# Effects of heavy oil cold production on Vp/Vs ratio

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## ABSTRACT

During the heavy oil cold production process, sand, gas, oil and water are produced by progressive cavity pumps, creating wormholes (high permeability channels) and foamy oil. These cold production effects create "footprints", and it is important to delineate the extent of these footprints in order to optimize enhanced heavy oil production. The seismic mapping of $V_p/V_s$ variations provides an effective tool for both lithology discrimination and the delineation of production footprints. In this paper, we demonstrate that $V_p/V_s$ ratios should decrease in the zones of cold heavy oil production.

## INTRODUCTION

Heavy oil *reservoir*s are an abundant hydrocarbon resource, particularly in Canada, Venezuela, and Alaska. Some estimates indicate that heavy oils represent as much as 6.3 trillion barrels of oil in place. This is equivalent to the known quantities of conventional oil. More than 50% of Canada's oil production is now from heavy oil (Batzle et al. 2006). Much of the heavy oil recovery in Western Canada involves steam injection, called 'hot production'. An alternative to thermal heavy oil production is 'cold production', a primary non-thermal process in which reservoir temperature is not affected. The cold production process has been economically successful in several unconsolidated heavy oil fields in Alberta and Saskatchewan, Canada (Sawatzky et al., 2002). During the cold production process, sand and oil are produced simultaneously *by progressive cavity pumps*, generating high porosity channels termed "wormholes". The development of wormholes causes reservoir pressure to fall below the bubble point, resulting in dissolved-gas coming out of solution to form foamy oil. Both foamy oil and wormholes are believed to be two key factors in the cold production of heavy oil recovery (Metwally, et al. 1995; Maini, 2004).

The development of wormholes and the formation of foamy oil will modify fluid properties in the reservoir during heavy oil cold production. Batzle et al. (2006) showed that the bulk modulus of heavy oil drops to near zero very quickly from about 2.6 GPa, after reservoir pressure becomes lower than the bubble point (at about 2 MPa). This phenomenon will probably be detectable by time-lapse seismic surveys.

To detect the roles seismic methods can play in mapping the disturbance of the initial reservoir state after a period of heavy oil cold production, Lines et al. (2003) revealed the possibility of detecting wormhole distribution rather than attempting to image individual wormholes by normal seismic method. Chen et al. (2004) calculated elastic parameters of heavy oil reservoir before and after cold production using Gassmann's equation, and discussed the possible use of time-lapse reflection seismology theoretically for detecting 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, showed an interesting correlation between time-lapse seismic changes and heavy oil cold production. Lines and

Daley (2007) showed that 3-D depth migration can delineate cold production zones to within the Fresnel resolution limits. All of the above research is encouraging and confirms that time-lapse seismology can play an important role in mapping the disturbance of initial reservoir state due to heavy oil cold production.

Among many seismic properties which can be analyzed from seismic survey, we researched how cold heavy oil production affect the $V_p/V_s$ ratio, in order to reveal the feasibility of using $V_p/V_s$ ratios to monitor the recovery process of cold heavy oil production.

## METHODOLOGY AND RESULTS

### Fluid substitution: Gassmann's Equation

Gassmann's (1951) equation has been used for calculating the effect of fluid substitution on seismic properties using the matrix properties. It 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:

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

where, $K^*$, $K_d$, $K_m$, $K_f$, and $\phi$ 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 $\mu^*$ of the saturated rock is not affected by fluid saturation, so that:

$$\mu^* = \mu_d , \tag{2}$$

where $\mu_d$ is the frame shear modulus.

The P-wave and S-wave velocities, $V_p$ and $V_s$, for an isotropic, homogeneous, elastic material are given by:

$$V_p = \sqrt{\frac{K^* + 4\mu^* / 3}{\rho^*}} , \tag{3}$$

and

$$V_s = \sqrt{\frac{\mu^*}{\rho^*}} , \tag{4}$$

where $\rho^*$ is the saturated rock bulk density and can be calculated as:

$$\rho^* = \rho_m (1-\phi) + \rho_f \phi , \tag{5}$$

where $\rho_m$ and $\rho_f$ are the densities of solid grains and the fluid mixture at reservoir conditions.

Equations (1) to (5) establish the relationships between the rock moduli and the seismic velocities. There are several assumptions regarding the accuracy of the Gassmann's equation for calculating the seismic velocities in the reservoir type under consideration. One of them is that the pores are filled with a frictionless fluid (liquid, gas, or mixture). This assumption implies that the viscosity of the saturating fluid is zero. This may be the most questionable assumption for heavy oil, especially at cold temperatures (about 20-40 ºC).

Fortunately, Batzle et al. (2006) found that although viscosity is influenced by pressure and gas content, it is primarily a function of oil specific gravity and temperature. Increasing the temperature will decrease a sample's viscosity, both bulk and shear moduli decrease approximately linearly with increasing temperature, and the shear modulus approaches zero at about 80 ºC. Moreover, the frequency also plays an important role for traveling waves propagating in heavy oil. At high frequencies, such as with laboratory ultrasonics, heavy oil sample is still effectively a solid at low temperature (0 ºC), but not for extremely heavy oil, at seismic frequencies. At +20 ºC, the shear modulus of heavy oil is negligible and heavy oil acts still like a liquid, especially after cold production when foamy oil is created due to the dissolved gas from heavy oil, and the mobility of reservoir fluids is much improved. In this case, Gassmann's equation can still help us understand the response of heavy oil reservoir to seismic survey for pre- and post- cold production.

Heavy oil cold production is being carried out in Plover Lake oil field, as described by Lines et al., 2005. The in-situ reservoir parameters from a Plover Lake oil well are listed in Table 1, the reservoir temperature is 27ºC and the specific gravity of heavy oil is API=12.1. From Batzle et al.'s paper (2006), we know that the heavy oil sample with a gravity of API=-5 can go through shear relaxation and acts like a liquid with shear modulus of zero at seismic frequencies by +20ºC. So, for the in-situ heavy oil in Plover Lake with an API=12.1, it should be acceptable to assume that the heavy oil acts like a liquid at seismic frequencies by 27ºC. To test the feasibility of Gassmann's equation, one in-situ well with dipole sonic log data and density log data is selected from Plover Lake oil field to do the calculation. To simplify the calculation, average values of P-wave velocity, S-wave velocity and density for pre-production condition are estimated for the production zone (Table 2).

Table 1. Reservoir parameters for the in-situ well.

| | |
|---|---|
| Heavy-oil API | 12.1 |
| Specific gravity of methane | 0.574 |
| Solution gas-oil ratio ($m^3/m^3$) | 16.64 |
| Reservoir temperature(ºC) | 27 |
| Reservoir pressure(MPa) | 6.4 |
| Water saturation(%) | 25 |
| Oil saturation(%) | 75 |
| Gas saturation(%) | 0 |
| Water salinity(ppm) | 19,280 |

Table 2. Estimated average values of production zone for $V_p$, $V_s$, and $\rho^*$.

| P-wave velocity $V_p$ (km/s) | S-wave velocity $V_s$ (km/s) | Density $\rho^*$ (g/cc) |
|---|---|---|
| 3.02 | 1.55 | 2.13 |

From the reservoir parameters in Table 1, we can calculate fluid properties using the Batzle-Wang formulas (Batzle and Wang, 1992). The physical properties of solid matrix mineral can be examined based on mineral composition, distribution and in-situ conditions (Han and Batzle, 2004). From these solid matrix mineral properties, and porosity from well log data based on equation (5), the unknown parameters $K_d$ and $\mu_d$ can be given in following equations (Mavko and Mukerji, 1998a,b):

$$K_d = K_m\left(1 - \phi / \phi_c\right) , \tag{6}$$

$$\mu_d = \mu_m\left(1 - \phi / \phi_c\right) , \tag{7}$$

where, $\phi_c$ is critical porosity, separating mechanical and acoustic behavior of rocks into two distinct domains: load bearing and suspension. For sandstone, $\phi_c \approx 38\%$. At this time, the saturated moduli can be calculated from equation (1) and (2), and the results are listed in Table 3, together with the calculated saturated moduli from well log data based on equations (3) and (4).

Table 3. Calculated saturated moduli from well log data and Gassmann's equation

| Parameters | Well log | Gassmann's equation |
|---|---|---|
| Saturated bulk modulus $K^*$ (GPa) | 12.60 | 11.61 |
| Saturated shear modulus $\mu^*$ (GPa) | 5.12 | 4.97 |

In reality, we can think that the calculated saturated moduli from well log data are reliable if the quality of well log data is good. From Table 3, we can see that Gassmann's equation gives very good estimations of both saturated bulk modulus and shear modulus. As stated previously, for oil that is not extremely heavy, the shear modulus of heavy oil is negligible and Gassmann's equation is still applicable at seismic frequencies for temperatures of +20ºC.

### Difference of heavy oil physical properties between pre- and post-production

As described previously, heavy oil reservoirs experience a dramatic change as a result of cold production: porosity increases due to sand extraction, pore pressure decreases due to porosity increase, and there is a phase transition of heavy oil to foamy oil due to pore pressure decrease. Table 4 lists a typical comparison of reservoir parameters between pre- and post cold production in Plover Lake oil field. These changes of reservoir parameters, especially the decrease of reservoir pressure from 6.4 MPa for pre-production to 0.6 MPa for post-production, will absolutely change the physical properties of heavy oil in the reservoir. Table 5 shows calculated physical properties of reservoir fluids before and after cold production based on the Batzle-Wang formulas (Batzle and Wang, 1992) and reservoir parameters are taken from Table 4.

Table 4. A typical comparison of reservoir parameters between pre- and post- cold production in Plover Lake oil field.

| Parameters | Pre-production | Post-production |
|---|---|---|
| Heavy-oil API | 12.1 | 12.1 |
| Specific gravity of methane | 0.574 | 0.574 |
| Solution gas-oil ratio ($m^3/m^3$) | 16.64 | 0.9 |
| Reservoir temperature(ºC) | 27 | 27 |
| Reservoir pressure(MPa) | 6.4 | 0.6 |
| Water saturation(%) | 25 | 19 |
| Oil saturation(%) | 75 | 62 |
| Gas saturation(%) | 0 | 19 |
| Water salinity(ppm) | 19,280 | 19,280 |

Table 5. Calculated physical properties of reservoir fluids for pre- and post- cold production.

| Parameters | Pre-production | | | Post-production | | |
|---|---|---|---|---|---|---|
| | Heavy oil | Gas | Water | Heavy oil | Gas | Water |
| Bulk modulus(GPa) | 2.2166 | 0.01 | 2.37 | 0.0636 | 0.0008 | 2.34 |
| Density(g/cc) | 0.97 | 0.048 | 1.01 | 0.97 | 0.004 | 1.0088 |

Compared with the bulk modulus of heavy oil for pre-production (2.2166GPa), the bulk modulus of foamy oil for post-production is just about 0.0636 GPa, which is a dramatic decrease. Such a decrease will cause the reduction of P-wave velocity, and will affect the response of seismic survey. However, regional and lithologic variations in P-wave velocity may be even greater than these anomalies. Hence, observations of P-wave velocity alone may not be sufficient to identify zones of interest. Theoretically and experimentally, the S-wave velocity of a porous rock has been shown to be less sensitive to fluid saturants than P-wave velocity, it can be used as a normalizing quantity with which to compare P-wave velocity, and observations of the ratio of the seismic velocities for P-wave and S-wave which traverse a changing or laterally varying zone could produce an observable anomaly which is independent of the regional variation in P-wave velocity (Tatham and Stoffa, 1976). Moreover, the $V_p/V_s$ ratio is especially sensitive to the pore fluid found in sedimentary rocks. In particular, the $V_p/V_s$ value is much lower

(10-20%) for gas saturation than for liquid saturation, and there is a characteristic drop in $V_p/V_s$ ratio for gas saturated sandstones (Tatham, 1982).

## Effects of heavy oil cold production on the $V_p/V_s$ ratio

As discussed previously, for heavy oil with an API more than 10, the shear modulus of heavy oil is negligible for seismic frequencies at +20ºC, and heavy oil acts still like a liquid, especially after cold production when foamy oil is created due to the dissolved gas from heavy oil, and the mobility of reservoir fluids is improved. In this case, Gassmann's equation can still help us understand the response of heavy oil reservoir to pre- and post-cold production seismic surveys.

Using the patchy model, where $K^*=K_p+K_d$, Murphy et al.(1993) introduced another expression of Gassmann's equation (1) as:

$$\rho V_p^2 = K_p + K_d + \frac{4}{3}\mu^* \ , \tag{8}$$

where $K_p$ is the pore space modulus, other parameters are same as those described previously. If we recall Gassmann's equation (1), $K_p$ can be expressed as (Murphy et al., 1993):

$$K_p = \frac{\alpha^2}{\dfrac{\alpha - \phi}{K_m} + \dfrac{\phi}{K_f}} \ , \tag{9}$$

where α is the compliance of the frame relative to that of the solid grains and is defined as (Murphy et al., 1993):

$$\alpha = 1 - K_d / K_m \ . \tag{10}$$

From equation (6), equation (10) can be written as:

$$\alpha = 1 - (1 - \phi / \phi_c) = \phi / \phi_c \tag{11}$$

To explicitly reveal the dependence of $K_p$ on porosity, equation (9) can be simplified as:

$$K_p \approx \frac{\phi}{\phi_c^2} K_f \ . \tag{12}$$

*(This simplification uses the result shown by Zhang (2007) that the second term in the denominator of equation (9) is much larger than the first term.)*

Equation (12) explicitly reveals the proportional dependence of $K_p$ on porosity and $K_f$. This relationship reveals the fact that the contribution of $K_p$ to $V_p$ is quite significant at high porosities compared with that at low porosities. The contribution of $K_f$ to $V_p$ is the same fact.

By dividing equation (2) into (8), the velocity ratio may be naturally expressed in the terms of the moduli that are introduced above:

$$R^2 = \left(\frac{V_p}{V_s}\right)^2 = \frac{K_p}{\mu^*} + \frac{K_d}{\mu^*} + \frac{4}{3} \tag{13}$$

From equations (2), (6) and (7), we obtain:

$$\frac{K_d}{\mu^*} = \frac{K_m}{\mu_m} \ . \tag{14}$$

To summarize this point, the ratio of the frame moduli $K_d/\mu^*$ is independent of the pore fluid. Finally, from above discussion, $K_p/\mu^*$ represents the pore fluid contribution, which is an important factor at high porosity and is insignificant at low porosity. This is the source that we can use time lapse technology to monitor the recovery process of unconsolidated reservoir.

Utilizing equations (2), (7), (12), (13) and (14), we can further reveal the contributions of $K_f$ and porosity to the $V_p/V_s$ ratio:

$$R^2 = \left(\frac{V_p}{V_s}\right)^2 \approx \frac{K_p}{\mu^*} + \frac{K_m}{\mu_m} + \frac{4}{3} = \frac{K_f \phi}{\mu_m \phi_c (\phi_c - \phi)} + \frac{K_m}{\mu_m} + \frac{4}{3} \tag{15}$$

Equation (15) defines the dependence of $V_p/V_s$ ratio on porosity and fluid saturation. For a completely gas saturated reservoir, $K_f \approx 0$, $K_p/\mu^* \approx 0$ so that equation (15) reduces to:

$$R^2 = \left(\frac{V_p}{V_s}\right)^2 \approx \frac{K_m}{\mu_m} + \frac{4}{3} \ . \tag{16}$$

The $V_p/V_s$ ratio is constant and the smallest compared with other fluid saturations. For partial fluids saturation, $K_f$ and $\phi$ have opposite effects on the $V_p/V_s$ ratio after heavy oil cold production, the smaller value of $K_f$ will decrease the $V_p/V_s$ ratio, and by contrast, larger porosity values will increase the $V_p/V_s$ ratio. Let's examine these two points further. For the Plover Lake oil sands typical values are: $\phi$=0.31, $\phi_c$=0.38, $K_m$=39 GPa, $\mu_m$=27 GPa, and equation (15) becomes:

$$R^2 = 0.432 K_f + 2.778 \tag{17}$$

Figure 1 displays the effect of $K_f$ on the $V_p/V_s$ ratio in this case showing that the $V_p/V_s$ ratio will decrease with the reduction of $K_f$.

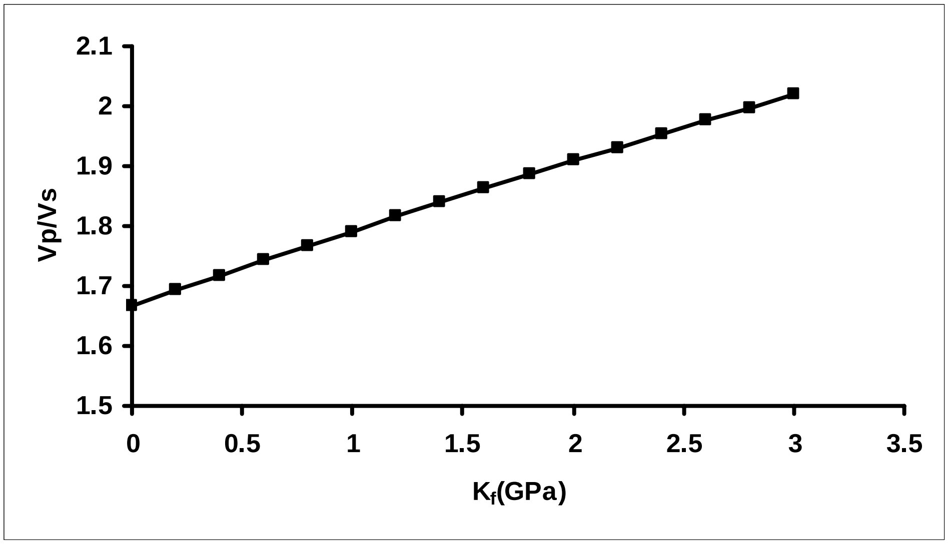


FIG. 1. The effect of Kf on Vp /Vs ratio.

As to the effect of porosity on $V_p/V_s$ ratio, it is a bit more complicated. Murphy et al. (1993) pointed out that $V_p/V_s$ ratio will increase at different rates for different fluids partial saturation. The $V_p/V_s$ ratio remains constant for gas saturated sands, and will increase more for water saturated sands with the increase of porosity. From Table 4 and 5, we can get $K_f \approx 0.244$ GPa based on V-R-H model (Hill, 1952) after heavy oil cold production, and equation (15) is:

$$R^2 = \frac{0.244\phi}{10.26(0.38-\phi)} + 2.778 \ . \qquad (18)$$

Figure 2 shows the result from equation (18). For $\phi<0.30$, $V_p/V_s$ ratio almost keeps constant and has very little increment with the improvement of porosity; but for $\phi>0.30$, $V_p/V_s$ ratio will increase relatively quickly.

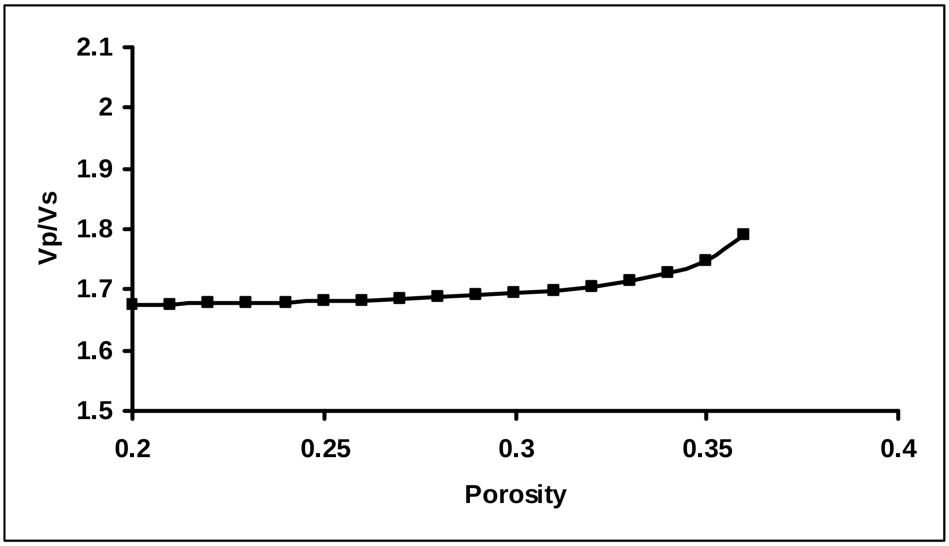


FIG. 2. The effect of porosity on Vp /Vs ratio.

For the in-situ case, let's see how $V_p/V_s$ ratio changes after heavy oil cold production. From Tables 4 and 5, and the V-R-H model (Hill, 1952), we get $K_f \approx 2.254$ GPa for pre-production, then from equation (17), $V_p/V_s \approx 1.937$. For post-production, from previous context, $K_f \approx 0.244$ GPa, which is a dramatic decrease attributed to the creation of foamy oil. Usually, the reservoir porosity will have much less improvement after heavy oil cold production. For example, if the reservoir porosity is increased from 0.31 to 0.32, then from equation (18), $V_p/V_s \approx 1.704$. The reduction of $V_p/V_s$ ratio is about 0.233 due to cold production. This value is for the assumption that fluids are mixed together between patchy and uniform. If fluids are mixed together uniformly, the bulk modulus $K_f$ will be decreased to 0.004 GPa from 2.254 GPa due to cold production resulting in the creation of foamy oil, $V_p$ /$V_s$ ratio will be reduced from 1.937 to 1.667 or about 0.270. So generally, even though porosity has an opposite effect on $V_p$ /$V_s$ ratio, the reduction of the fluids bulk modulus will have a more significant effect on $V_p$ /$V_s$ ratio, and $V_p$ /$V_s$ ratio will decrease after heavy oil cold production.

Figure 3 shows all three $V_p/V_s$ ratios for pre-production, wet and post-production conditions after fluid substitution. The curve in Track 4 is the difference of $V_p/V_s$ ratios between post- and pre-production conditions (Track 3 and 1). There are about 0.2 reduction of $V_p/V_s$ ratio after heavy oil cold production and about 10% reduction shown in Track 5. This figure provides a similar result with that calculated previously.

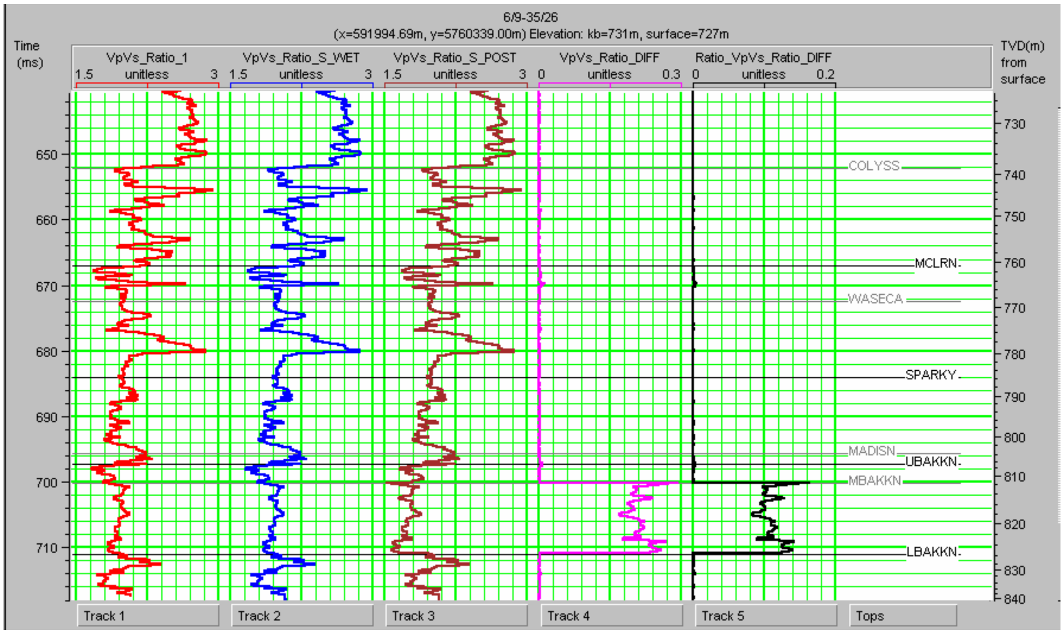


FIG. 3. All three Vp/Vs ratios for pre-production, wet and post-production conditions after fluid substitution and the difference of Vp/Vs ratios between post- and pre-production conditions.

## CONCLUSIONS

The generation of wormholes and the formation of foamy oil from simultaneous extraction of oil and sand during the heavy oil cold production will disturb fluid properties in the reservoir. This disturbance will be detectable by seismic surveys. For heavy oil in the 10-20 API range at ambient temperature of 20 ºC, 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 for pre- and post- 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 $V_p/V_s$ ratio. Due to the dramatic reduction of fluid's bulk modulus after heavy oil cold production, the $V_p/V_s$ ratio will have a detectable reduction, even though the increasing porosity from wormholes slightly increases the $V_p/V_s$ ratio. This significant result should greatly help us to interpret time-lapse multicomponent seismic surveys in cold production fields.

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