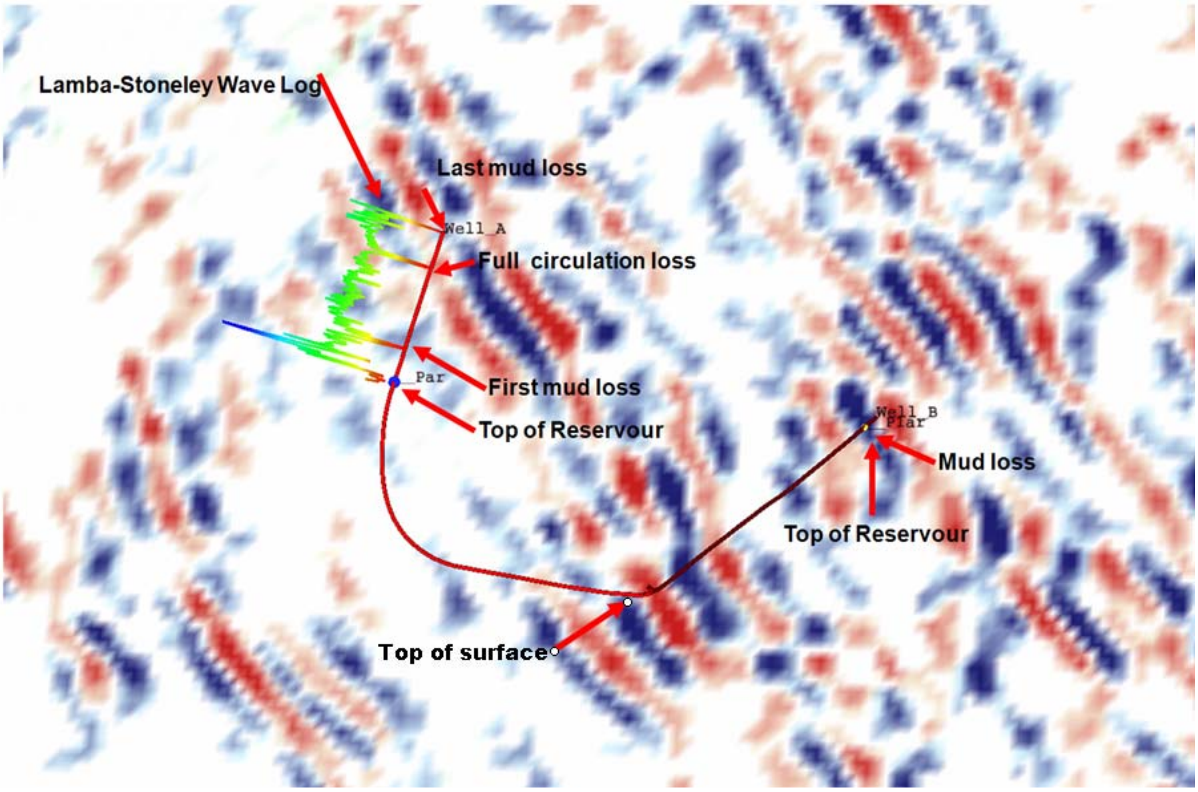

Figure 3 *DWM amplitude map used to determine horizontal drilling locations for the 2010 drilling program. Curve of Lamba-Stoneley Wave's Amplitude is shown from Top of Reservoir along Wellbore A.*

The next stage of our investigation endeavours to understand what level of reservoir characterization information can be realistically obtained using DWM technology. Also, can we perform a variant of AVA analysis on vertical geo-bodies using DWM? Many papers have been written recently that attest to the strong absorption characteristics of fluid filled fractures – can we use DWM technology to observe different levels of absorption? Also, we suspect that strong levels of mode conversion in the area of the fracture systems are likely to occur – can we use DWM to measure local shear wave velocities? To answer these questions, and more, we need to utilize full wave elastic forward modelling, DWM technology, and the detailed well log measurements.

We can use this known well log information to build a realistic model of the actual reservoir. High end full wave elastic forward modelling can then be used to generate synthetic data that simulates the response of seismic waves to these various geologic conditions. We then subject this synthetic data to the same set of DWM processing procedures as were used on the original data. We then are in a position to verify that the variations we see on the DWM amplitude map generated from the real data can actually be explained using full wave forward modelling. Further to this, we can make subtle changes to the known model and redo the forward modelling process to find out whether or not these changes in the reservoir model can actually be detected using seismic-based methods such as DWM.

Conclusions

This paper reports on the actual well results that were predicted using DWM technology that was described in an earlier paper (Khromova et al., 2011). Further, we have investigated the ability to utilize a set of specific fracture detection related technologies including DWM amplitude cubes, full wave forward modelling and actual well results to draw direct linkages between seismic-based methods and enhanced reservoir characterization. This work is intended to push the boundaries of seismic-based methods to contribute to enhanced recovery by enabling the creation of more detailed and accurate reservoir models. We conclude that geophysicists must make a sustained effort to communicate with reservoir engineers through the provision of information that is relevant to the exploitation process.

Acknowledgements

The authors would like to thank LUKOIL in Russian Federation for the permission to present these results.

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