Feasibility Study of Time-Lapse Seismic monitoring for Heavy Oil Reservoir Development – The Rock-Physical basis

Ulrich Theune* and Douglas R. Schmitt
Department of Physics, University of Alberta, Edmonton, AB, T6G 2J1
utheune@phys.ualberta.ca

ABSTRACT
We present a feasibility study for monitoring SAGD enhanced oil recovery with seismic methods in Western Canada. We determine the change in the elastic properties of the reservoir after steam injection based on well logs, a realistic but simplified steam chamber model, and the assumption that Gassmann's equation is applicable. Our calculations indicate that the seismic properties of the reservoir do not change substantially in this particular case without additional geotechnical effects, and therefore monitoring SAGD processes will be a challenging process.

Introduction

The heavy oil reservoirs in the Western Canadian Sedimentary basin are often produced using an enhanced oil recovery method such as Steam Assisted Gravity Drainage (SAGD, *Butler*, 1991). This method is relatively expensive and remotely monitoring of the steam chamber in the reservoir is an important tool in engineering decision processes. By-passed sections of the reservoir are an example for problems that may occur due to the complexity of the geology or completion problems of the horizontal wellbores. Seismic monitoring can be a useful tool to observe the growth of the steam chambers within the reservoir and to determine the in-situ conditions. However, injecting steam into a heavy oil reservoir causes relatively complicated changes of the seismic properties.

The feasibility of monitoring heated reservoirs with seismic methods is based on the dramatic decrease of the P-velocity with temperature (see, for example, *Wang and Nur*, 1988, and *Eastwood*, 1993). In their measurements the P-velocity of an oil-saturated sand decreases by about 20 % when the sample is heated to about 120 ºC. However, these studies did not consider a fluid replacement steam for oil. *Nur et al.*, 1984, described that injected steam as a carrier for heat causes only a small change of the seismic properties. Further, the amount of heated oil in a SAGD process may not be that large as in current engineering models there are large temperature gradients between the steam zone and the unheated reservoir.

To test the feasibility of seismic monitoring we carry out an extensive analysis of well logs from different reservoirs in the Western Canadian Sedimentary basin. From the well logs we identify the reservoir and determine the elastic properties of the composite material. To simulate a SAGD process we replace the oil in the pore space by a mixture of steam, water, and oil. Then we create modified well logs, and based on those we compute synthetic seismic traces. We will extract two seismic attributes from the synthetic seismic and compare them to those determined from the original well logs.

Methodology

a) Determination of the elastic properties

To determine the elastic properties of the porous material we assume that the *Gassmann*, 1951 equation can be applied. In Gassmann's equation all parameters except the frame properties are either easy to measure (e.g. porosity ϕ) or available in tables (such as the bulk modulus of the solid material, K_s, or the fluid bulk modulus, K_f). A value of the frame bulk modulus, K_d, that is consistent with the well log, can be found by solving Gassmann's equation for K_d:

$$K_d = \frac{1 + K_{eff}\left(\frac{\phi}{K_s} - \frac{1}{K_s} - \frac{\phi}{K_f}\right)}{\frac{1 - \frac{K_{eff}}{K_s} + \phi}{K_s} - \frac{\phi}{K_f}}. \qquad (1)$$

In this equation K_{eff} is the effective bulk modulus of the effective medium. We can determine its value from the well log as well:

$$K_{eff} = \rho\left(v_p^2 - \tfrac{4}{3}V_s^2\right). \qquad (2)$$

The shear frame modulus, μ_d, can be determined in a similar way from the density and S-sonic log.

As we do not know the elastic properties of the oil (and indeed there may be additional complication introduced by the oil viscosity), we determine the bulk frame modulus from the effective properties in the water layer. We assume that this value does not change in the oil layer.

b) Fluid substitution

In a SAGD process high quality steam is injected into the reservoir. This means that the steam consists of at least 70 % water in the vapor phase and the remainder in the liquid phase. Usually up to 80 % of the original oil can be produced. If some of the steam immediately condenses after injection, we can obtain the following model for the steam chamber (*fig. 2*). Within the steam chamber, the pore space is filled with a mixture of 65 % steam vapor, 15 % water, and 20 % oil. The temperature will be about 270 ºC, whereas the pore pressure does not change. Outside the steam chamber, we will have the original pore fluid and the original pore pressure and temperature.

The co-existence of steam and liquid water requires the temperature and pressure to be close to the saturation condition. The density and bulk moduli of steam and water under those conditions are widely available in steam tables (e.g. *Keenan et al.*, 1969, and *Irvine and Hartnett*, 1976).

To calculate the properties of the pore fluid after steam injection we assume that the three components are uniformly distributed in the steam chamber. Then we can use a volume averaging equation to calculate the effective density and a Reuss averaging method to determine the effective bulk modulus of the fluid.

c) Synthetic seismograms

We calculate the synthetic seismograms by a simple convolution method. From the density and P-sonic log we first calculate the impedance. Then this log is converted to a time series and finally convolved with a Ricker wavelet of different centre frequencies to obtain a seismic trace. From this trace we extract two seismic attributes that can be used to estimate the in-situ changes in the reservoir. First, we analyse the travel time lag of the reflection from the bottom of the reservoir. The second attribute is the change in the reflection strength at the top of the reservoir. We will test the feasibility to monitor SAGD processes by comparing these two attributes at two different times in the injection history.

Example

We apply this method to a well log recorded in Western Saskatchewan. The well penetrates an approximately 12 m thick reservoir. In *fig. 1* we show the part of the log at the reservoir depth. The oil bearing reservoirs in this area are easily identified by the coal and shale layers above and the carbonates below. The resistivity log helps us to distinguish between the oil sand and the water saturated sand. Additional information such as porosity and density of the solid material as well as saturation of oil and water in the reservoir are available from a core analysis.

All logs beside the resistivity log show that the reservoir layer is fairly uniform. This suggests that the petrophysical properties, especially the elastic moduli of the frame, do not change very much.

In a first step, we determine the elastic properties of the frame as described above. For the water layer, we determine a frame bulk modulus of 8.7 GPa, and the shear frame modulus is 4.5 GPa. The shear frame modulus decreases only a little bit to 4.3 GPa, which also supports our assumption that the reservoir is homogeneous. Applying the steam chamber model we calculate the effective seismic properties in the reservoir after steam injection. The results of our calculations are summarized in *table 1*. Generally, we observe a considerable decrease of the bulk modulus of the fluid, the effective density, and the effective bulk modulus of the composite material. However, the P-velocity decreases only marginally by 3.4 %.

The synthetic seismograms were calculated for a 75 Hz Ricker wavelet. The traces for the conditions before and after steam injection are plotted in figure 3 along with the reflectivity time series. The difference between the two traces are only very small in this case and it will be very difficult to detect changes in the reservoir with seismic methods under the current set of assumptions. The travel time to the bottom of the reservoir changes only by 1 ms, and the change in the strength of the reflected amplitude is negligible.

Conclusion

Based on detailed well logs and realistic assumptions of a SAGD process we determined the change in the elastic properties of the reservoir zone after steam injection. We observe that the seismic properties do not change very much. The difference in the two seismic attributes travel time lag and reflection strength before and after steam injection seem not to be large enough to be recordable with seismics. The reasons for this are most likely the relative stiff frame in the reservoir layer and the fairly thin reservoir. The stiff frame of the reservoir makes it rather insensitive to fluid replacement, and the thin reservoir, along with the small velocity change, does not allow to cause a significant travel time lag.

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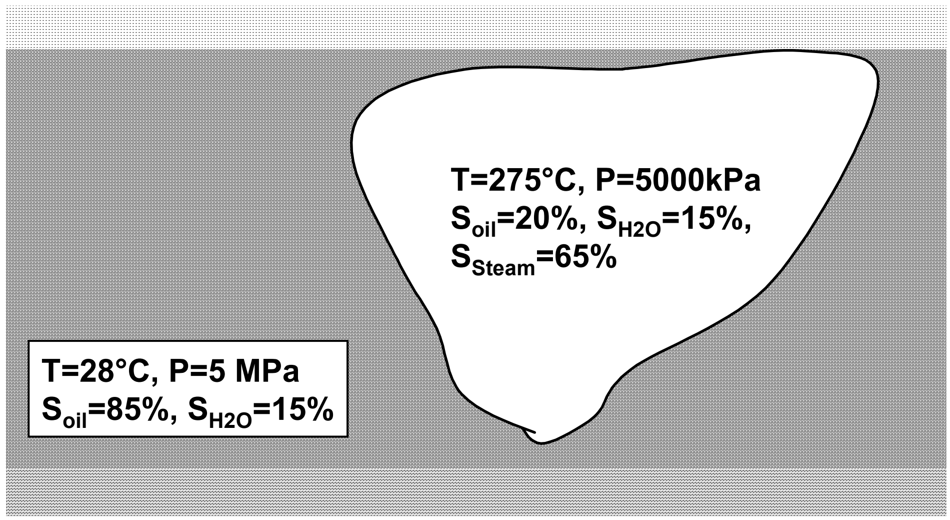

Fig. 1 shows the steam chamber model. Within the steam chamber a homogeneous distribution of the three different pore fluids is assumed.

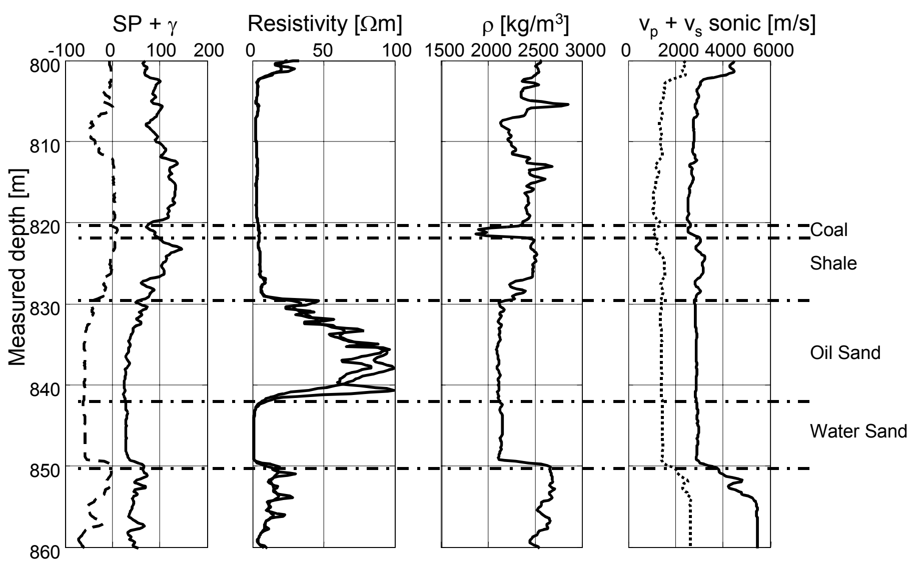

Fig. 2 In the well log the reservoir can be clearly distinguished from the coal and shale layer above and the carbonates below.

	Before	After	Change
ρ_{eff} [kg/m^3]	2120	1870	- 11.8 %
K_f [GPa]	2.38	9.6×10^{-3}	- 99.6 %
K_{eff} [GPa]	11.8	8.7	- 30.4 %
V_p [m/s]	2864	2767	- 3.4 %
V_s [m/s]	1403	1498	+ 6.8 %

Table 1 The seismic properties of the effective medium and the pore fluid before and after the steam injection, respectively. All values before fluid substitution have been determined from the well logs, whereas the data after steam injection were calculate using effective medium theories.

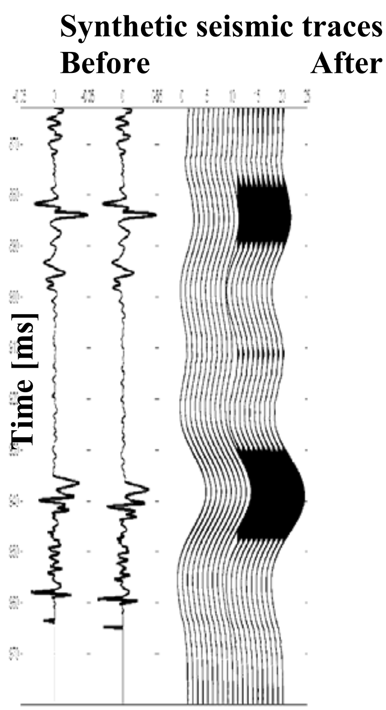

Fig. 3 The synthetic traces before (gray filling) and after fluid (gray filling) and after fluid replacement (black wiggles) along with the reflectivity time series for both cases.