3D ultrasonic imaging of a heavy oil recovery model

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Abstract

Ultrasonic acquisition over a glass bead-pack heavy oil model was conducted by CREWES in early 2001. The model was built by the Department of Chemical and Petroleum Engineering at the University of Calgary to study gravity drainage of reduced viscosity heavy oil at reservoir temperatures and pressures. Mobility of the heavy oil was improved by injection of a propane/methane mixture.

After the experiments were complete, a variety of ultrasonic surveys using 1 MHz piezoelectric transducers were conducted. These included 2D reflection lines (equivalent to a 2D stack), 2D walk-aways (equivalent to a 2D shot gather), a 3D reflection survey, and a 3D transmission survey. The purpose of acquiring these data was to determine if physical conditions within the model could be obtained by ultrasonic methods, which could lead to time-lapse analysis methods for detecting changes in actual petroleum reservoirs. We are also doing this experiment to provide data for fluid imaging algorithms, and plan to repeat these type of surveys to investigate time lapse imaging.

The contact between the injected propane/methane mixture and undiluted heavy oil is clearly visible on the ultrasonic data as a polarity change in the reflection interpreted to be the contact between an acrylic face plate and a glass bead-pack containing these fluids in its pore spaces. Due to model dimensions, reflections other than primaries, multiples and converted waves from the back of the acrylic are not obviously imaged in the reflection data. However, a velocity of 1918 m/s for the bead-pack plus heavy oil measured from the transmission data is comparable to a theoretical value of 1720 m/s.

Description of physical model

The glass bead-pack model simulates the “Vapex” process, where a mixture of methane/propane is injected into a heavy oil reservoir to reduce the oil viscosity and consequently increases the rate of gravity drainage into a production well (Butler and Jiang, 2000). Temperature and pressure for the reservoir modeled are 11°C and 1.03 MPa (150 psi). Under these conditions, the propane/methane mixture within the model is probably a liquid. However, pressure dropped quickly after the oil recovery experiments were completed, and this mixture was likely a gas when the ultrasonic data were acquired.

The physical model (Figure 1) was made of a 6.35 cm thick piece of aluminium, with a 3.18 cm cavity machined into it (Figure 2). This was covered with a 5.08 cm thick sheet of acrylic and a 0.64 mm steel flange. These layers were bolted together around the outside edge.

The cavity in the aluminium plate was filled with #16 to #20 size glass beads (~850-1200 μm in diameter), which were dropped into the cavity through an access port on the end of the model as it was vibrated, to insure maximum packing of the beads.

The model was driven to S_{wi} (saturation water initial), meaning heavy oil was injected into the model from below, displacing the water. The injection pressure was not significantly higher than the pressure inside the model. Some water remained in the bead-pack. The heavy oil was determined to have a viscosity of ~20,000 cps under reservoir conditions (11°C and 1.03 MPa).

A propane/methane mixture was injected into the model (top left, Figure 1) for eight hours (scaled time equals eight years of production), and the volume and composition of fluids and gas recovered by gravity drainage from the production well (bottom right, Figure 1) were measured. The pressure gradient across the model during this process was ~6.9 kPa (1 psi). This process resulted in a draw-down cone at the production well (Figure 1).

The recovery process resulted in four zones with varying physical properties. From top to bottom at the producing well: 1) glass beads with propane/methane in the pore spaces, 2) glass beads containing propane/methane and heavy oil residue, including asphaltenes, left behind when the heavy oil withdrew (draw-down cone, Figure 1), 3) glass beads with heavy oil penetrated by small-scale fingers of propane/methane, and 4) glass beads containing only heavy oil in the pore spaces (Figure 2).

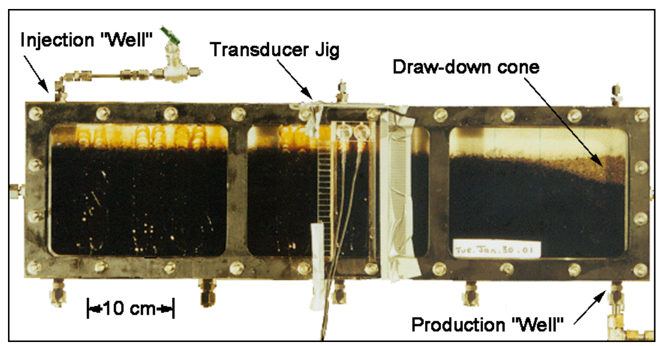

FIG. 1. Front view of the physical model. The jig and transducers for ultrasonic reflection acquisition are in the central window. A viscous couplant on top of the acrylic was used to improve acoustic coupling between the acrylic and the transducers.

Description of Equipment

Trace spacing and source-receiver offsets for the 3D reflection survey were maintained using a two-piece acrylic jig. Two Panametrics Ltd. V-103 P-wave transducers were attached to a small block of acrylic with a 2.0 cm (centre to centre) fixed offset. This block keyed into a slot machined in a larger piece of acrylic, which was taped to the face of the bead-pack model (Transducer Jig, Figure 1). In this manner, a uniform trace spacing of 0.667 cm was achieved.

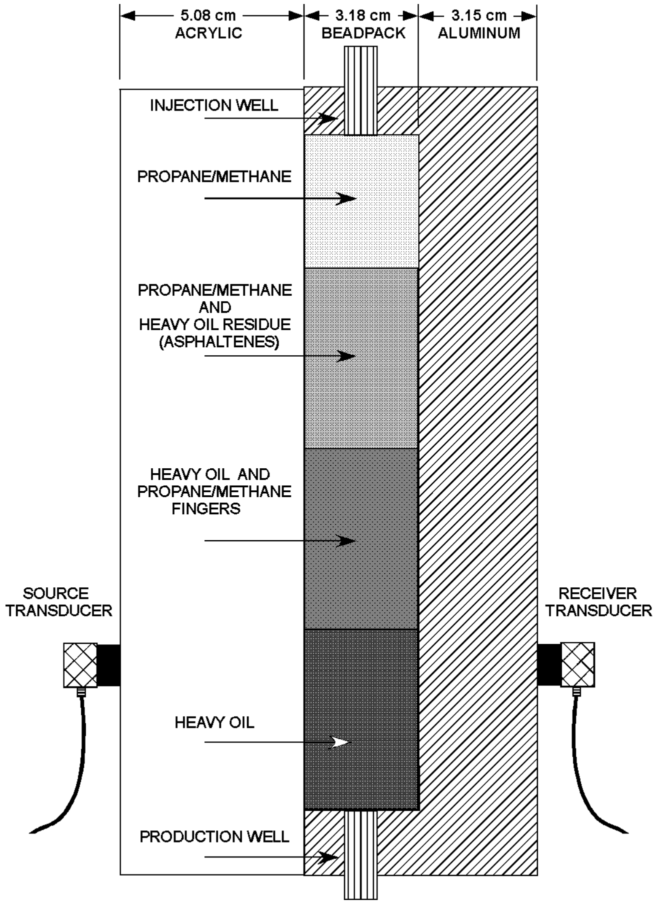

FIG. 2. End on view of the physical model. Note that the production and injection "wells" were at opposite ends of the model, lengthwise (Figure 1). Source and receiver locations are shown for acquisition of a single trace of a transmission survey (see below).

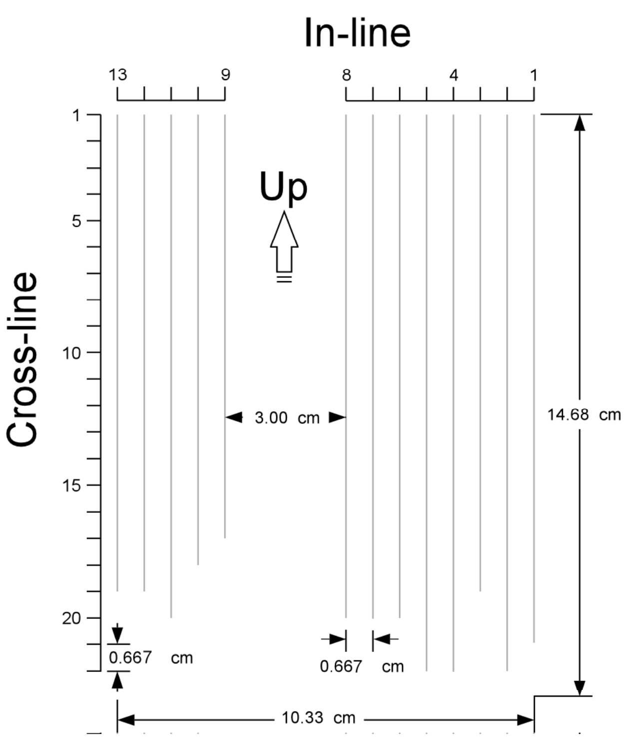

FIG. 3. Geometry of the 3D reflection survey.

Description of Survey geometry

The geometry for the 3D reflection survey is shown in Figure 3. The survey was started from the production well (right-hand side of the model) with in-line and cross-line spacings of 0.667 cm (Figure 3).

Thirteen in-lines were recorded from right to left, with a 3.0 cm gap between lines 8 and 9 due to a bolt that was in the way of the transducer jig. The number of traces recorded for each line is varied due to bolt interference with the transducer cables.

The 3D transmission survey was aquired with transducer placed as shown in Figure 2. The transducers were moved up the model 0.667 cm per trace. A total of five transmission lines were acquired, starting in the central window with in-line 5. This simulation used a lower viscosity oil, and when the fluids inside the model were observed to be moving, acquisition was quickly shifted to the right-hand window, and in-lines 1 to 4 were acquired from left to right at a line spacing of 2.5 cm.

THEORETICAL CONSIDERATIONS

Acrylic layer

The source-receiver offset is 2.00 cm (transducer centre to transducer centre), so the travel time for a primary reflection from the back of the acrylic is $2\sqrt{1.00^2+5.08^2}/V_P$, or about 37.7 µs for an acrylic velocity of 2750 m/s (Table 1). Angles of incidence and reflection are both equal to $\tan^{-1}$(1.00 cm/5.08 cm), or about 11.14° in this case. The distance traveled by P-P acrylic multiples is not an integer multiple of 5.08 cm. Instead, multiples will occur at travel-times of $n\sqrt{(2/n)^2+5.08^2}/V_p$, where n = 4,6,8,etc. Thus, we expect P-P multiples at 74.2 µs, 111.0 µs, 148.0 µs, and so on.

Since the angle of incidence is non-zero, it should be possible to see a P-S mode reflection from the back of the acrylic. For a V_P/V_S of 2.0 (Table 1), the angle of incidence is 14.83°, the angle of refraction is 7.35°, and the P-S mode reflection from the back of the acrylic should arrive at 56.4 µs.

	ρ (g/cm^3)	V_P (m/s)	V_S (m/s)	V_P/V_S
Acrylic	1.19	2750	1375	2.0
Aluminium	2.68	6360	3200	1.8
Glass	2.86	5900	3400	1.7
Heavy Oil	0.985	1609	--	--
Bead-pack (experimental)	--	1918	--	--
Bead-pack (theoretical)	2.17	1720	0	∞

Table 1. List of material properties. Values presented have been determined by laboratory measurements with the exception of, 1) the bead-pack numbers, which are detailed in this paper, and 2) the glass velocities, which were estimated from the measured density by correlation with literature values (obtained from Christensen, 1982).

Bead-pack layer

The bead-pack consists of either glass beads with fluids in the pore spaces or glass beads with gas in the pore spaces, depending on location (Figure 2). To interpret the ultrasonic results, it is helpful to estimate the velocity of the bead-pack and heavy oil. The confining pressure on the bead-pack is essentially zero (only the effect of gravity) so this system can be assumed to be a fluid suspension, in which the only pressure is the pore pressure.

Thus, we expect a zero shear modulus and focus on the compressional velocity, which can be obtained from the bulk modulus since this is equal to the P-wave modulus for zero shear. The bulk modulus for a suspension is given by the Reuss average:

$$\frac{1}{K_{suspension}} = \frac{1-\phi}{K_{glass}} + \frac{\phi}{K_{oil}} \qquad (1)$$

where $K_{suspension}$ is the bulk modulus and ϕ is the porosity (Mavko et al, 1998). Using values from Table 1, K_{glass} = 55.47 GPa and K_{oil} = 2.55 GPa. The porosity of the bead-pack is estimated to be 37% from lab measurements. Now, we can obtain $K_{suspension}$ = 6.39 Gpa (Equation 1). The total density of the heavy oil saturated region can now be calculated to be 2.17 g/cm^3, and the velocity of the oil-saturated region, $V_{P,suspension} = \sqrt{K_{suspension}/\rho_{total}}$, is predicted to be ~1720 m/s.

Taking Snell's law into account, we can calculate that the P-wave will travel roughly 10.26 cm at 2750 m/s through the acrylic and 6.38 cm at 1720 m/s through the bead-pack. Thus, we expect a back of bead-pack reflection at 74.4 µs (compare with 74.2 µs for the first P-P acrylic multiple). The angle of incidence at the acrylic/bead-pack boundary is 8.07^o and the angle of refraction is 5.03^o.

Aluminium layer

Assuming zero-offset geometry, the two-way travel time through the aluminium should be 0.063 m / 6360 m/s, or 9.9 µs. Taking into account earlier results, this implies a total two-way travel time of ~84.3 µs for the back of aluminium reflection.

PROCESSING AND INTERPRETATION

3D reflection survey

A 0.1-0.2-1.5-2.0 MHz bandpass filter was designed to minimize the effects of aliased electrical noise that was observed on some traces. Since amplitudes varied considerably from trace to trace, possibly due to variations in coupling pressure, the data was trace equalized on a 5-10 µs travel-time window, which contains reflections interpreted to be constant amplitude electrical noise, (not shown). Finally, a 10 µs window AGC was applied, resulting in the data shown in Figure 4.

Major reflections seen on Figure 4 have been interpreted based on the theoretical travel times derived earlier. Reflection 2 is the P-P acrylic/bead-pack reflection at 37.7 µs, Reflection 3 is a P-S mode acrylic/bead-pack reflection at 56.4 µs. Reflection 4 is either the first P-P multiple within the acrylic at 74.2 µs or the P-P bead-pack/aluminium reflection at 74.4 µs.

The preferred interpretation for reflection 4 is as a P-P multiple within the acrylic. This is based on the results of the transmission survey (see below), which show a significant increase in the total travel time through the model where the propane/methane mixture is present. In comparison, reflection 4 occurs at a constant travel-time for all traces in each in-line (Figure 4).

Reflections 2 and 4 have a polarity reversal that occurs at different positions on the in-lines, and correlates with the contact between zones 2 and 3 (compare with Figures 2 and 5). Reflection 3 does not exhibit a polarity change, which further supports its interpretation as a P-S mode reflection.

The polarity of reflections 2 and 4 are the same (both reverse) where propane/methane is present in the bead-pack, which can be explained if the polarity of the wavelet flips at both the front and back of the acrylic (Figure 4). In contrast, the first acrylic multiple is phase-shifted about ninety degrees relative to the reflection 2 where heavy oil is present in the bead-pack (Figure 4).

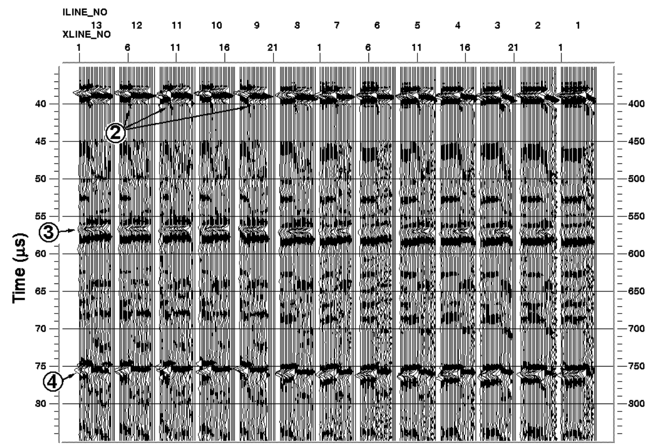

FIG. 4. In-lines 1-13 of the 3D reflection survey (see geometry in Figure 3). Interpretation based on theoretical considerations: Reflections (2) are P-P reflections from the acrylic/bead-pack interface. The polarity reversal correlates to the gas/fluid interface within the bead-pack (compare with Figure 5). Reflections (3) are P-S reflections from the acrylic/bead-pack interface. Reflections (4) are the first P-P multiples within the acrylic.

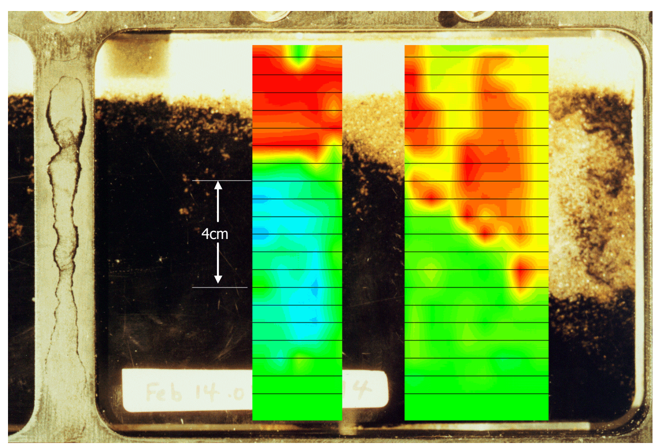

FIG. 5. Time-slice at 37.9 µs from the 3D reflection survey (compare with geometry in Figure 3 and reflection 2 in Figure 4). Note that the polarity reversal follows the contact between the heavy oil and the draw-down cone.

3D transmission survey

Due to aliased noise observed in the 3D reflection survey, the transmission survey was acquired with a 10 ns sample rate (compare with 20 ns for the reflection data), for a Nyquist frequency of 50 MHz. In general, the transmission data are of better quality than the 3D reflection data, and processing has been limited to a 10 µs AGC.

Events shown in Figure 6 are interpreted as follows: Transmission 1 is energy that has gone around the bead-pack, having traveled through the acrylic and aluminium only. The theoretical zero-offset travel time for this is 28.4 μs, which is observed at the outermost traces of each in-line. The slope of these events is related to increasing distance from the top and bottom of the model. The horizontal event labelled 1 on in-line 1 is consistent with this line having been acquired close to the right-hand side of the model (Figure 6).

Transmission 2 is the zero-offset direct arrival through the acrylic, bead-pack and aluminium. The break in slope is related to the position of the heavy oil/propane-methane contact within the model, and its position is consistent with the draw-down cone observed to the left of the simulated producing well (Figure 6, and compare with Figure 4).

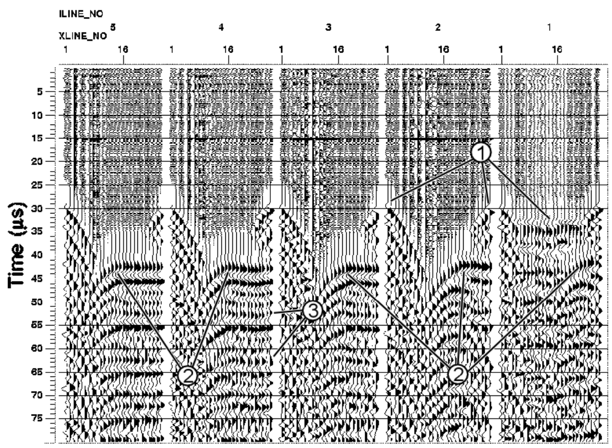

FIG. 6. Transmission survey with a 10 μs AGC applied. Interpretation: Transmissions (1) are edge effects from the sides of the aluminium cavity containing the bead-pack. Transmissions (2) are direct arrivals through the acrylic, bead-pack and aluminium. Reflections (3) are multiples of the direct arrival within the aluminium.

Two interpretations of the increasing travel times toward the top of the model (decreasing cross-line number) are possible: 1) A velocity gradient due to a gradual transition from heavy oil to propane/methane exists, or 2) the energy seen is traveling through the heavy oil only, and the increase in travel times towards the top of the model are due to greater distance traveled through the acrylic and aluminium. The second interpretation is similar to that proposed for transmission 1. Finally, reflection 3 is picked based on multiples of 9.9 μs, the theoretical two way travel-time through the aluminium.

A velocity through the heavy oil and bead-pack can be derived from the transmission data by using Equations 2 and 3.

$$t_{total} = t_{acrylic} + t_{bead\text{-}pack} + t_{Al} \tag{2}$$

$$V_{bead\text{-}pack} = d_{bead\text{-}pack}/(t_{total} - t_{acrylic} - t_{Al}) \tag{3}$$

A travel time of ~40 μs can be picked from the first negative deflection of the trace for the horizontal part of transmission 2 on in-lines 3 through 5. Since the thickness and velocity of the acrylic and aluminium are known (Table 1, Figure 2), and the thickness of the bead-pack is known (Figure 2), we can obtain a velocity of 1918 m/s for the heavy oil and bead-pack.

Conclusions and future work

The 3D ultrasonic reflection data acquired to date have successfully imaged the contact between propane/methane and heavy oil in a bead-pack model. This image is possible because of a polarity change in a P-P reflection with a ray-path entirely within the acrylic faceplate. Reflections from the back of the bead-pack are poorly imaged, if at all. This is due to the dimensions of the model, which cause the reflection from the back of the bead-pack to be obscured by a multiple within the acrylic. This could be avoided in future by using either a thicker or thinner acrylic faceplate.

The theoretical velocity derived for the heavy oil and bead-pack is 1720 m/s (Table 1), which is within 11% of the experimental velocity of 1918 m/s calculated from the transmission data. The difference may be due to the fact that the heavy oil used in the model prior to acquisition of the transmission data was less viscous than for the reflection data. Alternatively, this difference may be due to our initial assumption that the bead-pack behaves like a fluid suspension. If the heavy oil imparts some degree of cementation between adjacent glass beads, they will behave more like semi-consolidated sand than a simple fluid suspension. This could be tested by trying to measure a shear velocity through the bead-pack, and comparing to theoretical values.

Conditions within the model at the time of acquisition, particularly pressure, were not the same as would be encountered in the field, or even during the simulation. This raises the possibility that the propane/methane mixture changed phase from a liquid to a gas, and the seismic response is not similar to what might be seen in the field.

Problems with aliased electrical noise were encountered. The source of this noise should be identified and eliminated via improved shielding of the electronics, or by ensuring that an anti-alias filter is present in the analog-digital step of the recording process. Failing this, data should be digitized at the highest available sample rate.

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