Preliminary results of the AVO analysis at Pike's Peak

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ABSTRACT

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 Pike's 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 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 Lloydminster, 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 of more uniquely estimating 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. The 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 steaming. 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 anomalous behavior 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 processing 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^{o} C to 160 ^{o} 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^{o} C and the other at 100 ^{o} 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%.

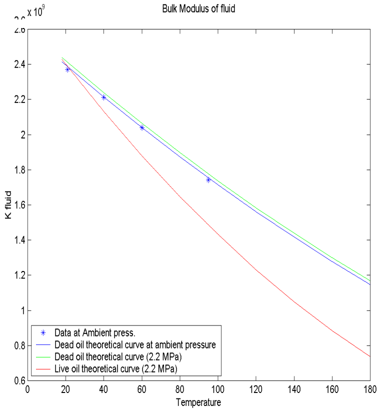
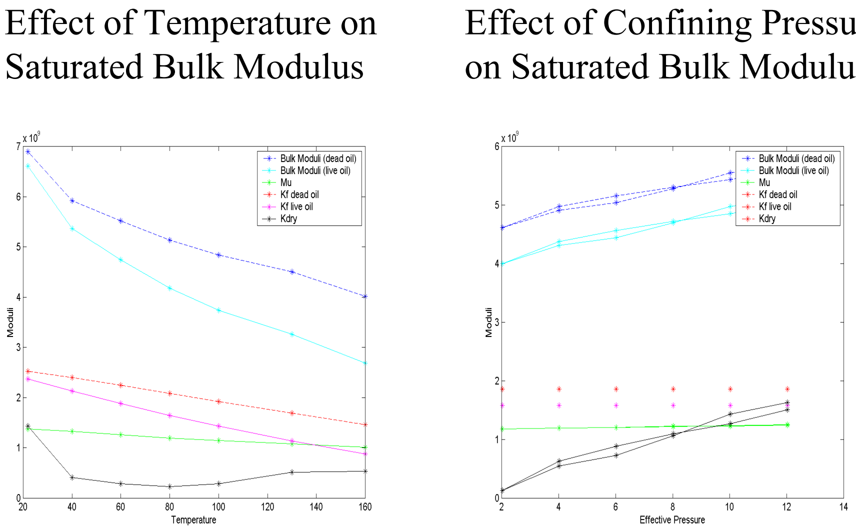


Figure 1: Figure illustrates the effect of gas on bulk modulus of the dead oil. The Blue stars are the measured values of bulk modulus for the Pikes Peak oil. The Blue curve is the empirical relationship based on Batzle and Wang (1992). The red curve is the empirical relationship for a live oil with the GOR at Pikes Peak.

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 influences 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 (Figure 1). 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 2 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.



Effect of Temperature on Saturated Bulk Modulus

Effect of Confining Pressure on Saturated Bulk Modulus

Figure 2: Based on the core observations and the fluid behavior (Figure 1) trends were 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).

Modeling study

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 (1992) relationship it is possible to model how the fluid modulus, $K_{fl,}$ changed as a function of temperature and pressure and therefore how Vp, Vs and density changed.

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, while the s-velocity and density only change 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. Figure 3 shows every 20th gather generated. These gathers are representative of the different combinations of effective pressure, temperature and fluid modeled. It is hard to analyze the significance of the AVO response by just looking at the gathers.

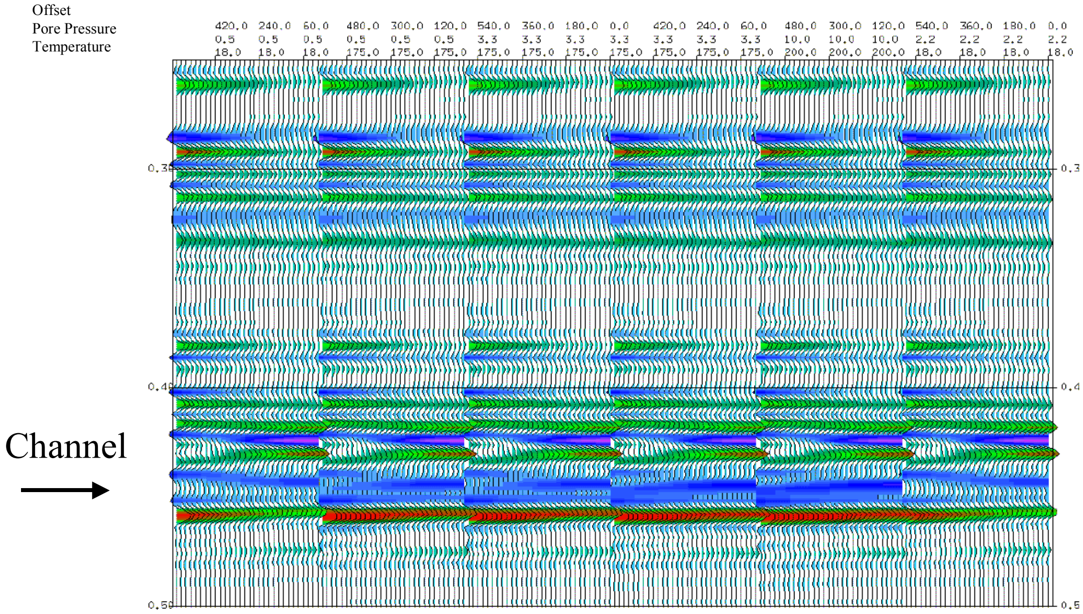
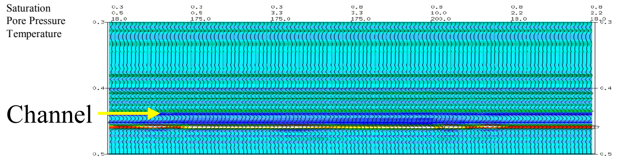


Figure 3: Synthetic gathers displayed for different saturations, temperatures and effective pressures.

Delta-λ model



Fluid stack

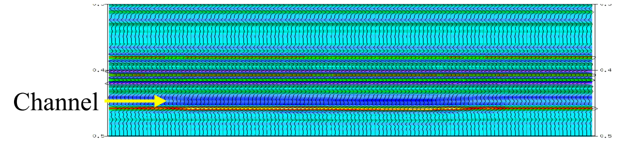


Figure 4: The fluid stack and delta-lambda stack respond to the elevated temperatures associated with the steam flooding

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. On the model, whenever there is an elevated temperature, there is a clear amplitude anomaly at the base of the reservoir (Figure 4). At elevated temperatures, the fluid will have a much smaller Lambda value than at lower temperatures (Figure 2). 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.

The fluid stack (Smith and Gidlow, 1987) also reacts anomalously at the reservoir level, probably for the same reasons as the delta-lambda section above. However, the fluid stack also exhibits extraneous anomalies above the zone of interest. The rocks are quite unconsolidated at these shallow depths, resulting in a poor correlation between the P-wave velocity and S-wave velocity. Thus the mudrock relationship, on which the fluid stack is based, is suspect. This makes the interpretation of the fluid stack more difficult.

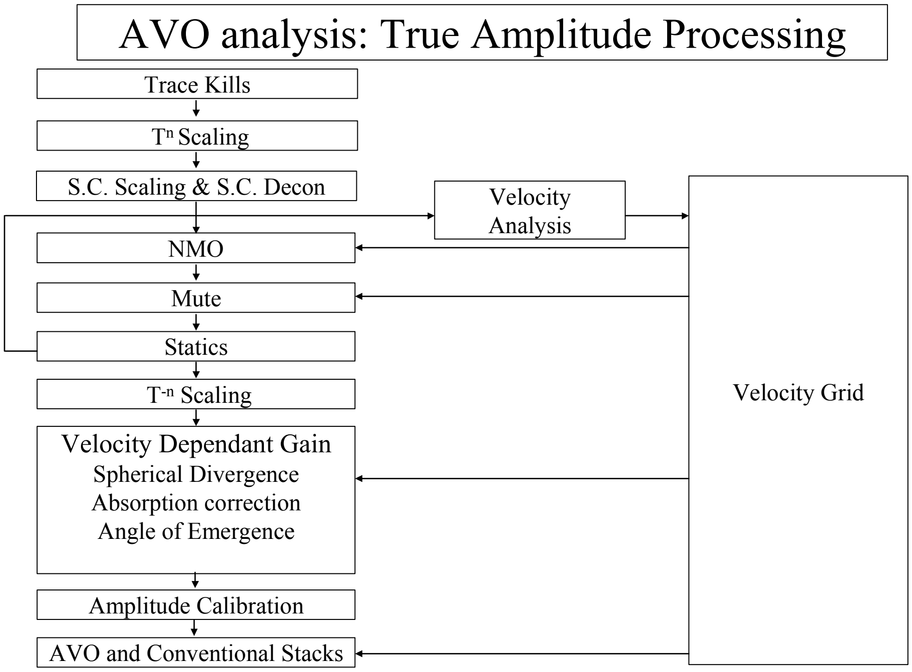


Figure 5: True amplitude processing sequence

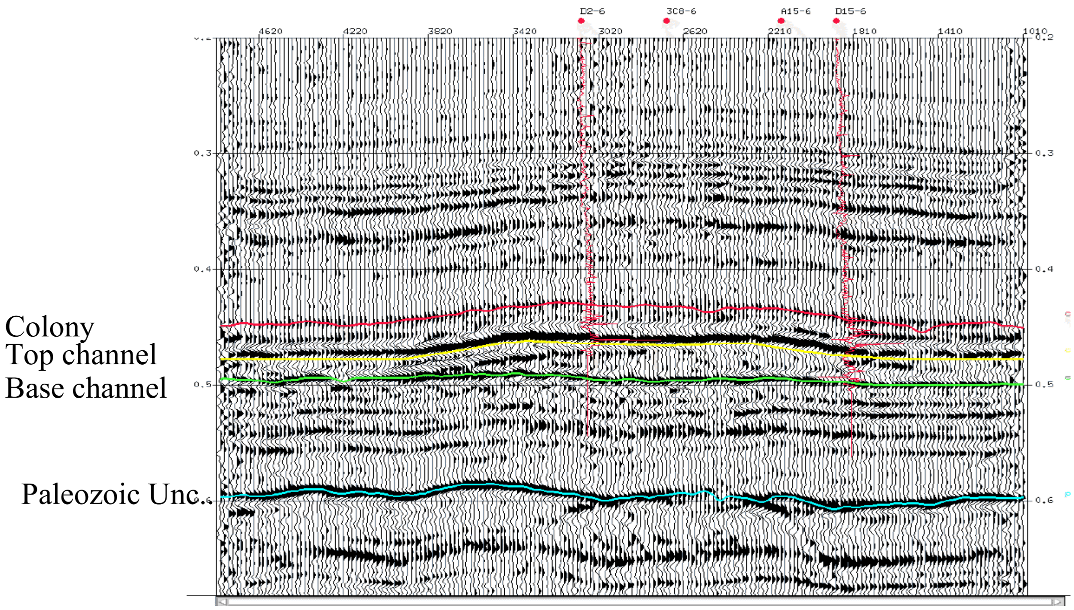


Figure 6: Full offset stack showing horizons of interest

Template seismic line

The vertical component of the 3-C seismic line was processed in an amplitude preserving fashion. Figure 5 shows a flow diagram of the processing sequence. Key steps include processing the data with surface consistent scaling and deconvolution and velocity dependant gain corrections. The well control was used to construct a velocity model used to ray trace the data set. From the ray tracing and the velocity field, velocity dependant gain corrections were constructed and applied to the data set. The final section is shown in Figure 6. The base of the channel shows up as strong amplitude at 0.49 seconds. Four wells intersect, or are close to the seismic line. Three of the wells D2-6, 3C8-6, A15-6 have been under steam injection for an extended period of time. The last well D15-6 was just completed before the seismic line was shot. On the full offset section there is little to differentiate the four wells.

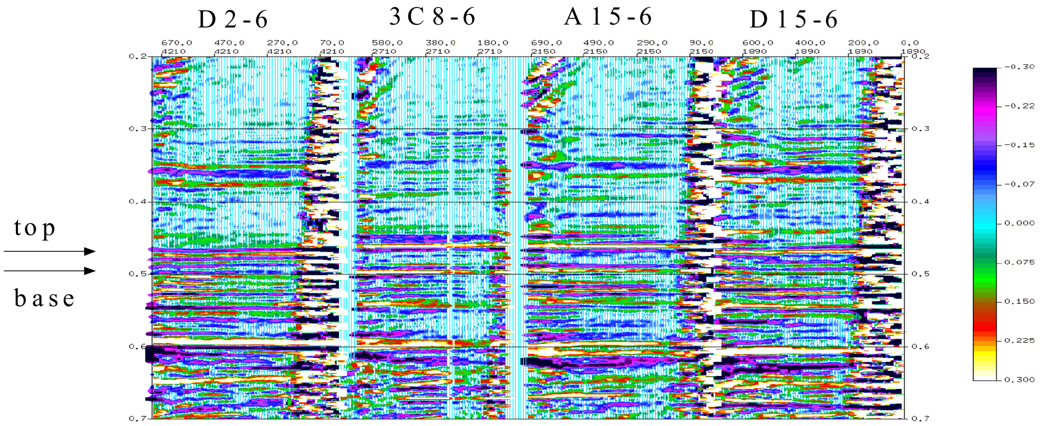


Figure 7: Ostrander gathers at the well locations. Note the near offset source noise.

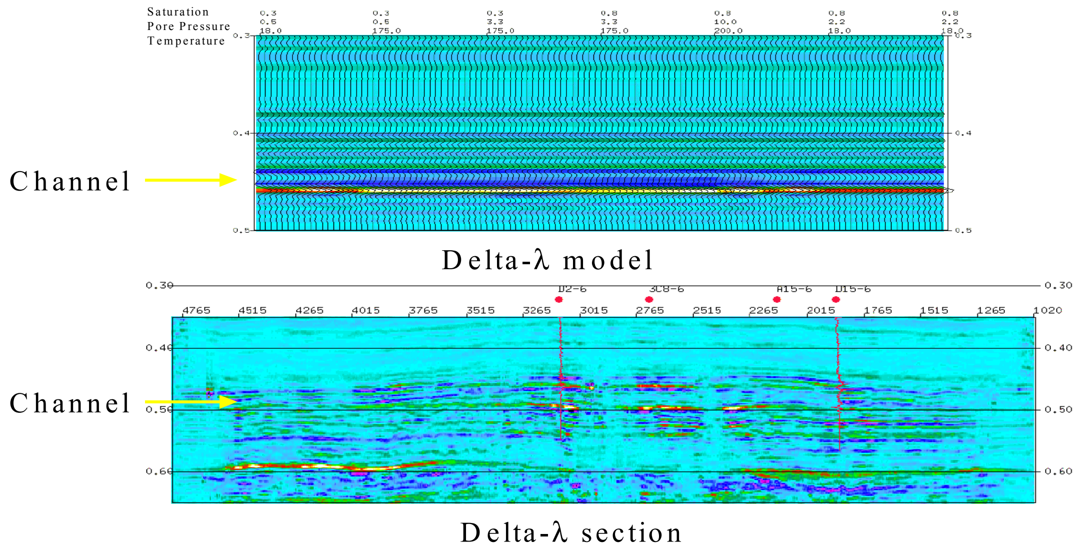


Figure 8: A comparison of the actual delta-lambda section and the modeled delta-lambda section. On the actual seismic there seems to be a strong anomaly at the base of channel at the locations of the wells undergoing steam injection, as predicted by the model.

Figure 7 shows the Ostrander gathers (Ostrander, 1984) for this line at the four well locations. There is significant near offset shot noise evident. The array data, acquired at the same time as the single geophone data, seems to have better noise characteristics for the near offsets, but needs more work before AVO inversion can be performed on it.

Figure 8 shows the delta-lambda section for this line. Despite the significant noise issues on the near offsets, there is an AVO response similar to that predicted by the forward modeling. The three wells undergoing steam injection show a strong amplitude anomaly at the base of reservoir at 0.49 seconds. The fourth well D15-6, which has not undergone steam injection, shows no amplitude anomaly.

The delta-lambda section conveys different information than the full offset stack. This is evident in Figure 9 where both these sections are displayed with the same scale. The fluid stack is also shown and conveys similar information as the delta-lambda stack. In both the AVO stacks it is possible to differentiate the wells, which are undergoing steam injection, whereas it is more difficult on the full offset stack.

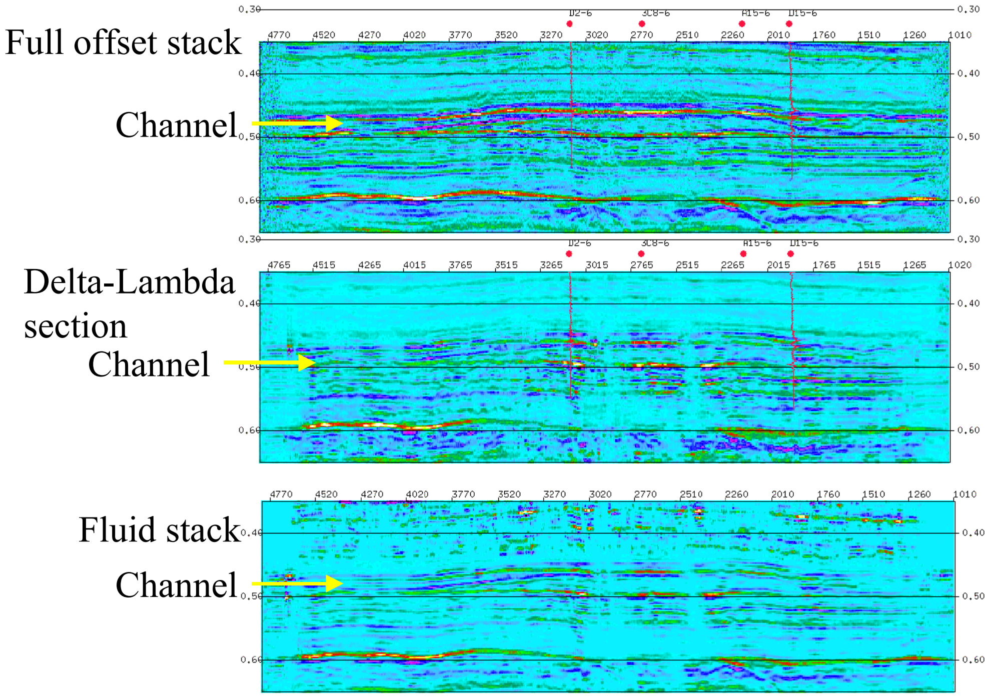


Figure 9: A comparison of the full offset stack, the delta-lambda stack and the fluid stack. Both the delta-lambda stack and the fluid stack react anomalously to the presence of steam.

Discussion and conclusions

There are lateral breaks on the delta-lambda section between the steam-injected wells, suggestive of lateral changes in the steam chamber. However, there is also quite substantial near offset noise in the prestack data, so these breaks could be noise related. Work is currently being done to estimate the uncertainty in the AVO results due to noise. In addition, array data was recorded at the same time as the 3C seismic was shot. Initial tests seemed to indicate that this data has better noise characteristics on the near offsets. This data is currently being processed with the aim of performing AVO analysis on it.

In addition, the model used to interpret the AVO inversions is probably too simplistic. The functional relationship between pressure, temperature, fluid saturation, and the elastic parameters of the reservoir is more complex than presented in this paper. In addition, there are other variables influencing the reservoir, which have not been examined. Incorporating these factors into the forward model is ongoing work.

Despite these limitations, the results of this AVO study are encouraging. 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 observe AVO anomalies as predicted by the forward modeling

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

Ostrander, W.N., 1984, Plane Wave Reflection Coefficients for Gas Sands at Non-normal Angles of Incidence; Geophysics,49,1637-1648

Smith, G.C. and Gidlow, P.M., 1987, Weighted stacking for rock property estimation and detection of gas; Geophysical Prospecting, 35, 993-1014.