Collaborative methods in enhanced cold heavy oil production

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Heavy oil reservoirs are an abundant hydrocarbon resource, which will in all probability comprise a significant portion of long-term world oil production. The world's heavy oil reserves have been estimated to be about 6 trillion barrels—roughly equivalent to conventional reserves. The largest heavy oil reserves are in Canada, Venezuela, the United States, Norway, Indonesia, China, Russia, and Kuwait.

Cold production is a low-energy production method that has been widely used in western Canada. Although the primary recovery rates are relatively modest, cold production of heavy oil requires much less energy than hot production methods such as cyclic steam injection (CSS) or steam-assisted gravity drainage (SAGD), and as a consequence results in much less hydrocarbon use in the recovery stage.

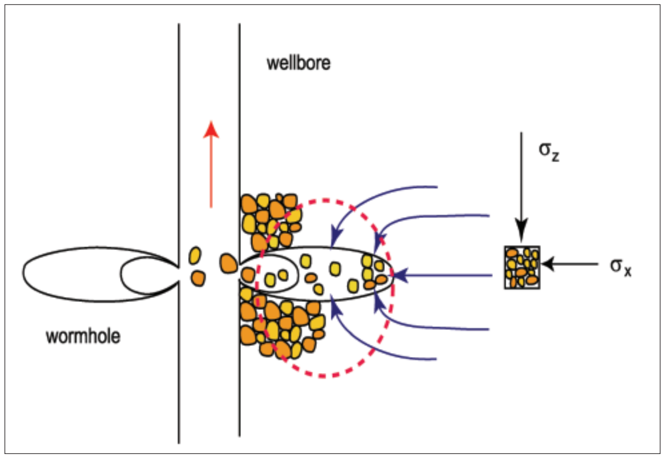

Figure 1. *In the cold production of heavy oil, progressive cavity pumps extract sand, oil, water, and gas from the borehole. This figure shows the geomechanics of the cold production process (courtesy of Jen Wang and Tony Settari of Taurus Corporation).*

Wormholes, foamy oil, and cold production

During the cold production process, sand, oil, water, and gas are produced simultaneously by using progressive cavity pumps which generate high-porosity channels termed "wormholes" (Figure 1). The characteristics of wormholes were described by Tremblay et al. (1999), Sawatzky et al. (2002), and Lines et al. (2003). Figure 2 shows a wormhole model from a western Canadian oil field. Wormholes have a fractal-like pattern similar to tree branches (Yuan et al., 1999). Typical dimensions of wormholes can be 100–200 m in length with circumference believed to be about 10–20 cm after several years of uninterrupted production.

Wormhole evolution causes reservoir pressure to decrease below the bubble point, resulting in gas coming out of solution to form foamy oil. The bubbles are trapped in oil of extremely high viscosity. The phenomenon of foamy oil development is similar to creation of bubbles in shaving cream, except that it is viscous oil that traps the bubbles rather than soap. Figure 3 shows a sample of foamy oil created at the Imperial Oil Research Laboratory in Calgary. Both foamy oil and wormholes are believed to be major driving factors in the cold production of heavy oil recovery.

Cold production is somewhat "miraculous" in that there is intentional sand production, along with oil, water, and gas by progressive cavity pumps. Initially the sand cut is very high, with a marginal amount of oil recovery. However, after a few weeks of pumping sand and fluids, an unexpectedly large amount of oil is produced and the sand cut diminishes exponentially. It is believed that this high oil recovery is the result of microbubbles in the solution gas drive. In effect a "horizontal well" has been created without actually drilling one.

In cold production of heavy oil, it is fundamental to delineate the depletion zones or footprints to optimize drilling strategies. Figure 4 illustrates this production strategy. Once the depletion footprints have been created by drilling a set of wells, we do not want to drill another well into these depletion zones. This would be a "wasted well" since the zone is depressurized and circulation would be lost from existing wells. We hope to delineate the production zones so that new infill wells will be productive and eventually allow maximum recovery with a minimal number of wells. Our objective is to delineate these cold production footprints by seismic methods.

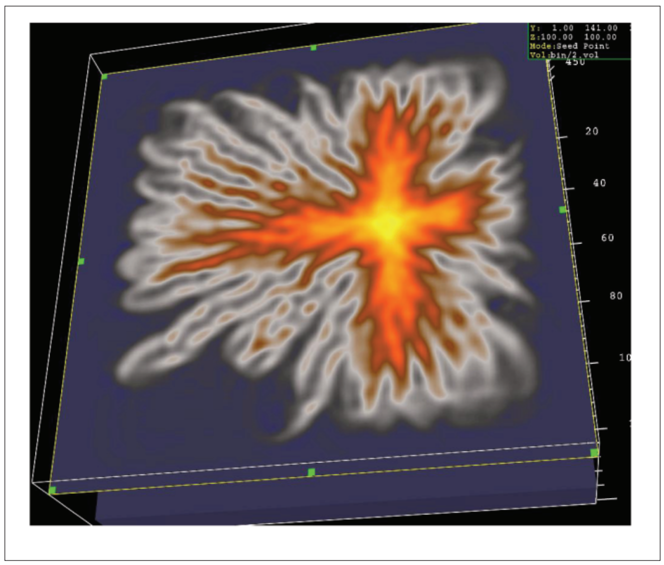

Figure 2. *Depth slice showing cold production wormholes from a study at Plover Lake, Saskatchewan. The well is centered at the bright yellow zone. The yellow-orange zones are high-porosity, high-permeability regions of low seismic velocity within the layer of undisturbed oil sands (dark blue).*

Seismic resolution of cold production zones

Lines et al. (2003) revealed the possibilities of detecting wormhole distribution rather than attempting to image in-

Figure 3. A sample of foamy oil from Chen (2004). The figure is originally from the Imperial Oil Research Laboratory and David Greenridge.

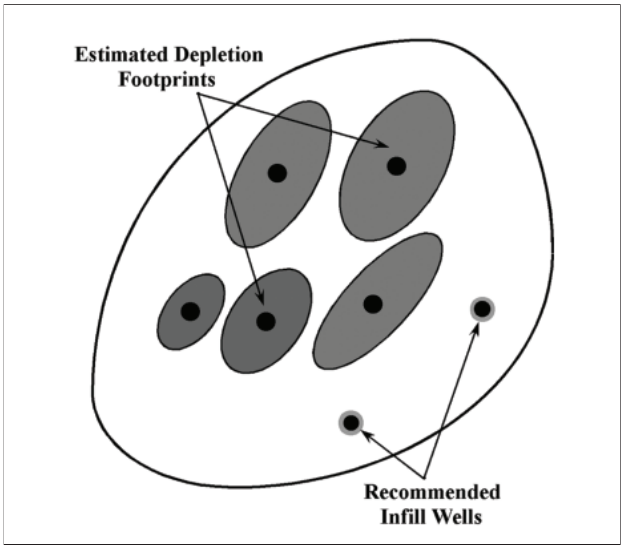

Figure 4. *This figure (from Lines and Daley) describes the challenge of cold production. As cold production wells begin producing, cold production footprints consisting of foamy oil and wormholes are created. For infill drilling we seek to drill new wells outside these depletion footprints to avoid loss of circulation and to optimize the production of the entire field.*

dividual wormholes by normal seismic method. Chen et al. (2004) calculated elastic parameters of a heavy oil reservoir before and after cold production using Gassmann's equation, and discussed the possible use of time-lapse reflection seismology (theoretically for the detection of the presence of foamy oil and wormholes). Zou et al. (2004) analyzed a repeated 3D seismic survey over a cold production field in eastern Alberta, which showed an interesting correlation between time-lapse seismic changes and heavy oil cold production. Lines and Daley (2007) showed that 3D depth migration can delineate cold production zones to within Fresnel resolution limits.

Figure 5 shows time-lapse surveys illustrating the effects of cold production. In this figure, a 3D survey near Provost, Alberta acquired in 1989 is compared with a survey in 2000. The red arrows denote the changes in seismic amplitude and traveltime for reflectors at the Mannville and Rex sandstone levels. The decrease in the P-wave velocity during cold pro-

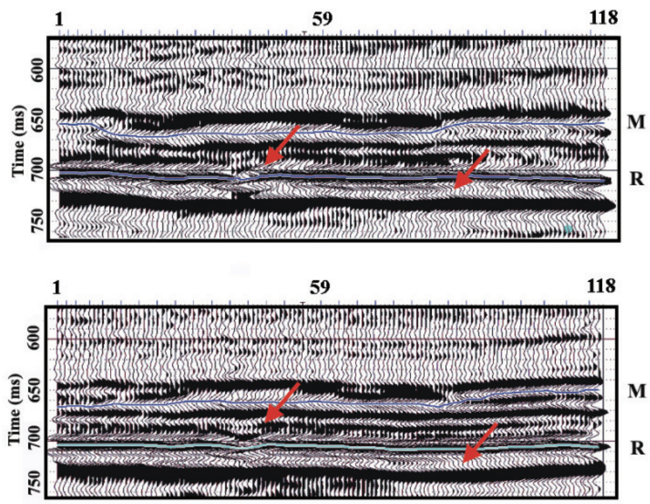

Figure 5. *These time-lapse seismic results (from Zou et al.) show that cold production will affect both seismic amplitudes and traveltimes. The upper line is from a 3D survey near Provost, Alberta in 1989 and the lower figure shows the line from a 2000 survey over the same location. Red arrows denote that amplitudes are altered and traveltimes are delayed by lower seismic velocity in the reservoir zones.*

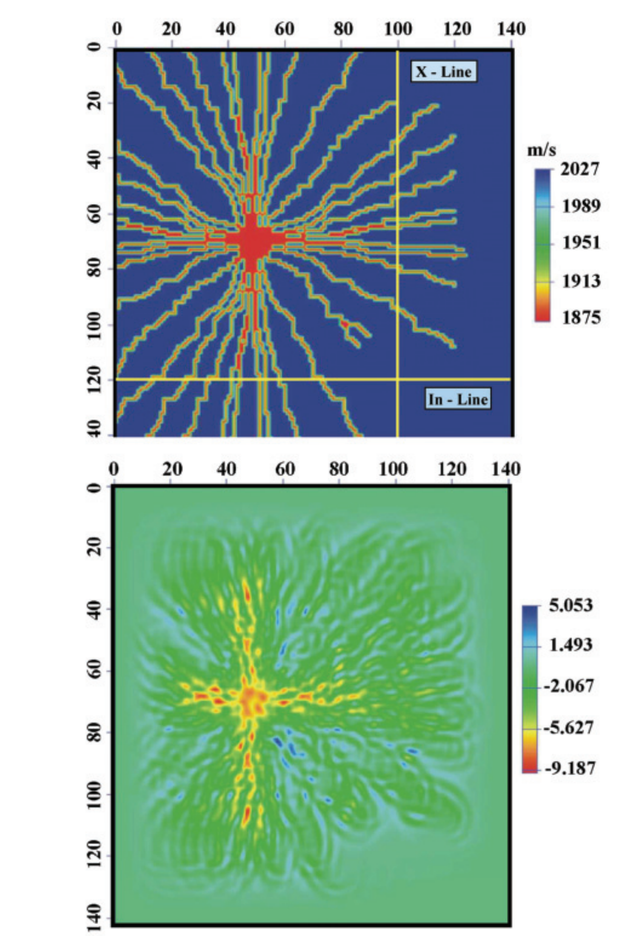

Figure 6. *A comparison of an idealized wormhole model (top) with its seismic image at typical seismic frequencies (bottom). This figure (from Lines and Daley) illustrates that seismic resolution is limited by the Fresnel zones. While the individual wormhole zones may be blurred, the edge of the cold production zones can be delineated.*

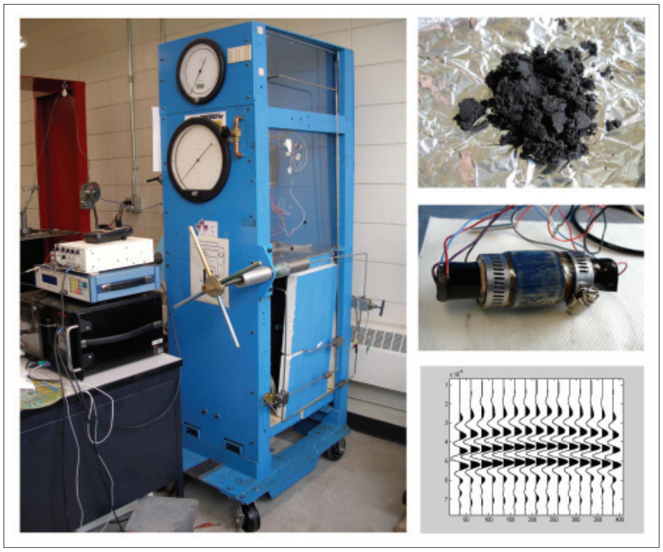

Figure 7. Rock physics apparatus (left) for measuring seismic velocities on core (upper right) held between transducers (middle right) to produce seismic response (lower right)

duction causes changes in seismic amplitudes and delays in traveltimes.

Figure 6 compares a velocity model for a wormhole network (top) with the depth slice from a 3D depth-migrated seismic section. Due to the band-limited nature of the wavelength, the seismic image is a somewhat blurred image of the actual model. However, note that the edges of the model are reasonably well-defined. While the production effects are seen in the amplitudes and traveltimes, they can also be seen in inversion estimates of the seismic impedance (these are to be shown as part of Wang's master's thesis).

All the above research is encouraging and confirms that time-lapse seismology can play an important role in mapping the variation from the initial state due to an interval of cold heavy oil production.

A particular emphasis of our research concerned how cold heavy oil production affects the V_P/V_S ratio and the feasibility of using it to monitor recovery. Recent studies, focused on rock physics, showed that pressure reduction in the reservoir should cause a 10-15% reduction in the V_P/V_S ratio.

Rock physics of cold production of heavy oil

Gassmann's equation predicts the bulk modulus of a fluid-saturated porous medium using the known bulk moduli of the solid matrix, the frame, and the pore fluid in the following manner:

$$K^* = K_d + \frac{(1 - K_d / K_m)^2}{\dfrac{\phi}{K_f} + \dfrac{1-\phi}{K_m} - \dfrac{K_d}{K_m^2}} \quad (1)$$

Where K^*, K_d, K_m, K_f, and ϕ are the saturated porous rock bulk modulus, the frame rock bulk modulus, the matrix bulk modulus, the fluid bulk modulus, and the porosity. It is assumed that the shear modulus μ^* of the saturated rock is not affected by fluid saturation, so that

$$\mu^* = \mu_d \quad (2)$$

with μ_d being the dry frame shear modulus.

The P-wave and S-wave velocities, V_P and V_S, for an isotropic, homogeneous, elastic material are

$$V_P = \sqrt{\frac{K^* + 4\mu^*/3}{\rho^*}} \quad (3)$$

and

$$V_S = \sqrt{\frac{\mu^*}{\rho^*}} \quad (4)$$

where ρ^* is the saturated rock bulk density and can be calculated as

$$\rho^* = \rho_m(1-\phi) + \rho_f\phi \quad (5)$$

where ρ_m and ρ_f are the densities of solid grains and the fluid mixture at reservoir conditions.

Equations 1–5 establish the relationships between rock moduli and seismic velocities. However, there are several assumptions that could impact the accuracy of Gassmann's equation for calculating the seismic velocities in a reservoir (Han and Batzle, 2004). One is that the pores are filled with a frictionless fluid (liquid, gas, or mixture). This implies that the viscosity of the saturating fluid is zero, which may be questionable for heavy oil, especially at cold temperatures (about 20–40°C).

Despite these simplifying assumptions and somewhat surprisingly, Gassmann's equation provides a reasonable description of the elastic moduli for heavy oil sands even at the low temperatures of cold production. Zhang (2007) analyzed heavy oil sands from cold production fields at Plover Lake, Saskatchewan, comparing the bulk modus and shear modulus from Equations 1 and 2 to the elastic moduli computed using Equations 3 and 4 on dipole sonic velocities. He found that the estimates of the Gassmann estimates for bulk moduli and shear moduli differed by less than 10% and 3%, respectively, for the values obtained using dipole sonic logs.

Rock physics measurements help to provide an essential link between seismic velocities and the physical properties used in petroleum reservoir simulation. The measurements of seismic properties (such as amplitudes and traveltimes) as a function of varying reservoir properties (such as pressures, temperatures, fluid properties, and lithologies) provide the crucial relationships that relate seismic models to reservoir models. Figure 7 shows the rock physics apparatus in Schmitt's laboratory at the University of Alberta where seismic measurements on rocks have been made for more than 20 years. Rock cores (upper right) are placed between transducers (middle) to produce the seismograms (lower right).

Reservoir simulation of heavy oil cold production

Relationships between seismic velocity and reservoir model parameters will allow us to enhance reservoir modeling. Reservoir models for cold production of heavy oil are shown in Figure 8. The reservoir model prior to cold production (left) shows random distribution of porosities with most cells hav-

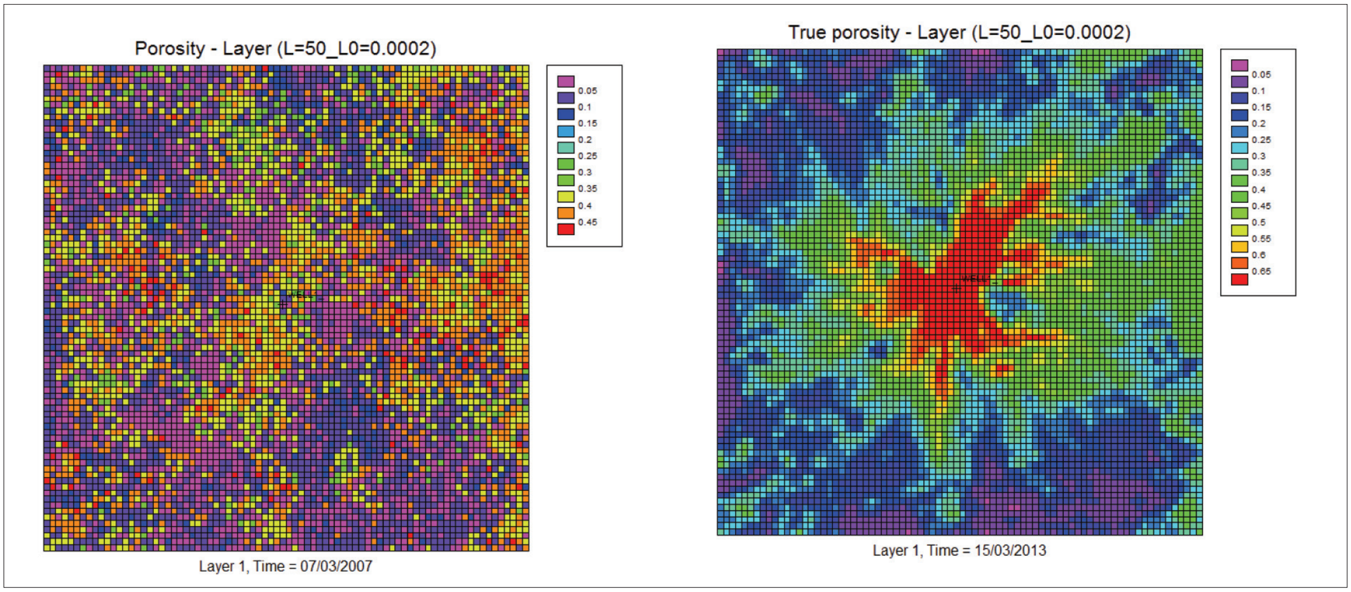

Figure 8. *A comparison of porosity models for cold production prior to reservoir production (left) and after 10 years (right).*

ing 20–40% porosity. Following 10 years of cold production for a well at the center of the model, we see extremely high porosities exceeding 60% emanating out from the well (right). The map of porosities is highest at the well location, but does show preferential branching directions which can be determined by time-lapse seismology.

Our experience has shown that time-lapse seismology and rock physics can aid in the reservoir characterization of porosities. Our next immediate goal will be to use seismic and rock physics data to characterize reservoir fluids, in particular, the heavy oil viscosity.

Conclusions

The generation of wormholes and the formation of foamy oil from simultaneous extraction of oil and sand during heavy oil cold production will change fluid properties in the reservoir. This change will be detectable by seismic surveys. For heavy oil in the 10-20 API range at ambient temperature of 20°C, the shear modulus is negligible and heavy oil still acts like a liquid at seismic frequencies, especially after cold production. Gassmann's equation can still help us understand the seismic response of heavy oil reservoirs before and after cold production. The V_P/V_S ratio is a function of both fluid bulk modulus and porosity. For unconsolidated sands with high porosity, pore fluids have a significant influence on the final value of the ratio. Due to the dramatic reduction of fluid's bulk modulus after heavy oil cold production, the ratio will have a detectable reduction. This should help interpret time-lapse multicomponent seismic surveys in cold production fields.

Suggested reading. "Seismic properties of pore fluid" by Batzle and Wang (Geophysics, 1992). "Heavy oils--seismic properties" by Batzle et al. (*TLE*, 2006). "Foamy oil and wormhole footprints in heavy oil cold production reservoirs" by Chen et al. (CSEG *Recorder*, 2004). *Time-lapse Seismology to Determine Foamy Oil and Wormhole Footprints in Heavy Oil Cold Production Reservoir* by Chen (master's thesis, University of Calgary, 2004). "Gassmann's equation and fluid-saturation effects on seismic velocities" by Han and Batzle (Geophysics, 2004). "Seismic pursuit of wormholes" by Lines et al. (*TLE*, 2003)."Seismic detection of cold production footprints in heavy oil extraction" by Lines et al. (*Journal of Seismic Exploration,* 2007). "V_P/V_S characterization of heavy-oil reservoir" by Lines and Daley. (*TLE*, 2005). "Foamy oil flow in cold production of heavy oil" by Maini (2004 Distinguished Lecture, Petroleum Society of CIM). "Bounds on low-frequency seismic velocities in partially saturated rocks" by Mavko and Mukerji (Geophysics, 1998a). "Comparison of the Krief and critical porosity models for prediction of porosity and V_P/V_S" by Mavko and Mukerji (Geophysics, 1998b). "Heavy oil reservoir mechanisms, Linbergh and Frog Lake Fields, Alberta, Part 1: Field observations and reservoir simulation" by Metwally and Solanki (46th technical meeting of the Petroleum Society of CIM, 1995). "Modulus decomposition of compressional and shear velocities in sand bodies" by Murphy et al. (Geophysics, 1993). "Tracking cold production footprints" by Sawatzky et al. (2002 CIPC Conference). "A review of cold production in heavy oil reservoirs" by Tremblay et al. (EAGE 10th European Symposium of Improved Oil Recovery, 1999). "A wormhole network model of cold production in heavy oil" by Yuan et al. (SPE paper 54097, 1999). *Application of V_P/V_S and AVO Modeling for Monitoring Heavy Oil Cold Production* by Zhang (master's thesis, University of Calgary, 2007). "Time-lapse seismic analysis of a heavy oil cold production field, Lloydminster, Western Canada" by Zou et al. (SEG 2004 *Expanded Abstracts*).

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