Datapages/Search and Discovery Article #90224 GeoConvention © 2014, FOCUS - Adapt, Refine, Sustain Calgary, Alberta, Canada, May 12-16, 2014

Laboratory Studies of the Seismic Properties of Bitumen Saturated Grosmont Carbonates

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Summary

The variations in pore fluid pressure, temperature, saturation state, and confining stress during enhanced oil recovery such as steam assisted gravity drainage (SAGD), or cyclic steam stimulation (CSS), produce substantial changes in the elastic properties of saturated bitumen and its host porous rock. These effects can be observed on the overall rock seismic responses in time lapse (4D) seismic surveys. To better understand these seismic field observations we have conducted ultrasonic measurements of the compressional (P) and shear (S) wave velocities of bitumen saturated carbonate taken from Grosmont formation core. At a constant effective pressure of 5 MPa the P and S wave speeds decreased by ~11.5% and ~8.5% with a temperature increase from 10 °C to 102 °C. Increasing confining pressure (5 to 40 MPa) at room temperature with no pore pressure results in an increase in the P-velocities by ~ 4.8%, and the S-velocities by ~3.6%. Pore fluid pressure variation, solely, also show the change in seismic velocities. Further, spectral ratio method is used to calculate the quality factor (Q-factor). The Q-values lie in the range of 4-18 with temperature and confining pressure variation but reaches as high as 73 for 17 MPa of pore pressure and at room temperature.

Introduction

As of 2012, the Grosmont carbonate Formation in north-eastern Alberta may hold in excess of 64.5 billion m^3 (406 billion barrels) initial volume of bitumen in place (ERCB, 2013). As with the nearby and overlying oil sands, the bitumen saturating these carbonates is essentially immobile at the ambient *in situ* temperature (~13 °C) and their recovery requires sufficient heat to lower the bitumen viscosity. The characteristics of carbonate reservoirs, however, differ significantly from porous, weakly consolidated oil sands. The geological structural variations in the Grosmont mandate the use of geophysical methods for better characterization of the reservoir. The proper interpretation of geophysical methods however, requires a solid understanding of the saturated reservoir rock's behaviour under changing conditions of saturation, temperature, and effective stress.

The variations in elastic moduli of subsurface formations during the recovery process lead to changes in seismic properties (Kato et al., 2008; and Bianco et al., 2010). These changes in reservoirs *in situ* conditions can be observed with time lapse seismic monitoring (e.g., Schmitt 1999). Wang and Nur (1990) observed both the compressional P- and shear S-wave speeds in bitumen saturated sand decline by more than 25% as temperature is raised from room conditions to 120 °C. To our knowledge, however, there are no generally available studies of the variations in bitumen saturated carbonates under varying conditions. Here, ultrasonic measurements have been conducted in laboratory in a bituminous core plug from a Grosmont formation reservoir at the practical range of temperature from pre steam reservoir conditions of ~13 °C to steam temperatures in excess of 100 °C, and pore fluid variations from about 3 MPa to above 5 MPa to develop a laboratory based, experimental time lapse model. The attenuation of the sample is also estimated using spectral ratio method.

Method

The custom-built laboratory apparatus used in this study was designed, in part, to measure the arrival times of ultrasonic pulses for porous and non-porous solid materials. It has the ability to discretely control both the pressure of the hydraulic fluid surrounding the sample (confining pressure) and the pore fluid pressure within the sample (e.g. Bakhorji, 2009; Njiekak et al., 2013). The newly incorporated chiller system allows varying and stabilizing the temperature of the pressure vessel from ~ 0 °C to ~ 110 °C. The experimental set up consists of a cylindrical pressure vessel, pulser/receiver, reservoir tanks, pumps, and a temperature controller with a thermocouple. A set of low-impedance laterally polarized 1 MHz shear transducer (S-wave) and a low-impedance axially polarized 1 MHz compressional transducer (P-wave) stacked on an aluminium end cap are placed on each end of the sample (Figure 1); one to act as transmitter and the other as receiver of the pulse. The velocity measurements for a core sample with known length are made by recording the total travel time of the P- and S-waves through both aluminum end-caps and the sample. The receiving is subsequently recorded by a digital oscilloscope (NI USB-5133 8 bit, 100 MS/s digitizer) at a sampling interval of 10 ns. Switching between P- and S-wave transducers, temperature, and confining pressure control and data acquisition are accomplished using the LabVIEW® software package. The Grosmont core samples were provided in a frozen state in order to limit bitumen desaturation (at room temperature bitumen will bleed out of the samples). Furthermore, bitumen undergoes substantial volumetric changes with increasing temperature which may affect pore pressure within the sample. A hand driven pressure generator is used to control the pore pressure to keep it safely lower than the confining pressure. The pore pressure system is filled with silicon oil (Dow Corning Corp. 200 fluid) which applies back pressure to the bitumen within the sample. This fluid was employed because of its temperature stability and high immiscibility to hydrocarbon fluids.

Examples

In order to observe the influence of temperature, confining pressure and pore fluid pressure changes on the elastic properties of both the fluid and rock frame expected during a steam assisted recovery operation, one must be able to isolate the effects of each variable independently. To accomplish this, P- and S-waveforms were obtained during the following suites of measurements:

1. Varying confining pressure with atmospheric pore pressure at various temperatures (21.3 °C and 10 °C).
2. Varying temperatures (10 °C to 102 °C) at a constant effective pressure (confining pressure – pore pressure).

3. Varying pore pressure at constant effective pressure and at different temperatures.

All the plots shown here are the results from one core plug sample of 5.9 cm length and 3.81 cm diameter from the Grosmont formation. For this initial measurement, a core sample from a portion of the Grosmont having lower porosity was chosen so the core sample would be both competent and homogeneous (i.e. no vugs or fractures).

Figure 2 shows the effects of confining pressure as the increase of P-wave velocities at low (10 °C) and room (21.3 °C) temperature. Changes in the S-wave velocities were rather muted between the two temperatures. This might be due to the reason that the P-wave velocity is sensitive to the changes in the bulk modulus of the bitumen with temperature; the bulk modulus of oils decreases rapidly with temperature. In contrast, the S-wave propagation may be more dependent upon the viscosity of the fluid that is under consideration. The observed wave speeds from 21.3 °C to 102 °C in Figure 3 show a substantial decrease in the wave speeds of about 11.5% and 8.5% for the P- and the S-wave, respectively, and the effective pressure of 5 MPa here is expected to be closer to the *in situ* values.

Q-factor estimation

The amplitude spectral ratio of two signals propagated through the reference sample and rock sample respectively were considered to calculate Q (Toksoz et al., 1979). The natural logarithm of the spectral ratio was plotted as the function of frequency. The quality factor, Q is measured from the slope of the spectral ratio. Q factor and attenuation are calculated for the frequency range 0.7 MHz to 1.1 MHz (maximum amplitude) and the values are in the range of 4-18, in Figure 4, resulted due to the temperature and confining pressure changes. At higher pore pressure high viscous silicone oil, immiscible with bitumen, is pushed into the sample and the Q factor goes high to a value of approximately 73.

Conclusions

The P- and S- wave speeds were measured in a low porosity, bitumen-saturated carbonate rock sample cored from the Grosmont formation. These observations will help develop a time lapse model to monitor the reservoirs by relating changes in the elastic properties of both the bitumen and the formation as a function of changing reservoir parameters (temperature, pressure and saturation). Despite the low porosity in this sample, substantial changes in the ultrasonic P- and S-wave speeds were observed particularly in relation to temperature variations. It is likely that the strong temperature dependence of bitumen bulk modulus, density, and viscosity all contribute to these observations. Future work will include theoretical modeling of the responses and conducting similar measurements with more samples at different saturation levels (i.e. fractures and vugs) Future investigations as part of this will focus on obtaining static and dynamic moduli over a wide range of Grosmont reservoir types (i.e. numerous core samples). In addition, the studies as part of a full NSERC collaborative research and development (CRD) grant will also investigate the geomechanical properties of the reservoir, as well as testing new methods to address the issue of dispersion.

Acknowledgements

These measurements were conducted as part of a NSERC Engage grant. The authors greatly appreciate Laricina Energy Ltd. and OSUM Oil Sands Corp. in providing the frozen core and for permission to publish this suite of measurements.

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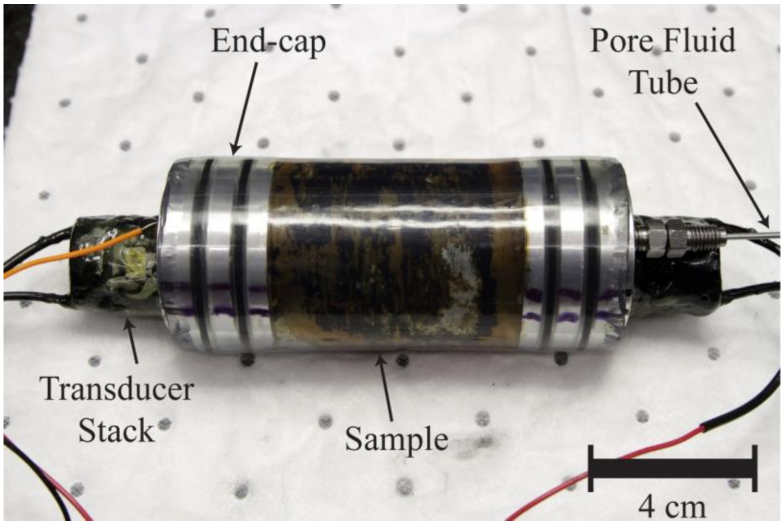

Figure 1: The sample assembly consisting of the core sample, aluminum end-caps and transducer stacks. A flexible PVC tube (Kuri Tec) covers the sample to isolate it from the confining fluid. The sample also shows the high saturation of bitumen.

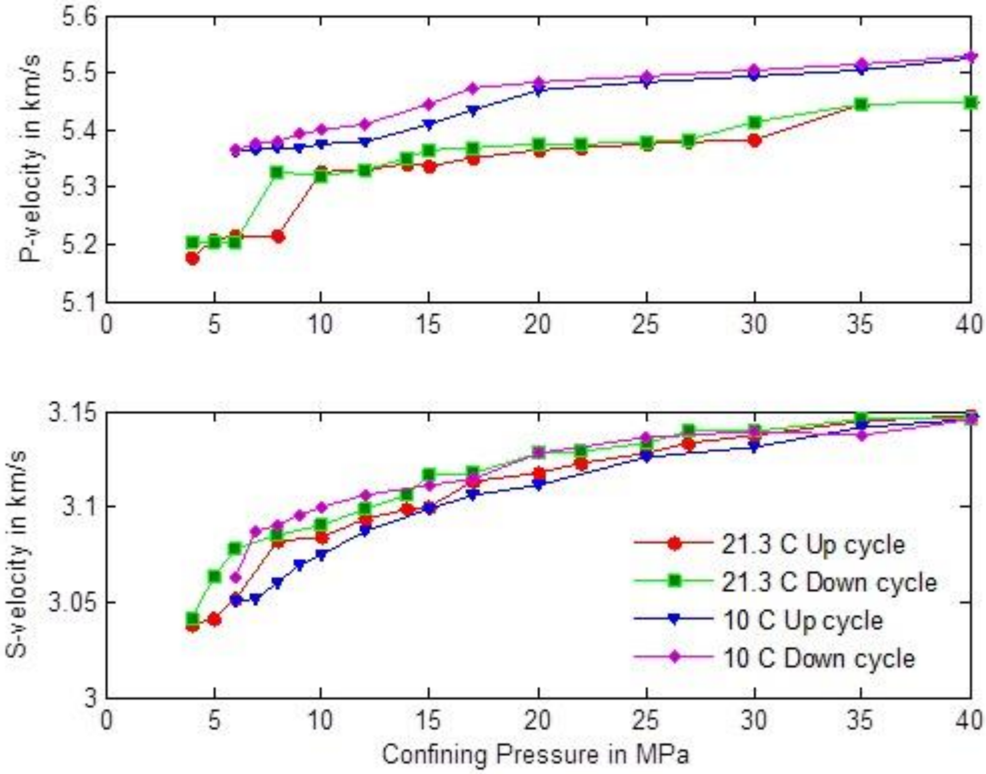

Figure 2: Velocities measured at room temperature (21.3 ºC) and at 10 ºC as a function of confining pressure for both the up and down cycles. Pore pressure was not controlled and was maintained at atmospheric. Confining pressure variations increases p-velocities by ~ 4.8% and S-velocities by ~3.6%.

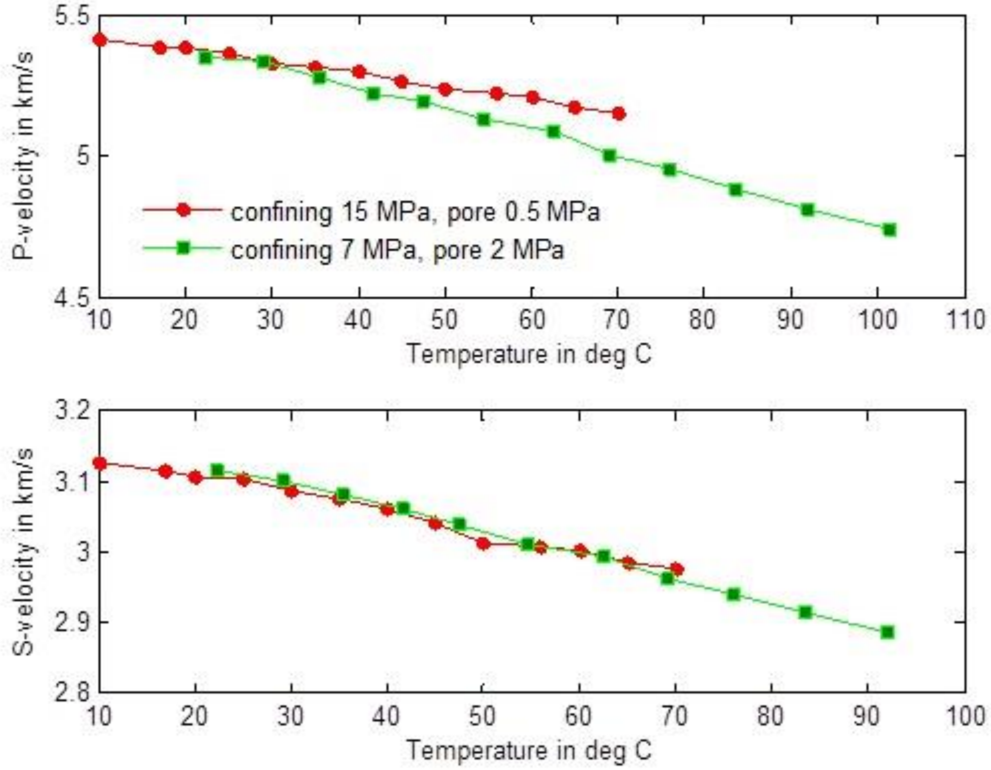

Figure 3: A change of ~11% decrease in P-wave and ~7% in S-wave velocities with a temperature change from 21 ºC to 102 ºC and at 5 MPa of effective pressure (7 MPa and 2 MPa of confining and pore pressure respectively). Red line represents temperature change from 10 ºC to 70 ºC at 14.5 MPa effective pressure (15 MPa confining and 0.5 Mpa pore pressure).

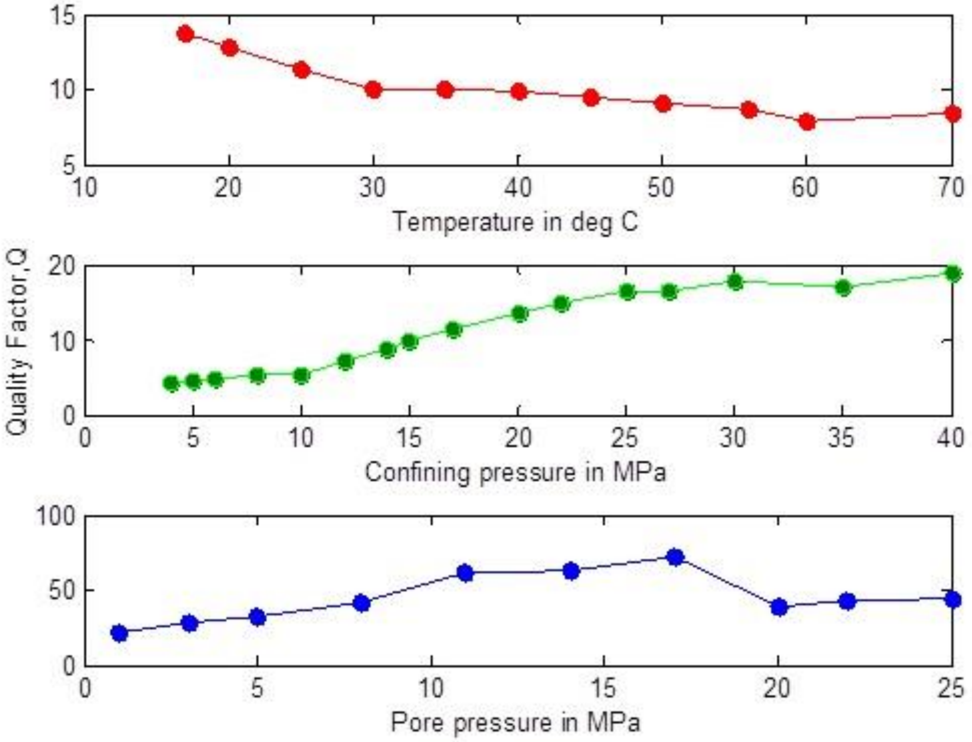

Figure 4: (Top) Q factor for P-wave with changing temperature at constant effective pressure (at 15 MPa of confining and 0.5 MPa of pore pressure), (middle) confining pressure with no control in pore pressure at room temperature, and (bottom) with varying pore pressure at room temperature (21.3 ºC) with 15 MPa of constant effective pressure.