Ultrasonic imaging of a heavy oil recovery model

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ABSTRACT

High-frequency (ultrasonic) acquisition over a glass bead-pack heavy oil model was conducted 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 transmission survey, and a 3D reflection 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 these properties being detected in the field using seismic methods.

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 absorption and timing, 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 can be measured from the transmission data, and is compared 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 increase the rate of gravity drainage into a production well (Butler and Jiang, 2000). Temperatures and pressures for the reservoir modeled are 11^{o}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.

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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^{o}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 methane/propane in the pore spaces, 2) glass beads within the draw-down cone containing methane/propane and heavy oil residue (including asphaltenes) left behind when the heavy oil withdrew, 3) glass beads with heavy oil and small-scale fingers of propane/ methane below zones 1 and 2, and 4) glass beads containing only heavy oil in the pore spaces (Figure 2).

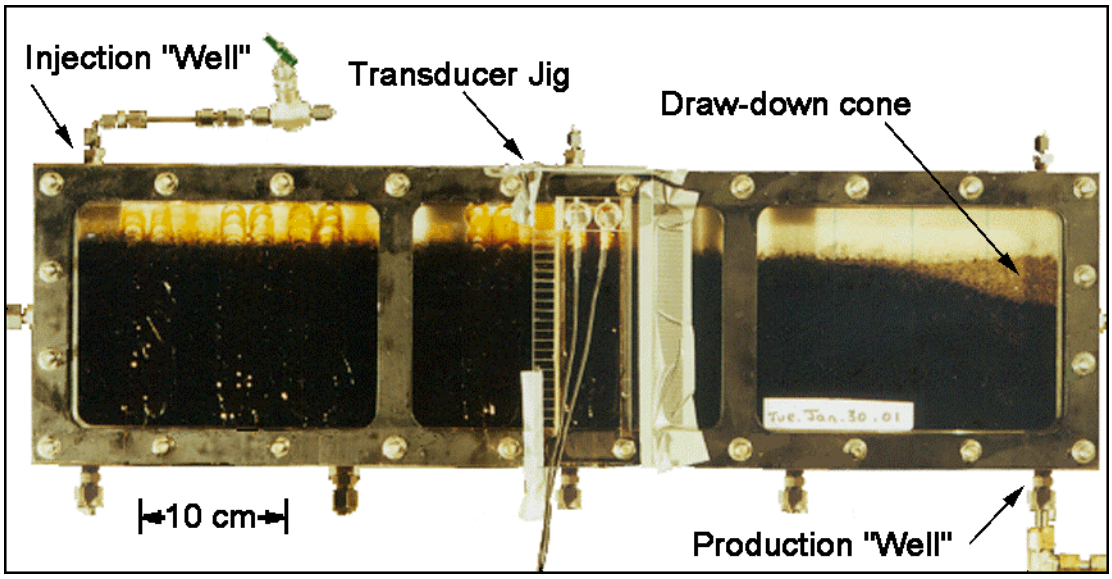

FIG. 1. Front view of the physical model. The jig and transducers for ultrasonic reflection acquisition are in the central window. The brown material on the left and centre windows (visible at the top) is molasses on top of the acrylic, which was used to improve acoustic coupling between the acrylic and the transducers.

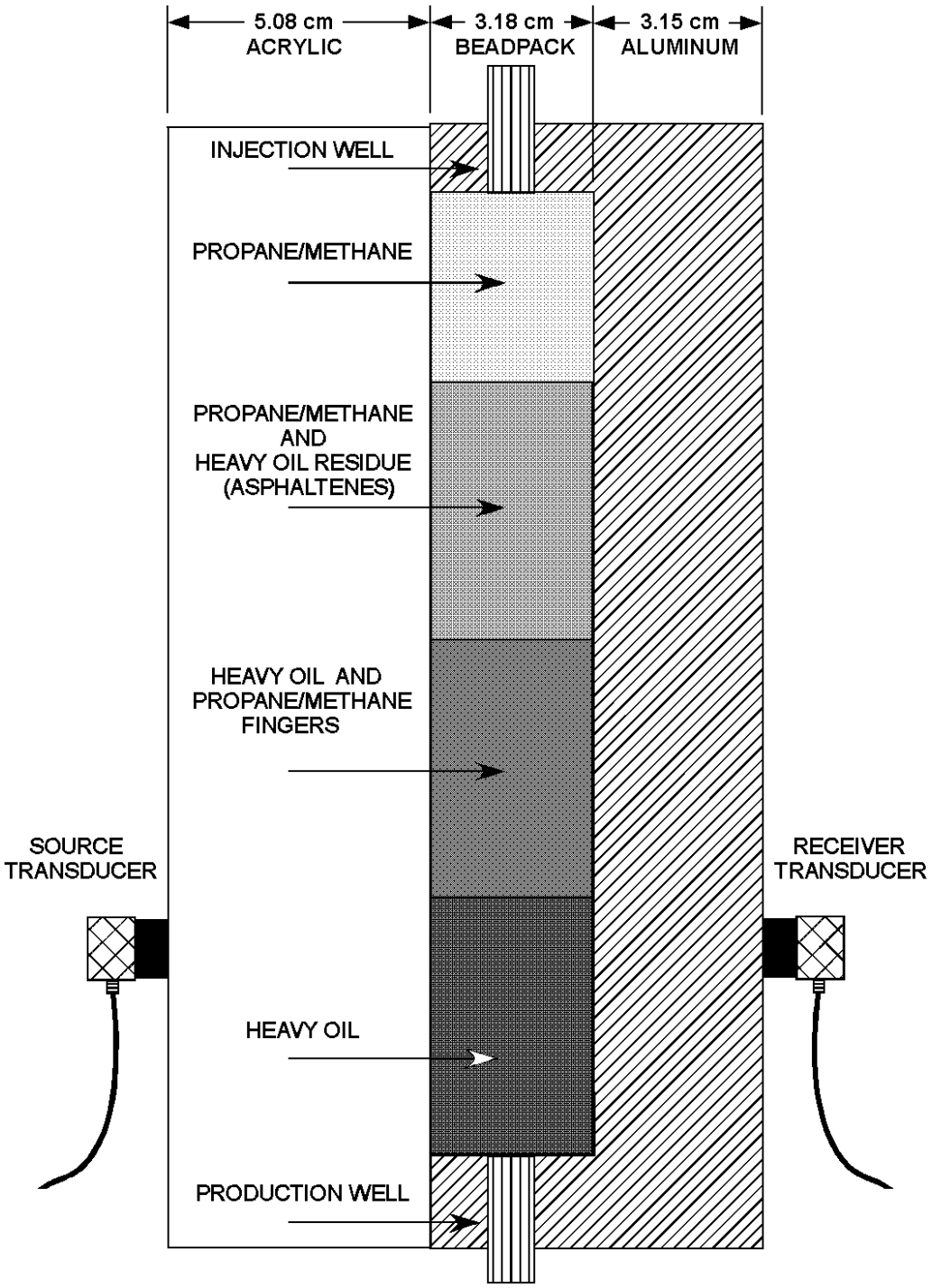

FIG. 2. End on view of the physical model. Note that the production and injection “wells” were at opposite ends of the model, lengthwise (Figure 1). Source and receiver locations are shown for acquisition of a single trace of the transmission survey (see below).

DESCRIPTION OF EQUIPMENT

Two of the ultrasonic surveys recorded over the physical model are presented in this paper, the 3D reflection survey and the 3D transmission survey. Trace spacing and source-receiver offset for the reflection survey were maintained using a two-piece acrylic jig. The transducers were held together in a block of acrylic with a 2.0 cm (centre to centre) fixed offset (Figure 3). This block fit into a vertical slot machined into a larger piece of acrylic that was fitted to the face of the bead-pack model. One side of the slot and one side of the block had a rack gear (straight gear) attached, which was used to key the block into the jig in order to align the transducers and maintain an even trace spacing of 0.667 cm. The piezoelectric transducers used to record the data were Panametrics Ltd. V-103 P-wave transducers.

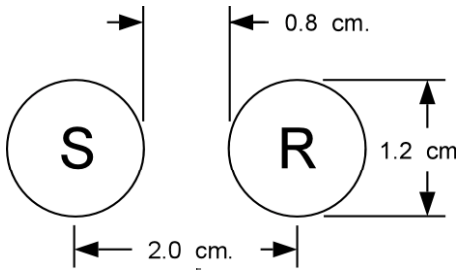

FIG. 3. Vertical motion transducer geometry (Source=S and Receiver=R) for ultrasonic reflection acquisition. The source-receiver offset is taken to be the centre-centre distance of 2.0 cm. Trace locations are taken to be at the midpoint of a line between the transducer centres.

THEORETICAL CONSIDERATIONS

Acrylic layer

The source-receiver offset is 2.00 cm (transducer centre to transducer centre, Figure 3), so the travel time for the primary reflection from the back of the acrylic will be $2\sqrt{1.00^2 + 5.08^2}\,/V_P$, or about 37.7 μs for an acrylic velocity of 2750 m/s (Table 1). The angles of incidence and reflection are both equal to $\tan^{-1}$(1.00 cm/5.08 cm), or about 11.14°.

Due to the source-receiver offset, the distance traveled by acrylic multiples will not be an integer multiple of 50.8 mm. Compressional wave multiples will occur at travel-times of $n\sqrt{(2/n)^2 + 5.08^2}\,/V_P$, where n = 4,6,8, etc. Therefore, we expect P-P multiples at 74.2 μs, 111.0 μs, 148.0 μs, and so on.

Since the traces are not zero-offset, it should be possible to see a P-S mode reflection from the back of the acrylic, with angles of incidence and reflection that depend on the V_P/V_S ratio. For acrylic V_P/V_S = 2 (Table 1). The angle of incidence is 14.83° and the angle of refraction is 7.35°. Given the acrylic properties shown in

Table 1, the two-way travel-time for the P-S mode reflection from the back of the acrylic is predicted to be 56.4 μs.

The above elastic data, along with those for the bead-pack (see below), allow us to calculate the Zoeppritz R_{PS} coefficient, which has a value of about 0.24. The receiver should detect sin(7.46°) = 0.13 or 13% of the reflected S-wave amplitude.

	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 density of the oil from Dr. B. Maini (Pers. Comm, 2001), 2) the bead-pack and heavy oil numbers, which are detailed in this paper, and 3) 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 (heavy oil, propane/methane) or glass beads with gas in the pore spaces (propane/methane), depending on location. To analyze the ultrasonic results, it is helpful to estimate the velocity through the bead-pack.

The confining pressure on the bead-pack is essentially zero (only the effect of gravity) so this system is better considered to be a fluid suspension, in which the only pressure is the pressure of the fluid (also called the pore pressure). Thus, we expect a zero shear modulus and focus on the compressional velocity.

This 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 (Mavko et al, 1998),

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

where K_{material} is the bulk modulus and ϕ is the porosity. Using values from Table 1, the value of K_{glass} is $\rho_{\text{glass}}(V_{P,glass}^2 - (4/3)V_{S,glass}^2)$, or 55.47 GPa (pg 52, Mavko, 1998), and K_{oil} is $\rho_{\text{oil}}V_{P,\text{oil}}^2$, or 2.55 GPa. From lab measurements, the porosity of the bead-pack was estimated at 37%. This was confirmed in the lab by measuring the quantity of water required to saturate a given volume of glass beads. From Equation (1), we then obtain $K_{\text{suspension}}$ = 6.39 GPa. The porosity also allows us to calculate the total

density, $\rho_{total} = (1-\phi)\ \rho_{glass} + \phi\ \rho_{oil}$, which is equal to 2.17 g/cm^3 in the heavy oil saturated region (using ρ_{glass}, and ρ_{oil} from Table 1). The velocity for the oil-saturated region, $V_{P,suspension} = \sqrt{K_{suspension} / \rho_{total}}$, is predicted to be about 1720 m/s.

Taking Snell's law into account, we can calculate that the P-wave will travel roughly $2d_{acrylic}$ at 2750 m/s through the acrylic and $2d_{bead\text{-}pack}$ at 1720 m/s through the bead-pack, by finding an x that satisfies Equation 2, which was derived for the geometry shown in Figure 4. For a source-receiver offset of 2.0 cm and using the theoretical bead-pack velocity of 1720 m/s obtained above, x is approximately 0.28 cm. For this value of x, $d_{acrylic}$ is 5.13 cm, $d_{bead\text{-}pack}$ is 3.19 cm, and we expect a back of bead-pack reflection at 74.4 μs. The angle of incidence (θ_1) at the acrylic/bead-pack boundary is 8.07^o and the angle of refraction (θ_2) is 5.03^o.

$$(V_{bead\text{-}pack}/V_{acrylic})((h-x)/d_{acrylic}) - (x/d_{bead\text{-}pack}) = 0 \qquad (2)$$

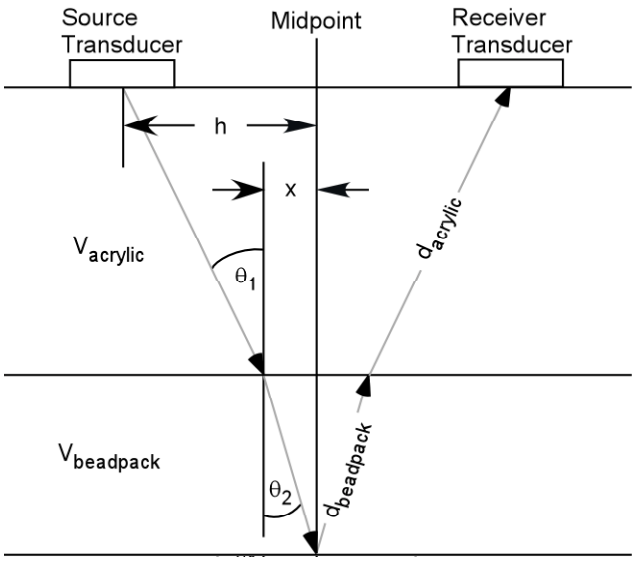

FIG. 4. Geometry used to derive equation 2. The ray path in grey is for a P-P reflection from the back of the bead-pack.

Aluminium layer

Assuming zero-offset geometry, the two-way travel time through the aluminium should be 2 * 0.0315 m / 6360 m/s, or 9.9 μs. Taking into account earlier results, this implies a total two-way travel time of about 84.3 μs for the back of aluminium reflection. Multiples within the aluminium would be expected at 94.2, 104.1, etc.

DESCRIPTION OF SURVEY GEOMETRY

The geometry for the 3D reflection survey is shown in Figure 5. The survey was started from the producing well (right-hand side of the model) with source and receiver at a fixed offset of 2.0 cm (Figure 3) and an in-line and cross-line spacing of 0.667 cm (Figure 5).

Thirteen lines were recorded for the reflection 3D, 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.

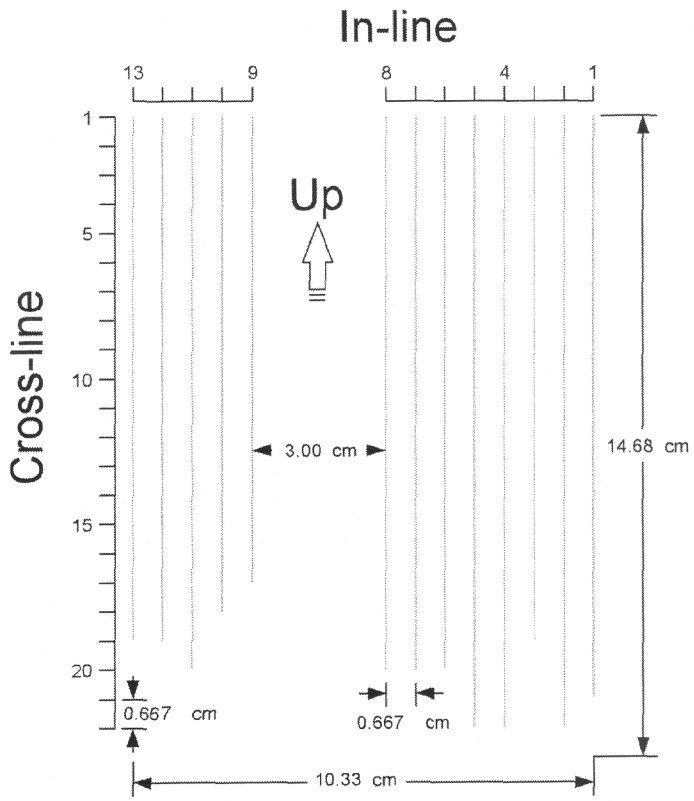

FIG. 5. Geometry of the 3D reflection survey. This survey was carried out entirely in the right hand window of the physical model.

The transmission survey geometry is partly 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.

PROCESSING AND INTERPRETATION OF THE 3D REFLECTION SURVEY

Figure 6 shows unprocessed traces from in-line 7 of the 3D reflection survey. While some of the traces appear to be fairly noise free (Figure 6a), others contain aliased noise with peaks in the amplitude spectra every 5 MHz, including near-zero and near-Nyquist (Figure 6d).

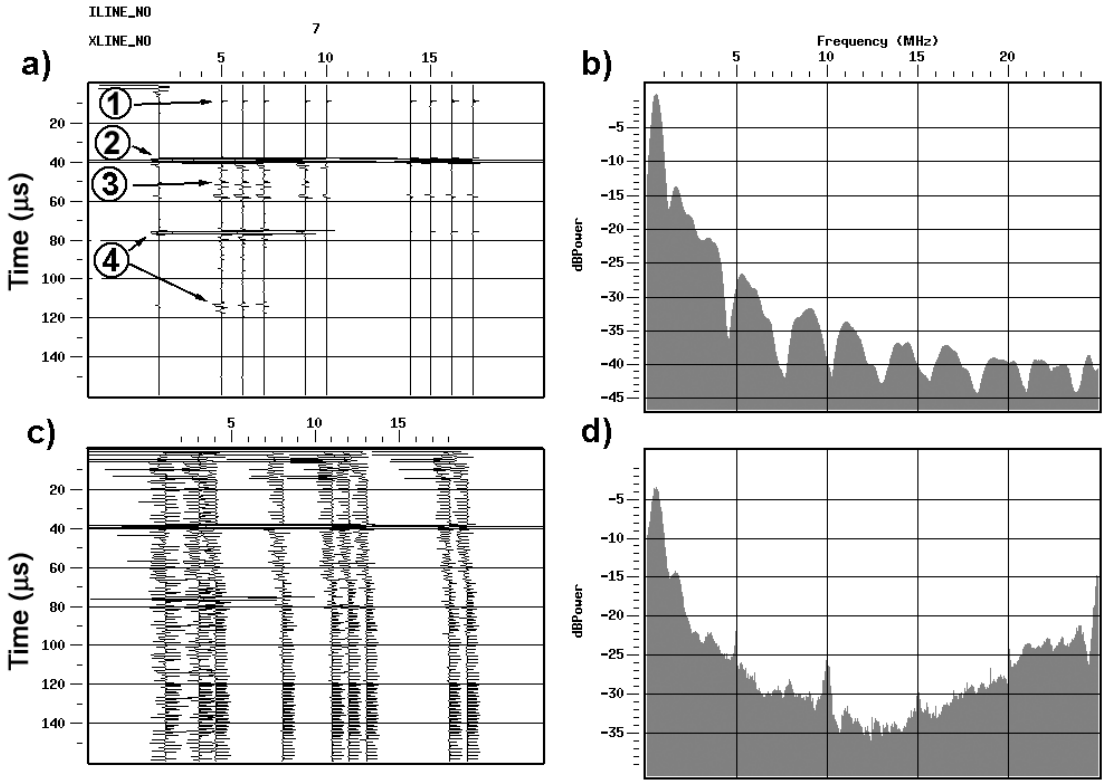

FIG. 6. Raw traces and corresponding averaged amplitude spectra of in-line seven, from the 3D reflection survey. Figures 6a and 6b show normal traces, Figures 6c and 6d show traces with aliased noise from an unknown source. Reflections (1) are interpreted to be constant amplitude electrical noise, and are used for trace equalization in the processing step. Reflections 2,3 and 4 are described in Figure 7. This data was recorded with a 20 ns sample rate, which gives a Nyquist frequency of 25 MHz. Central frequency of the transducers is about 0.33 MHz.

One effect of the aliased noise is low frequency noise, such as the wave that causes amplitudes at early times (before 40 μs) to be entirely negative, and amplitudes at greater times (after 80 μs) to be entirely positive (Figure 6c). Another effect is the high frequency noise that varies from positive to negative amplitude every sample (Figure 6c). The cause of this noise is unknown at this time, but may be electronic noise from the hardware.

A 0.1-0.2-1.5-2.0 MHz bandpass filter was designed to minimize the effects of the aliased noise. 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, (Reflections 1, Figure 6a), Finally, a 10 μs window AGC was applied, resulting in the data shown in Figure 7.

The major reflections seen in Figure 7 are 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.

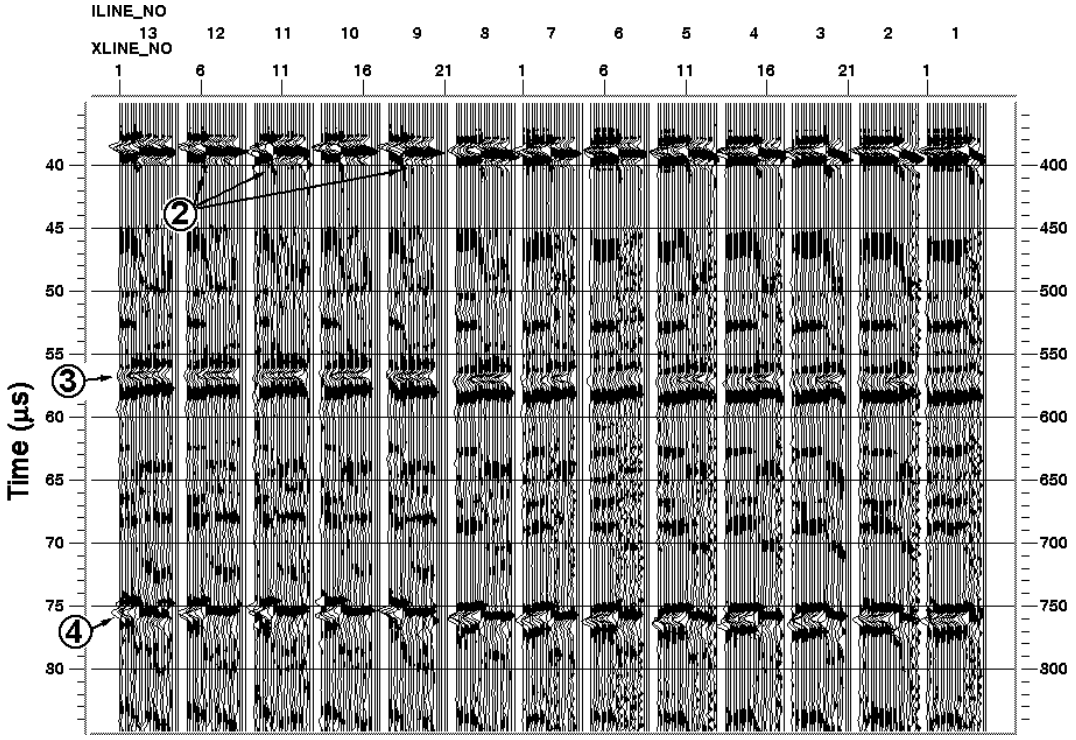

FIG. 7. In-lines 1-13 of the 3D reflection survey (see geometry in Figure 5). Interpretation based on theoretical considerations: Reflections (2) are P-P reflections from the acrylic/bead-pack interface. The polarity reversal correlates to the gas/fluid interface within the bead-pack (compare with Figure 8). Reflections (3) are P-S reflections from the acrylic/bead-pack interface. Reflections (4) are the first P-P multiples within the acrylic.

Reflection 2 has a polarity reversal that occurs at different positions on the in-lines, and correlates with the contact between heavy oil and the propane/methane mixture within the bead-pack (compare with Figure 8). Reflection 3 does not have a polarity change, which further supports its interpretation as a P-S mode reflection.

Finally, 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 7).

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 7). 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 7).

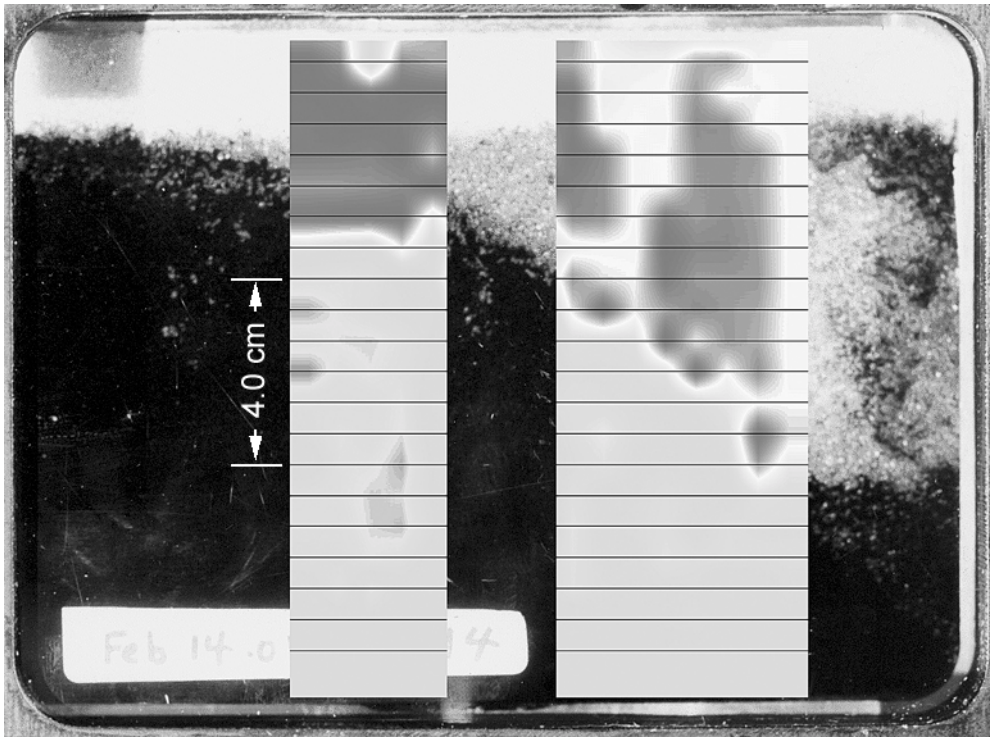

FIG. 8. Time-slice at 37.9 μs from the 3D reflection survey (compare with geometry in Figure 5 and reflection 2 in Figure 7). Note that the polarity reversal follows the contact between the heavy oil and the draw-down cone.

PROCESSING AND INTERPRETATION OF THE TRANSMISSION SURVEY

Due to the aliasing problems 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. The amplitude spectrum still has a near-Nyquist peak, but at 55 dB down it is not visible when the unprocessed data are plotted (Figure 9). Unlike the 3D reflection data, the amplitude spectrum does not have a peak every 5 MHz. Instead, there are peaks at about 8, 25 (Nyquist at 20 ns), and 46 MHz (Figure 9b, compare with Figure 6d). When a 10 μs AGC is applied, the near-Nyquist noise still has a low enough amplitude that the data is dominated by signal, although the noise is visible before the direct arrivals (Figure 10). In general, the transmission data are of better quality than the 3D reflection data, and processing has been limited to an AGC.

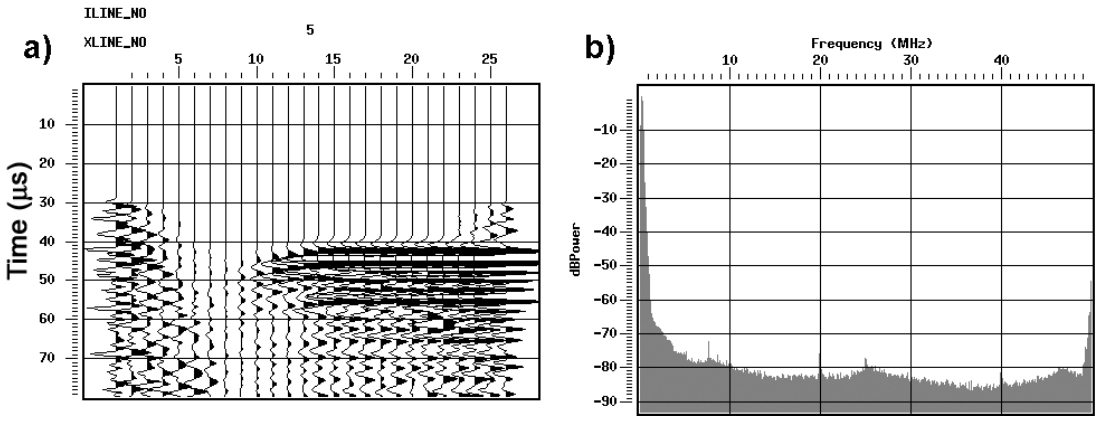

FIG. 9. a) In-line five of the transmission survey, and b) the corresponding average amplitude spectrum of unprocessed traces.

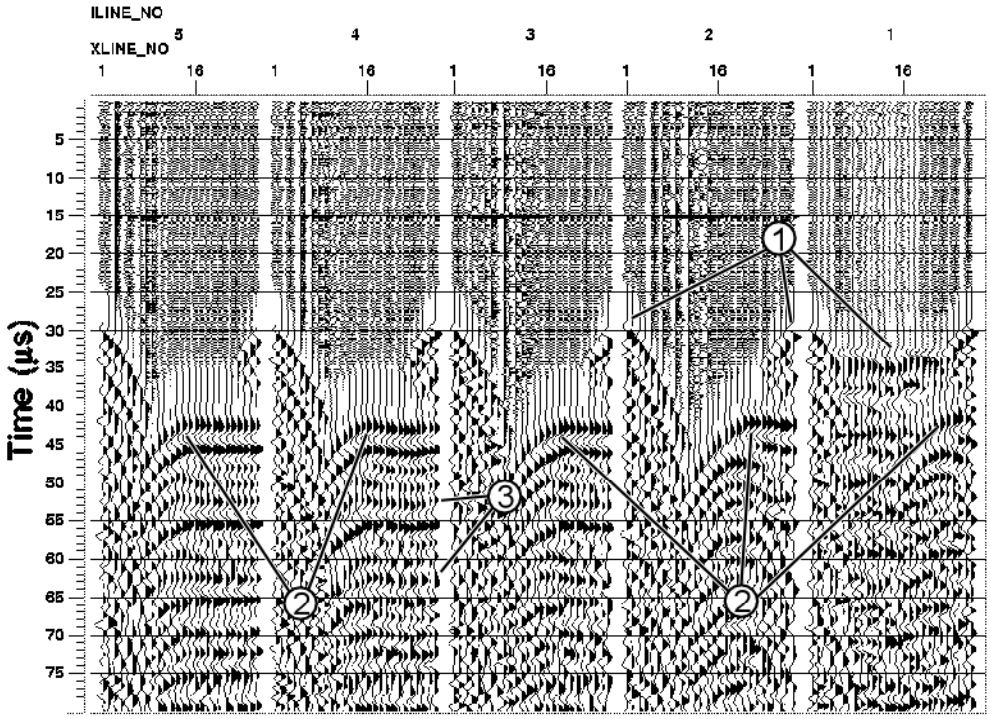

FIG. 10. Transmission survey with a 10 µs AGC applied. Interpretation: Transmissions (1) are edge effects from the sides of the aluminium cavity containing the bead-pack. Transmissions (2) are direct arrivals through the acrylic, bead-pack and aluminium. Reflections (3) are multiples of the direct arrival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

The events shown in Figure 10 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 also observed at the outermost traces of each inline. 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 10).

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 10, and compare with Figure 8). 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 the theoretical two way travel-time for multiples within the aluminium 9.9 μs).

A velocity through the heavy oil and bead-pack can be derived from the transmission data by using Equations 3 and 4.

$$t_{total} = t_{acrylic} + t_{bead\text{-}pack} + t_{Al} \quad (3)$$

$$V_{bead\text{-}pack} = d_{bead\text{-}pack}/(t_{total} - t_{acrylic} - t_{Al}) \quad (4)$$

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.

DISCUSSION

Comparison of theoretical and experimental velocities

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 calculated from the transmission data. This difference between theory and reality implies that our initial assumptions were incorrect. If we assume that the stickiness of 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. For a fluid suspension, $V_{P,suspension} = \sqrt{K/\rho}$, while for an elastic solid $V_{P,solid} = \sqrt{(K + \frac{4}{3}\mu)/\rho}$ (Mavko, 1998). If this explanation is valid, then $V_{P,solid}^2 - V_{P,suspension}^2 = (1918\ m/s)^2 - (1720\ m/s)^2 = 7.2 \times 10^5\ m^2/s^2 = \Delta K/\rho + 4\mu/3\rho$, where ΔK represents the increase in the bulk modulus from cementation. Using the relation $V_S = \sqrt{\mu/\rho}$ we obtain $V_S \leq 735$ m/s. Thus, one way to test our original hypothesis would be to see if the bead/oil mixture has a shear velocity, and if it is equal to or less than the value obtained here.

Absence of non-acrylic reflections

The theoretical travel times for the reflection from the back of the bead-pack (74.4 μs) and the P-P multiple within the acrylic (74.2 μs) are within 0.2 μs of each other. If we use the experimental velocity of 1918 m/s, and re-calculate a travel time to the back of the bead-pack, we obtain 70.6 μs. This number may be misleading, since a lighter oil was used in the model prior to the transmission test, than for the reflection data. However, 70.6 ms correlates to a very low amplitude, low frequency event in the ultrasonic reflection data that can only be seen on the heavy oil part of some of the in-lines (Figure 11, compare with in-lines 7-13, just above reflections 4, Figure 7).

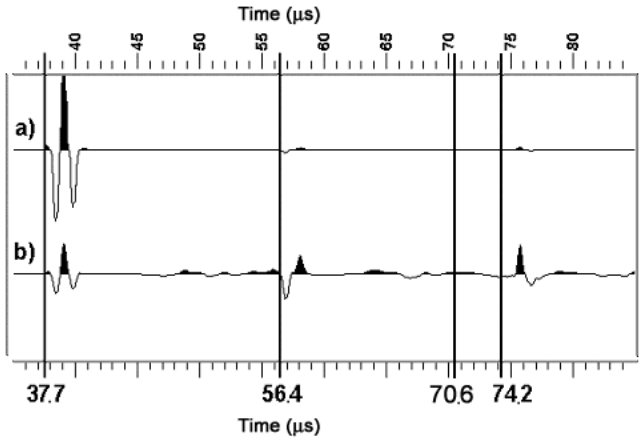

FIG. 11. Figure 11a is an unfiltered, four trace stack with no AGC from in-line 7 of the 3D reflection survey. Figure 11b, is the same stack, but with processing applied as in Figure 7. The bottom scale shows the theoretical times calculated for 1) the reflection from the acrylic/bead-pack interface (37.7 μs), 2) the P-S converted wave reflection from the acrylic/bead-pack interface (56.4 μs), 3) the reflection (?) from the bead-pack/aluminium interface at 70.6 μs using the velocity obtained from the transmission survey, and 4) the first P-P multiple in the acrylic (74.2 μs) The theoretical time for the back of bead-pack reflection is 74.4 μs. Note the large difference in amplitude between the events at 37.7 and 70.6 μs. In general, there is good agreement between the theoretical travel-times and observed reflections.

Since the heavy oil is a highly viscous substance, and it would be expected that significant attenuation losses will occur due to absorption processes, and that the high frequencies will be preferentially filtered. Here we attempt to estimate the magnitude of these losses.

The central frequency (f) of the transducers is about 0.33 MHz, and the velocity through the bead-pack is 1918 m/s (experimental) so the wavelength in that region is ~5.8 mm. The bead-pack is 31.8 mm thick, so the shortest path through it would be ~5.5 wavelengths long. Note that the beads are on the order of 1 mm, so the waves see the material as essentially homogeneous. Most of the absorption will be due to the heavy oil, so as a first approximation we may consider the absorptive attenuation as being equal to that caused by transmission through (0.37)(5.5) wavelengths worth of pure oil, where 0.37 is the porosity of the bead-pack. One way to estimate Q is from the viscosity (η) of the oil. The viscosity of 20,000 cps, corresponds to a Q factor of 46.1 using Equations 5 and 6 (page 213 of Mavko et al., 1998).

$$Q^{-1} = 2\sqrt{(\sqrt{1+z^2}-1)/(\sqrt{1+z^2}+1)} \tag{5}$$

$$z = 8\,\pi\,\eta\,f\,/\,3\,K_{\text{oil}} \tag{6}$$

A one-way attenuation of amplitude due to absorption can be estimated by $\exp[-\pi\, x\,/\,Q\,\lambda] = \exp[-5.5\,\pi\,/\,Q] \approx 0.687$. This is the fraction of amplitude that would survive after absorption processes of a single transmission. Two passes through the bead-pack, as would be required for reflection from its lower interface, would have an attenuation factor of $(0.687)^2 = 0.473$. This level of attenuation, coupled with the proximity of the P-P multiple, fails to explain why we were able to transmit sound through the model, but were unable to conclusively image a reflection from the bead-pack/aluminium contact. However, Schmitt (1999) indicates that oil sands have Q values of 10 to 20, so our Q estimate may well be too high. A Q of 10 could mean that about 97% of energy is absorbed by attenuation alone during a two-way pass through the bead-pack. This appears consistent with the peak at 70.6 μm in Figure 11, especially considering its low frequency character. Figure 12 shows a comparison between the time-slice at 70.6 μs and a photograph of the model (compare with Figure 8).

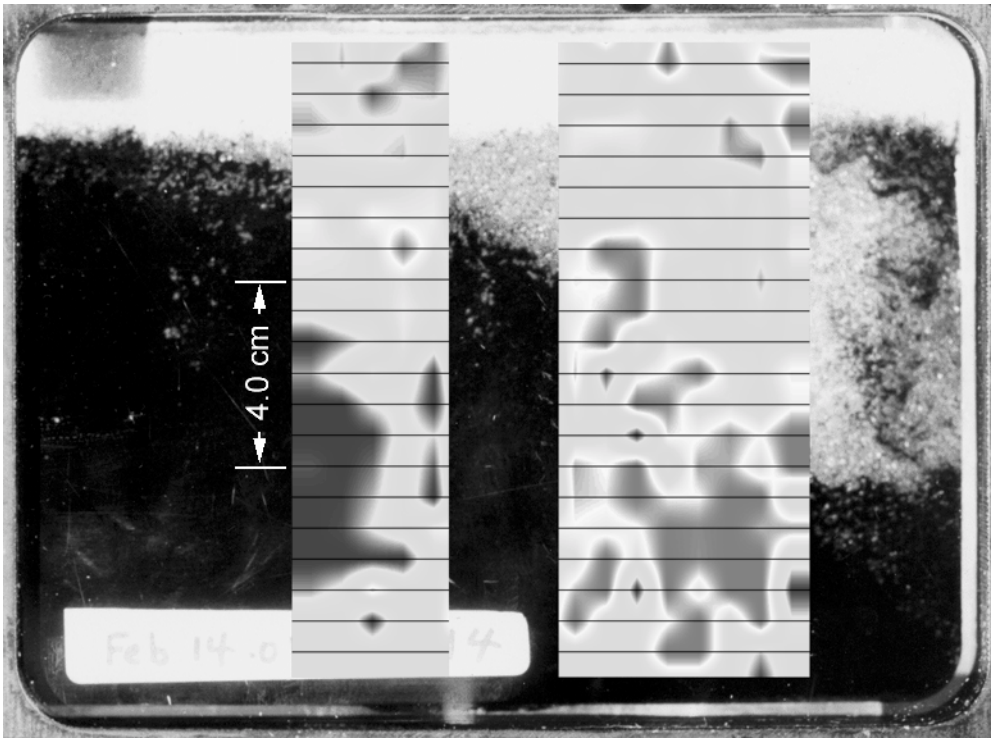

FIG. 12. Time-slice at 70.6 μs from the 3D reflection survey (compare with geometry in Figure 4).

CONCLUSIONS AND FUTURE WORK

The 3D ultrasonic reflection data acquired to date has 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 high amplitude multiple within the acrylic, if the theoretical bead-pack velocity of 1720 m/s is correct. This could be avoided in future by using a thicker or thinner acrylic faceplate.

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

Problems with noise aliasing across the seismic signal were encountered. The source of this noise should be identified and eliminated. Anti-alias filters should be present in the analog-digital step of the recording process, or data should be acquired at the highest possible sample rate.

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