AVO analysis at Pikes Peak

Jonathan E. Downton and Laurence R. Lines

summary

An AVO study was performed to determine the potential of AVO to map the steam chamber, to aid in the enhanced oil reservoir production of the Pikes Peak Thermal Project. The study consisted of three phases: a rock physics study, a modeling study and a template seismic study. The rock physics study helped determine the relationship between the elastic properties of the reservoir and the extrinsic variables: temperature and pressure. This understanding was used along with log control to do a forward modeling study. Synthetic gathers were generated under a variety of reservoir conditions to model the seismic response of the reservoir. The knowledge gained from the modeling study was used to design and interpret the AVO study.

Two AVO inversion techniques were found helpful in describing reservoir changes. The bandpassed reflectivity estimate of lambda and the fluid stack react anomalously to the high temperatures and low fluid modulus associated with the steam front. This was predicted based on forward modeling and then observed on the actual seismic. This offers the potential for 4D AVO studies to map the steam front as a function of time.

Introduction

The Pikes Peak Thermal Project is located close to the Alberta / Saskatchewan Border east of Loydminster, Saskatchewan. The reservoir has been undergoing steam injection since 1981. To aid in monitoring the progress of the steam chamber various seismic technologies have been studied. This study examines the usefulness of AVO to monitor the steam chamber. AVO analysis and inversion offers the potential to more precisely estimate the reservoir properties, than interpretations based on poststack seismic, since AVO makes use of the extra information available in the prestack data. In order to understand and predict the AVO response, it is important to understand how the elastic parameters are influenced by cyclic steam injection.

Methodology

A rock physics study was performed to understand how the extrinsic variables, temperature and pressure influence the elastic parameters of the reservoir. A study was performed at Core Laboratories on a series of core plugs from the Pikes Peak reservoir. These measurements examine how the oil saturated reservoir rock respond to pressure and temperature similar to conditions experienced under cyclic steam injection at Pikes Peak.

This information was used to do a forward modeling study. The forward models were generated based on P-velocity, S-velocity, and density well log data. The log data was perturbed, based on results from the core study, to simulate different reservoir conditions. Synthetic gathers were generated based on this and processed to predict the AVO response. The models indicate that there is a unique AVO response associated with elevated temperature and lower effective pressure as a result of the steam injection. The modeling suggests there are several AVO stacks, such as the fluid stack (Smith and Gidlow, 1987) and the delta-lambda section (Gray et al. 1999), that exhibit anomalies due to the conditions associated with the steaming.

A template 3 component seismic line was recorded in February 2000 over a number of known wells undergoing steam injection. The line was processed in a manner suitable for AVO analysis (Mazotti and Ravagnan, 1995). AVO sections created based on the above modeling indicate anomalies, which positively correlated with the known geology and well control.

Results

Rock physics study

Four oil saturated samples from the Pikes Peak reservoir were tested to examine the influence of temperature and pressure on the compressional velocity (Vp) and the compressional to shear velocity ratio (Vp/Vs). The first set of tests were done at a constant pore pressure of 2.2 MPa and confining pressure of 9.2 MPa. As the temperature was increased from 22° C to 160° C, Vp dropped 21% and the Vp/Vs ratio dropped 8%.

The next set of tests, examined the effect of changing the effective pressure. One set of tests was done at 25° C and the other at 100° C. The pore pressure was held constant at 2.2 MPa while the confining pressure was varied from 14 MPa to 4MPa. This resulted in effective pressures similar to what the reservoir would experience under different stages of cyclic steaming. For both these tests, Vp dropped 8% and Vp/Vs dropped 6%.

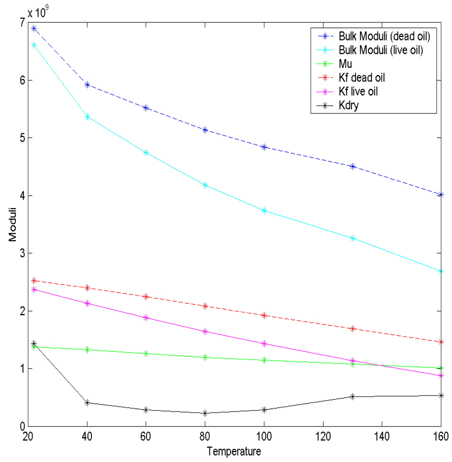

Figure 1: Based on core and fluid measurements trends were established on how temperature and pressure would influence the bulk modulus of the reservoir

All the above tests were performed on samples saturated with dead oil. The actual reservoir is saturated with live oil. To understand how the presence of gas will influence the measurements, a fluid substitution was performed on the core samples, substituting live oil for dead oil. As part of the above tests, the velocity of dead oil was measured at a variety of temperatures. The measurements were consistent with predictions suggested by Batzle and Wang (1992) for oil with a similar API. Mavko et al. (1997) published modifications to account for the presence of gas in the oil. Based on these two curves a fluid substitution was performed using the Gassmann relationship (Gassmann, 1951). Figure 1 shows the effect of temperature on the saturated bulk modulus for the original dead oil and the K_{sat} for the predicted live oil saturated samples. The Bulk modulus is also shown for the two fluids. Note that the live oil has a lower bulk modulus for all temperatures established on how temperature and pressure would influence the bulk modulus of the reservoir.

The dry shear and bulk modulus is, to a first order, constant as a function of temperature. Most of temperature dependence of the saturated bulk moduli is a result of changes in the fluid bulk moduli consistent with observations by Eastwood (1992). Also, note that the low values for the shear and bulk modulus are a result of the high porosity of the samples. The samples have porosities from 37 % to 38.5% close to critical porosity normally associated with sandstones (Nur et al., 1998).

AVO modeling

Based on the above core analysis results, it is possible to understand the first order influence of temperature and effective pressure on the reservoir by just doing a fluid substitution. Based on the Batzle and Wang's relationship (1992) it is possible to model how the fluid modulus, $K_{fl,}$ changes as a function of temperature and pressure and therefore how Vp, Vs and density change.

Several wells had full suites of logs recorded in which there was P-velocity, S-velocity and density information at ambient temperatures and pressures. A fluid substitution was performed on one of these well logs to simulate different effective pressures, temperatures and saturations that occur throughout the cyclic steam injection. Based on this analysis, the P-velocity changes the most, with the S-velocity and density only changing slightly. Temperature is the dominant extrinsic variable. Oil saturation and effective pressure are second order influences.

A series of prestack gathers were created based on the reservoir model. The gathers were then processed and an AVO inversion performed. Various AVO extraction methodologies were tested. The AVO section that gives the best defined anomaly associated with steam injected reservoir is the delta-lambda section. Whenever there is an elevated temperature, the model shows a clear amplitude anomaly at the base of the reservoir (Figure 2). At elevated temperatures, the fluid will have a much smaller Lambda value than at lower temperatures (Figure 1). The high porosity sand has extremely low Lambda values; hence the delta-lambda section reacts to changes in the fluid due to the steaming. As long as the temperature is high, the anomalous AVO response is present, even when there is considerable variation in saturation and effective pressure.

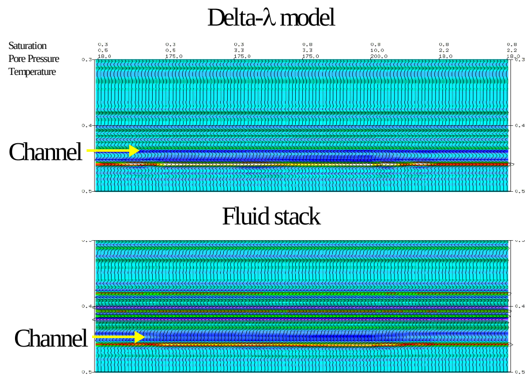

Figure 2: The fluid stack and delta-lambda stack respond to the elevated temperatures associated with the steam

In a similar fashion the fluid stack (Smith and Gidlow, 1987) also reacts anomalously at the reservoir level. It is responding to changes in the fluid content due to the high temperatures and pressures. In the model most of the response is seen at the base of the reservoir.

Template Seismic Line

The vertical component of the 3-C seismic line was processed in an amplitude preserving fashion (Figure 3). The base of the channel shows up as strong amplitude at 0.49 seconds. The template line goes through a variety of well types. The wells are displayed in a color coded fashion on top of the seismic to indicate the well status when the line was shot in February 2000. The wells that were producing are shown in black, the injectors shown in red, suspended in blue or not in production yet, in orange.

Both the delta-Lambda and fluid sections (Figure 3) show amplitude anomalies at the base of channel at 0.49 seconds for the producing wells. The AVO sections accurately show the difference between the producing well 3B1-6, at station 326, and the suspended well 1A2-6 at station 333. There are amplitude variations within the main field. There is no amplitude anomaly between station 280 and 300 suggesting the South part of the field is separated from the North. However, it is somewhat suspicious that the injector well 3B8-6, at station 280, is just showing up at the edge of the anomaly. There are probably some noise issues at this well, which is indicated in the uncertainty analysis. The AVO Delta-Lambda section is consistent with the well control and shows an anomaly consistent with that predicted by the modeling.

Conclusions

Based on this study, AVO seems a promising technology to map fluids within a heavy oil reservoir. The rock physics analysis suggests that there should be significant changes in the elastic parameters of the reservoir as result of steaming. The forward modeling suggests that these changes in the elastic parameters should be observable using AVO. Lastly, the template seismic line seemed to correspond to the well control as the forward modeling predicted.

However, this data set is noisy for the purposes of AVO. The near offsets are all contaminated by noise and influence the solution. The uncertainty analysis done suggests that the level of noise is tolerable, but the noise is responsible for some of the amplitude variation evident of the AVO stacks

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References

Batzle, M. and Wang, Z., 1992, Seismic properties of pore fluids, Geophysics, 57, 1396-1408.

Eastwood, J., 1992, Temperature-dependent propagation of P- and S-waves in Cold Lake oil sands: Comparison of theory and experiment; Geophysics, 58, 863-872.

Gassmann, F., 1951, Uber die elastizitat poroser medien: vier. der natur gesellschaft, 96, 1-23.

Gray, D., Goodway, B. and Chen, T., 1999, Bridging the Gap - Using AVO to Detect Changes in Fundamental Elastic Constants: 61st Mtg. Eur. Assoc. Expl Geophys., Extended Abstracts, European Association Of Geophysical Exploration, Session: 6050.

Goodway, B., Chen, T., Downton, J., 1997, Improved AVO fluid detection and lithology discrimination using Lame petrophysical parameters: 67th annual international SEG meeting, expanded abstracts, 183-186.

Mavko, G., Murkerji, T., Dvorkin, J., 1998, The rock physics handbook, Cambridge University Press.

Mazotti, A. and Ravagnan, G., 1995, Impact of processing on the amplitude versus offset response of a marine seismic data set, Geophysical Prospecting, 43, 263-281.

Nur, A., Mavko, G., Galmudi, D., 1998, Critical porosity: A key to relating physical properties to porosity in rocks; The Leading Edge, 17, No. 3, 357-362.

Smith, G.C., and Gidlow, P.M., 1987, Weighted stacking for rock property estimation and detection of gas; Geophysical Prospecting, 35, 993-101

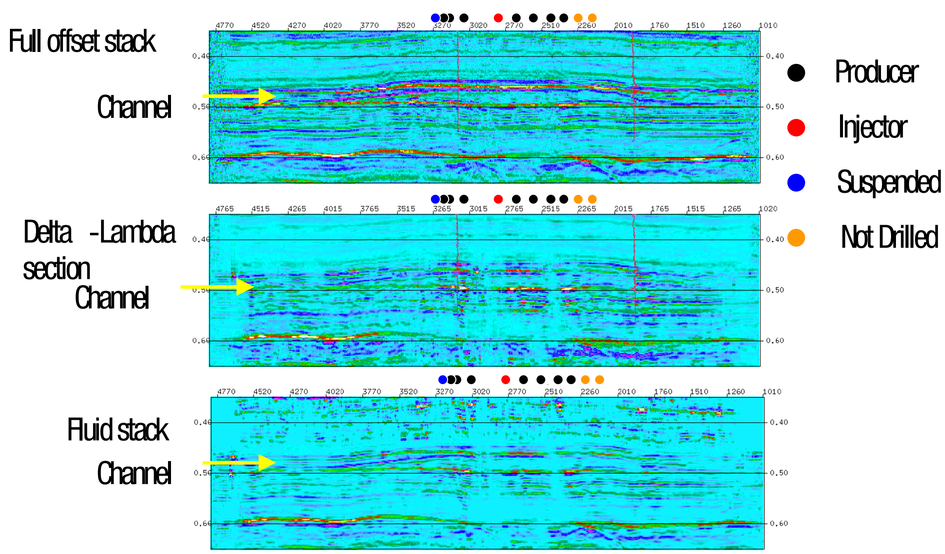

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Figure 3: A comparison of the full offset stack, the delta-lambda stack and the fluid stack. Both the delta-lambda stack and the fluid stack react anomalously to the presence of steam.