Delineating a sand channel reservoir using 3C-3D seismic data: Ross Lake, Saskatchewan

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ABSTRACT

Lithology estimation is an important application of converted-wave data, especially as applied to a sand-shale system. Husky Energy Inc.'s Ross Lake oilfield, located in southwestern Saskatchewan, Canada, is a sand-channel reservoir. Multicomponent 3-D seismic data, a walkaway VSP, and well logs are used to further refine assessment of the reservoir. The far-offset VSP is used to identify the events on a PS seismic section and provide a bridge to correlate PP and PS seismic data. From vertical-source and horizontal-source zero-offset VSPs, the interval V_p/V_s in well 11-25 is calculated. This, in turn, allowed us to estimate an S-velocity log by dividing the P-velocity log by the derived V_p/V_s curve. A resultant PS synthetic seismogram increased our confidence in PS seismic event identification and provided us with a guide to picking PS horizons which correspond to same geological formation as PP horizons. Combining PP and PS time-thickness maps, a V_p/V_s map between horizons surrounding the reservoir suggests a shale-cut or shaly part within the target sand body. This interpretation is supported by horizontal well results. Other anomalies from the V_p/V_s map suggest further drilling targets.

INTRODUCTION

The Ross Lake oilfield, operated by Husky Energy Inc., is located in southwestern Saskatchewan, Canada. The reservoir lies at a depth of about 1150 m and is interpreted as a lower-Cretaceous, incised-valley channel sand in the Dimmock Creek member of the Cantuar formation of the Mannville Group. The sand has high porosity (>30%) and high permeability (3 Darcies). Well 11-25 has over 30 m of sand and about 12–13 m of oil pay without a gas cap.

A 3-D multicomponent VectorSeis® seismic survey was shot by Veritas DGC using 0.5 kg dynamite in May, 2002. In June 2003, a multi-offset VSP survey was conducted by Schlumberger Canada and the CREWES project in well 11-25. The zero-offset VSP used two types of source: a vertical vibrator (as a P-source) with an 8–180 Hz sweep and 5–100 Hz horizontally sweeping mini-vibe (as an S-source). All the offset VSPs used only the vertical source.

ROCK PROPERTIES

The measured shear sonic logs are necessary to interpret the converted-wave data through PS-wave synthetics. Unfortunately, none of the wells within this 3C-3D seismic survey has shear-wave log. For the clastic formations of the Cretaceous and above at fairly shallow depth, the rock properties would primarily follow the empirical relations. To verify this, and to get a localized general trend of V_p/V_s, we used 4 regional wells with measured shear sonic logs to create a crossplot of V_p and V_s (Figure 1). The gamma-ray value shown in colour roughly indicates the lithology. The green dots with V_p ~ 3000 m/s are the channel sands. The red line is a regression of all the points (excluding two grey colour zones) with value of $V_p = 1.416*V_s + 1070$. If we exclude some higher V_p/V_s value points, it will be closer to the mudrock line (pink line). Three constant V_p/V_s lines (1.5, 2.0 and 3.0, respectively, black) are overlain too. The V_p/V_s value ranges from 1.8~3.0 for shallow layers above the reservoir.

Crossplot of P-velocity and S-velocity from 4 regional wells

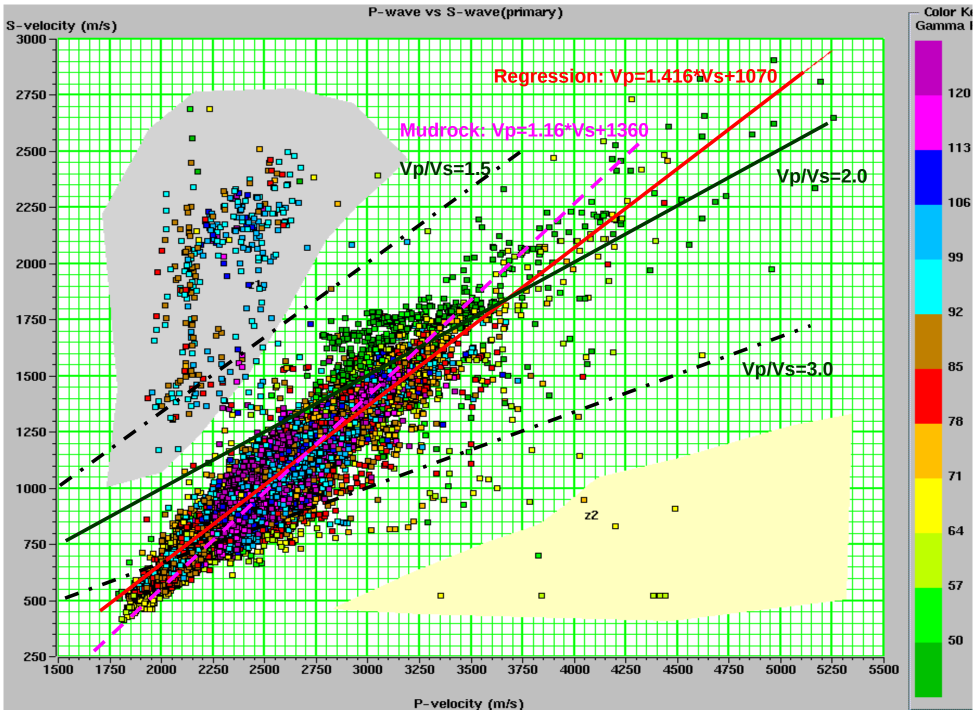

FIG. 1. Crossplot of measured V_p and V_s logs from 4 regional wells.

LOGS AND SYNTHETICS

Due to a lack of shear sonic logs in well 11-25, we used a P- and S-source zero-offset VSP to derive an interval V_p/V_s curve by picking first-break time of all the 130 downhole geophones (7.5 m interval) from PP and SS downgoing wavefields (1-way traveltime). Then, dividing the P-velocity log by VSP-derived V_p/V_s curve, we get the pseudo-V_s log in well 11-25. A 10/15–40/50 Hz Ormsby wavelet is used to generate the PS synthetic seismogram. Figure 2 shows the zoomed-in part of the unstretched, unsqueezed PP (left panel) and PS (right panel) synthetics. In general, they both have good correlation. It is also observed that, around the target zone, the correlation between the PP synthetic and PP seismic trace looks better than the one between PS synthetic with PS seismic trace.

The PP and PS synthetics guided us to picking the same horizons on both PP and PS seismic data, which correspond to the same geological formation.

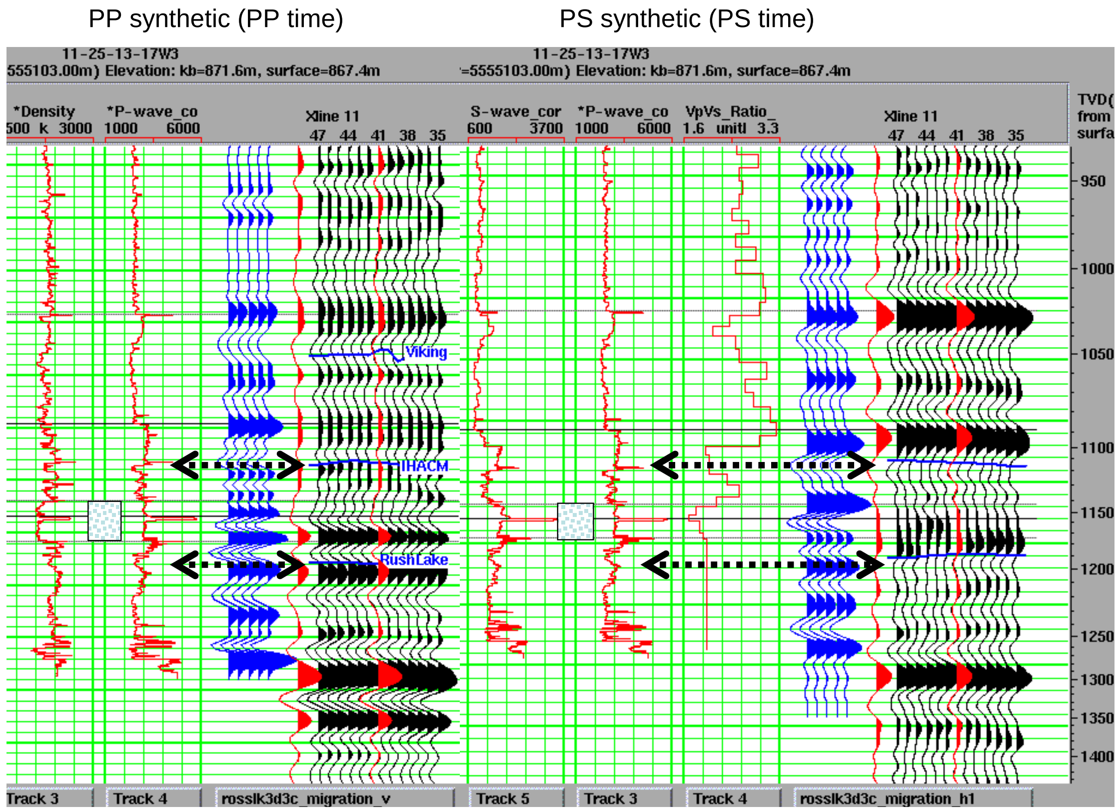

FIG. 2. Logs at well 11-25: PP synthetic and PP seismic; PS synthetic and PS seismic.

3C-3D SEISMIC DATA INTERPRETATION

The poststack Kirchhoff-migrated datasets of vertical- (denoted PP), radial-, and transverse-component are available. The data cover about 7.5 km^2 with N-S Inline range 1-132 and E-W crossline 1-91 in 25-by-25 m CDP bin. Xu and Stewart (2003) compared the frequency bandwidth of these 3 component datasets and observed that: (1) The PP data show an average signal bandwidth of about 8–100 Hz at an 800–1300 ms window; (2) The PS-radial data, in the window of 1000–2000 ms, have a narrower frequency bandwidth of about 10–60 Hz; (3) The PS-transverse data in same window as PS-radial shows an even narrower bandwidth of 10–40 Hz. Only PP- and PS-radial data is interpreted. By default, PS refers to the processed PS-radial component in the following text. The target is at about 1150 ms on the PP section and about 2100 ms on the PS data.

A proposed multicomponent data interpretation work flow is shown in Figure 3. The normal PP data interpretation should always be done first. When interpreting the PS data, the most difficult part is event registration. Measured shear-wave logs and offset VSP would greatly help in identifying the PS events which correspond to the same PP events. After horizons are picked on both PP and PS volumes, PP and PS time-structure maps and time-thickness maps along a certain horizon can be obtained. Finally, we can use PP and PS time-thickness maps to calculate the V_p/V_s map that indicates the horizontal variation of lithology.

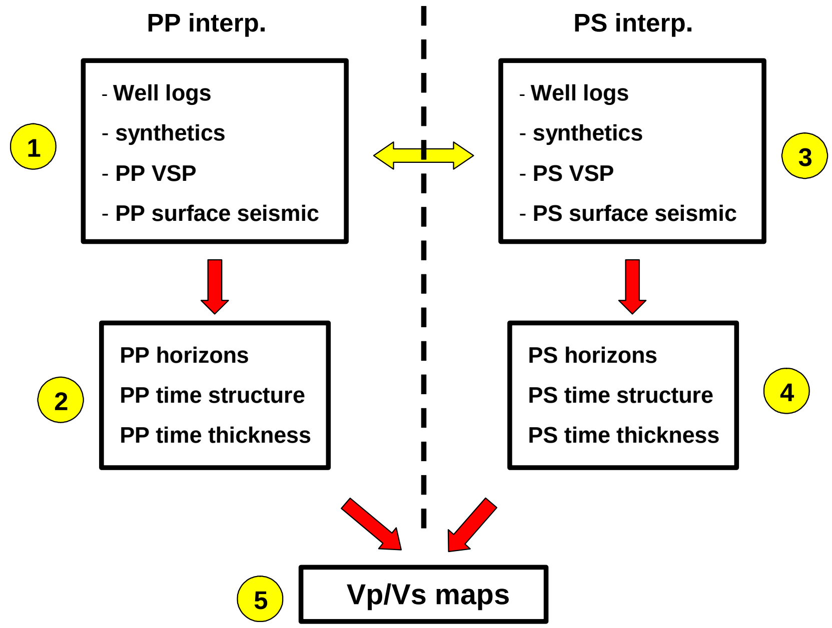

FIG. 3. Multicomponent seismic data interpretation workflow.

PP data interpretation

The PP data were preliminarily interpreted by Xu and Stewart (2003). The PP synthetic seismogram from well 11-25 (E-W crossline 11 and N-S inline 41) and the zero-offset PP corridor stack are used to develop the correlation between geological formations and seismic events. The PP seismic data show very good correlation with the synthetic and zero-offset VSP. The PP time-thickness map between the RushLake horizon and the IHACM (Index Horizon Above Cantuar Marker) shows a clear north-east to south-west bar-shaped anomaly with large time thickness (Figure 4).

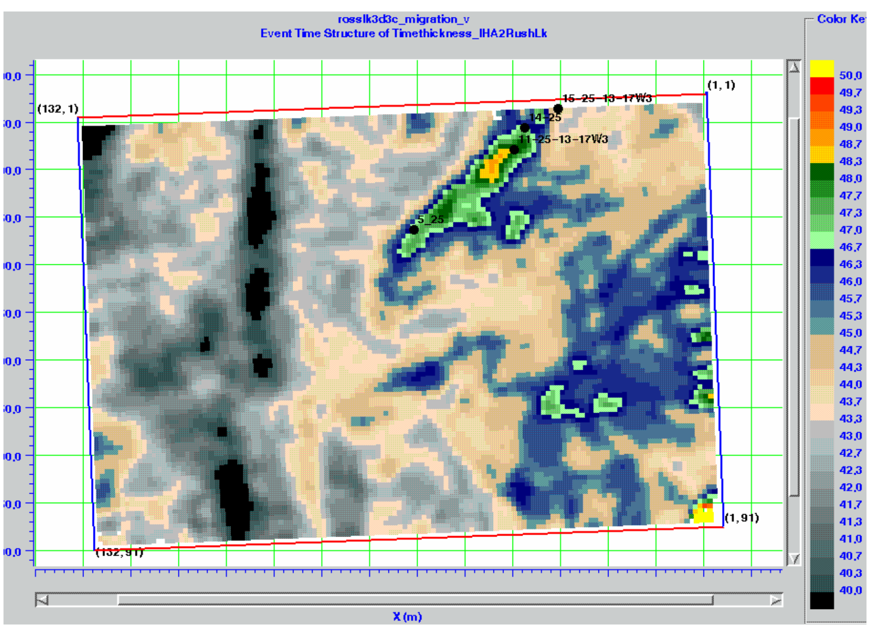

FIG. 4. PP time-thickness map from the 3C-3D seismic survey.

PS data interpretation

To display PS data side-by-side with PP data in same time domain (i.e., PP time domain), an initial estimate of the V_p/V_s value should be given to convert the PS time into PP time. A fixed $V_p/V_s = 2.35$, or a squeezing factor of $(1 + 2.35)/2 = 1.675$ for PS time, is used here, and we get a proximate PS-to-PP data correlation. It is observed that an additional 125-ms time-shift (up) is also needed for the time-compressed PS data. This relationship is confirmed by inserting the 700-m offset VSP's PS-CDP map in-between the PP and PS seismic sections (Figure 5).

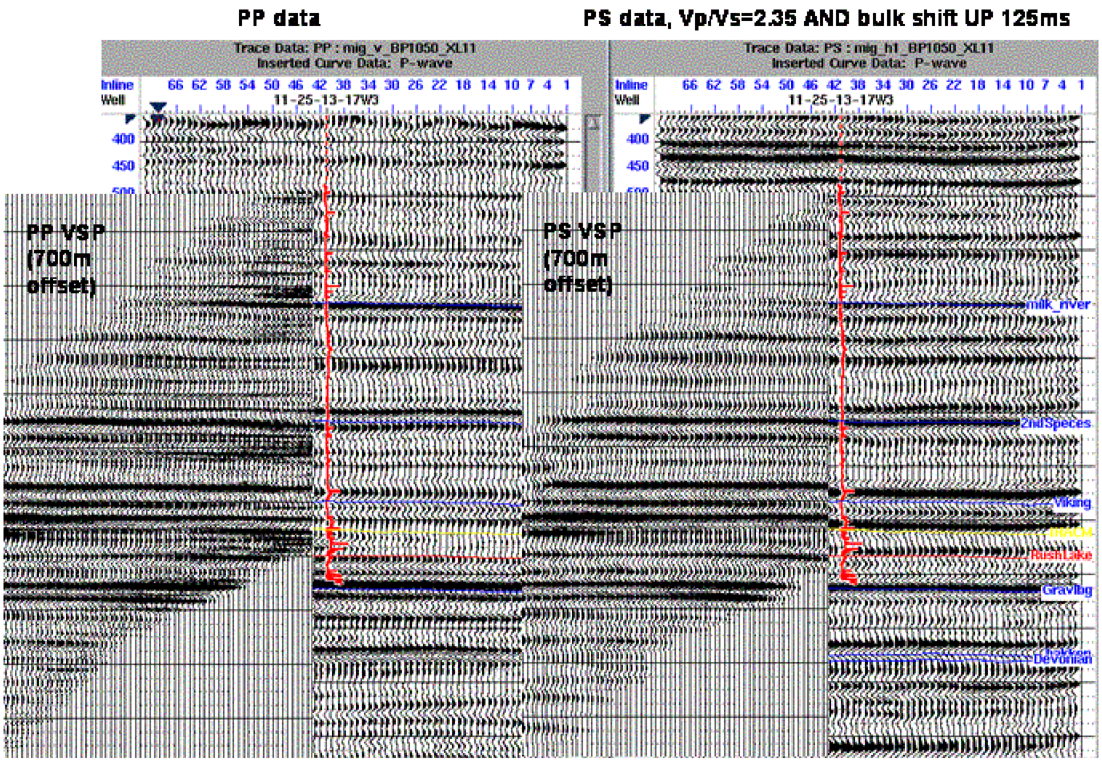

FIG. 5. The correlation between PP seismic, PS seismic, 700-m offset PP-VSP and 700-m offset PS-VSP, all plotted in PP time. Seismic data have a 5/10–50/60 Hz bandpass filter applied.

Guided by PS synthetics at well 11-25 (Figure 2), the PS horizon, the RushLake horizon, and the IHACM are picked (Figure 6). The corresponding PP horizons are converted into PS time by $T_{ps} = (T_{pp} + 125) \times 1.675$ and displayed as red lines for cross-checking the general trend. One observation is that the set of PS horizons show fairly consistent differences when compared with the set of PP horizons on the left of this line, and extend over other E-W lines. This may indicate that the PS-wave data have slightly questionable solutions for refraction or long-wavelength statics.

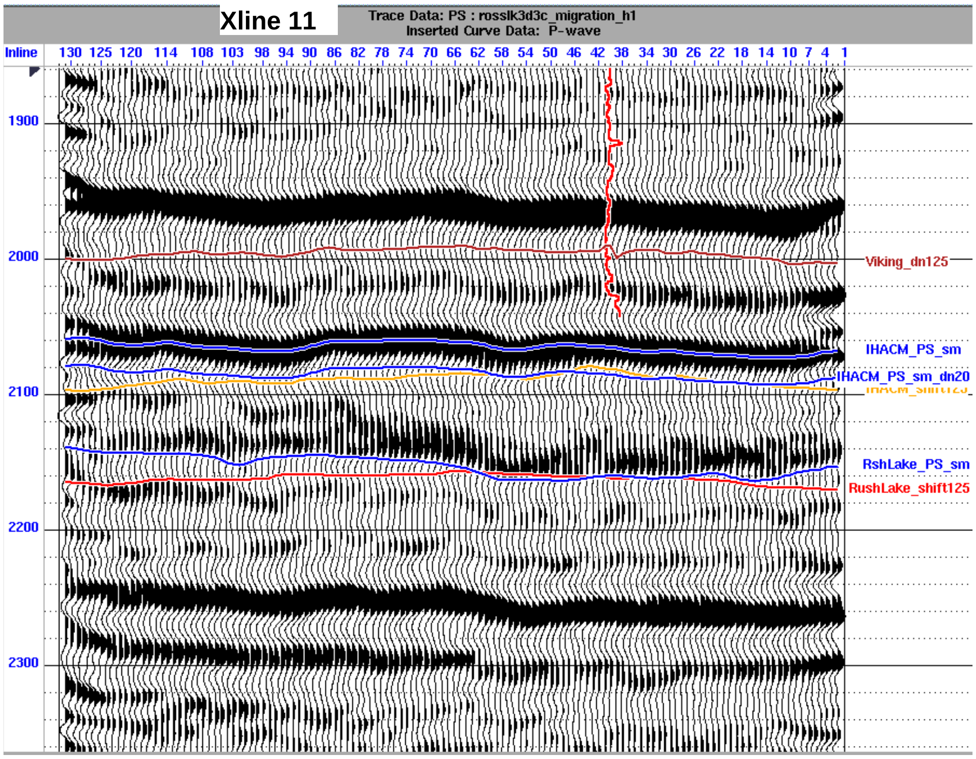

FIG. 6. Horizon pickings on the PS seismic section. Blue lines are picked PS horizons while red lines are same PP horizons shown in PS time, using the constant V_p/V_s=2.35.

As with the PP data, the PS time-thickness map between the IHACM and the RushLake horizon is then calculated (Figure 7). Compared to the PP map (Figure 4), the PS map has a larger time variation — 60–84 ms (40% change) versus 40–50 ms (25% change) — but lower horizontal resolution.

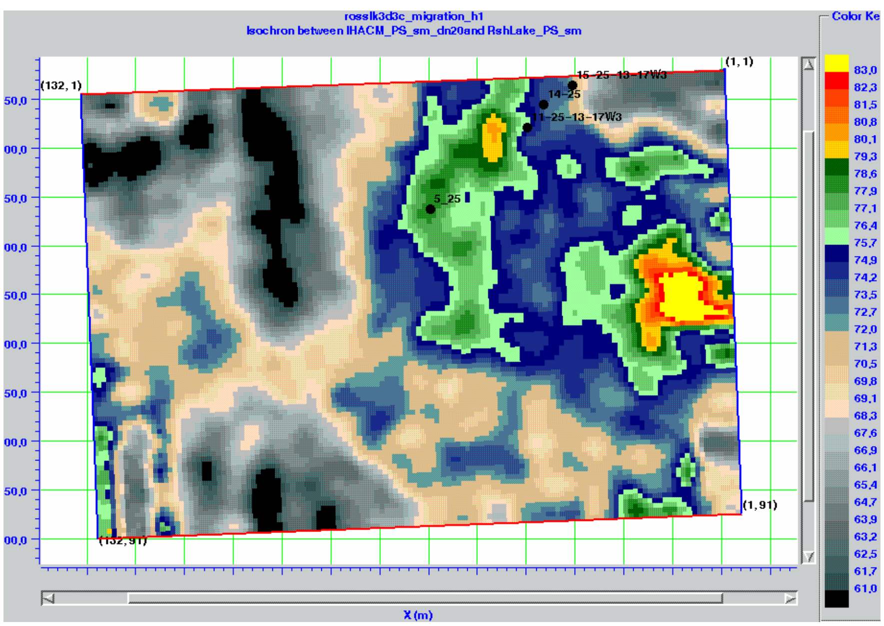

FIG. 7. PS time-thickness map for the IHACM and the RushLake horizon.

V_p/V_s map and lithology interpretation

Given the above, we can use

$$V_p / V_s = \frac{2 \cdot \Delta T_{ps}}{T_{pp}} - 1 \tag{1}$$

to create the apparent average interval V_p/V_s map between the IHACM and the RushLake horizon (Figure 8).

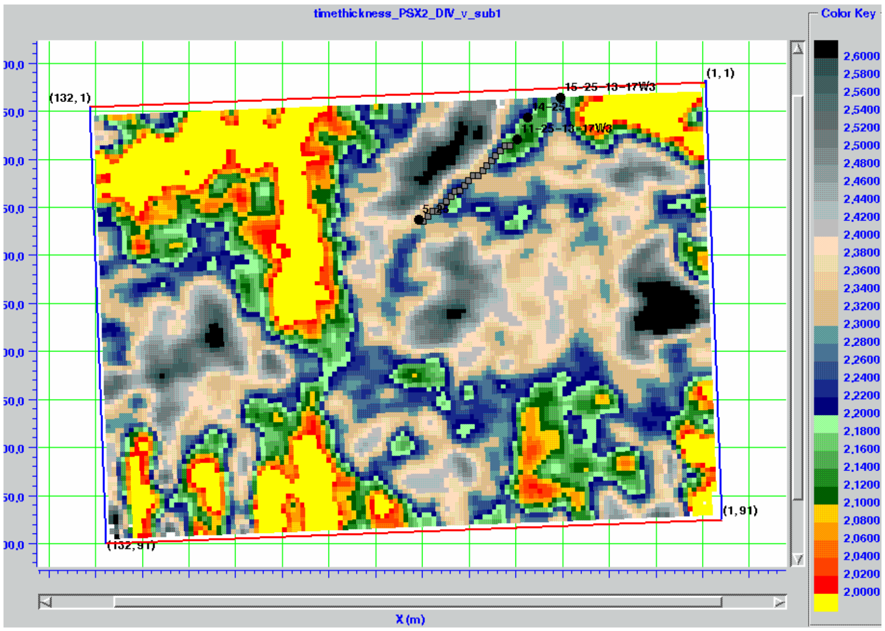

FIG. 8. V_p/V_s map between the IHACM and the RushLake horizon. The yellow and green colours are interpreted as sands while black and grey are interpreted as shale or shaly sands.

The V_p/V_s map has some significant features:

1. Higher resolution than PP or PS time-thickness maps.

2. Very low V_p/V_s values (1.7~2.0, bright yellow colour) forming the north-south trend on the left-hand side of the image, and noticeable in the upper right-hand corner, may indicate thick, dense sands through which the P-wave travels fast. Possibly, they may indicate other incised features not belonging to the Dimmock Creek member.

3. Four dark blocks with high V_p/V_s value (> 2.4) are interpreted to be shale or high shaly.

4. The grey block near the upper right-hand corner seems to be a closure feature. The PP time-thickness anomaly (previously interpreted as the reservoir sand body), with V_p/V_s values about 2.15~2.25, has been divided into two parts by a horizontal stripe with V_p/V_s values about 2.3~2.4 which, prior to having the horizontal well results, we interpreted as a shale cut or shaly-sand.

In summary, for this high-porosity, high-permeability, loose-sand play, saturated with heavy oil, the hydrocarbon accumulation is correlated with: (a) a large PP time-thickness, and (b) mid-range V_p/V_s values of about 2.15~2.25.

Horizontal well result

Based on the conventional P-wave interpretation, Husky drilled a horizontal well, 5-25, on the PP time-thickness anomaly in July 2002. The horizontal section of this well is about 600 m long and drilled completely within the Dimmock Creek formation sand. It cuts across about 19 CDP bins on the seismic map. Figure 9 shows the zoomed V_p/V_s map with the trajectory of the horizontal interval of well 5-25. To find the relationship between the measured (while drilling) Gamma Ray (GR) log and seismic-derived V_p/V_s values, a local normalization is applied to both GR and V_p/V_s. Figure 10 displays the normalized variation of GR and V_p/V_s, with the x-axis as the horizontal section of well 2-25's trajectory, starting from the location of the drill-bit cutting into the Dimmock Creek formation (CDP bin #1, northeast end) and ending at the bottom of the hole (CDP bin #19, southwest end). The V_p/V_s map predicted a shaly interval that was indeed encountered in the well. These two curves show a promising correlation.

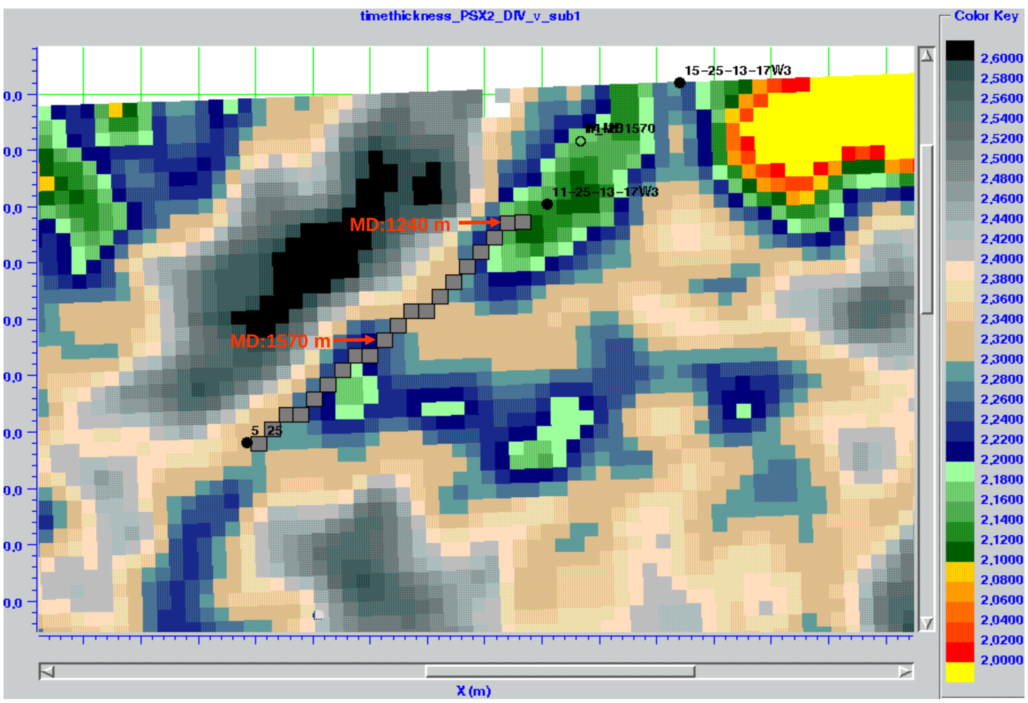

FIG. 9. Zoomed V_p/V_s map with the projection of the horizontal well (grey squares). The top red arrow indicates the starting point of the horizontal borehole.

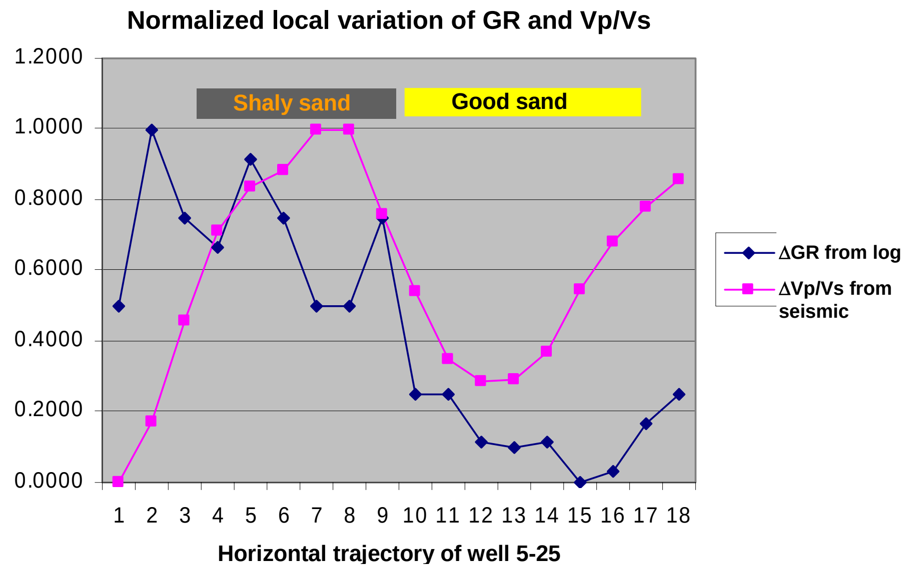

FIG. 10. Plot showing the normalized variation of MWD GR and seismic V_p/V_s along the trajectory of the horizontal section of well 5-25.

CONCLUSION

As expected, the VSP data are a great help to interpreting PP and PS seismic. The zero-offset PP corridor stack has an excellent correlation with PP seismic at the well location. The far-offset PS VSP-CDP map dramatically helps to identify the events on the PS seismic section and is a key component in correlating PP and PS seismic data.

P-source and S-source zero-offset VSPs provide the interval V_p/V_s curve in well 11-25 which, in turn, helps estimating pseudo-shear velocity log. The PS synthetic seismogram increases the confidence of PS seismic-event identification and provides an essential guide to picking PS horizons.

On the PP time-isopach map, the target sand body clearly stands out as a thick anomaly with only a small variation (2~3 ms) within it.

Combining the PP- and PS-horizon time-isopach maps provides a V_p/V_s map between IHACM and the RushLake horizon to give more detailed lithology information. It suggests there is a shale-cut or shaly area within the target sand body. This interpretation is supported by the existing horizontal well. Other anomalies from the V_p/V_s map also suggest further drilling targets.

ACKNOWLEDGEMENTS

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