Design of a horizontal well using 3C-3D seismic data at the Ross Lake, Saskatchewan heavy oilfield

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ABSTRACT

The Ross Lake oil field, operated by Husky Energy Inc. is located in south-western Saskatchewan, Canada. The reservoir is associated with a Cretaceous sand channel in the Dimmock Creek member of the Cantuar formation of Manville group. Four vertical wells and one horizontal well were drilled within the sand body. A 3C-3D seismic survey helped us to design a new horizontal well in the pool. Combining PP and PS time thickness maps for the target horizon, results a Vp/Vs map which suggests thick sandy bodies eastward from the drilled horizontal well. We designed two different wells with different well paths through these bodies. The whole recoverable oil is estimated about 610,000 bbl. A small sand bar in the eastern part of the anomaly is evaluated to be prospective with about 140,000 bbl. Drilling costs may be modest compared to recoverable reserves, thus a 775m horizontal well is recommended.

INTRODUCTION

Geology

The Ross Lake oilfield, operated by Husky Energy Inc, is located in south-western Saskatchewan, Township 13 Range 17 West of 3rd Meridian. The reservoir is at about 1150m depth and interpreted as being associated with a lower-Cretaceous-age incised-valley channel sand in the Dimmock Creek member of the Cantuar formation of Mannville Group with high porosity (>30%) and high permeability (3 Darcies). Four vertical wells, 10-25, 11-25, 14-25, 15-25, and one horizontal well, 5-25, were drilled within the channel sand body. Well 11-25 has over 30 m thick sand and about 12-13 m of oil pay without gas cap. The produced oil is heavy, about 13° API. The pool is on primary production and there is no water flood. The reservoir strategy is not complete yet.

Seismic and VSP acquisition

A 3D multi-component VectorSeis® seismic survey was shot by Veritas DGC using 0.5 kg dynamite in May, 2002. The total survey covers 7.5 km^2 with a 25 m by 25 m bin size. The N-S Inline range is 1-132 and the E-W Crossline is 1-91. Veritas processed this 3C-3D data, and delivered stack and post-stack Kirchhoff migration datasets of vertical, radial and transverse component to the CREWES Project on October, 2003. 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: 8 - 180 Hz sweep vertical-vibe and 5 - 100 Hz sweep horizontal-mini-vibe. All the offset VSPs used only the P-wave source. A Dipole Sonic Log (DSI) was run in the cased well 11-25 in attempt to acquire shear information through casing. However, the logging results were quite poor and largely unusable (Xu and Stewart, 2003).

Interpretation

The post-stack Kirchhoff migrated datasets of vertical, radial and transverse component are available. Only PP and PS1 data are interpreted here. By default, PS refers to the processed PS1 component in the following text. The target is at about 1150 ms on PP section and about 2100 ms on PS data. The sand channel is characterized by a bump on IHACM (abbreviation of Index Horizon Above Cantuar Marker) horizon.

The PP time thickness map between Rush-Lake and IHACM (Fig 1.) shows a clear north-east to south-west bar shape anomaly with large time thickness (Xu and Stewart, 2004). This may be due to the differential compaction of the sand and surrounding sediments. Based on the conventional P-wave interpretation, Husky drilled a horizontal well 5-25 on the PP time thickness anomaly in July 2002. This well has about a 600 m horizontal reach staying within the Dimmock Creek Member sand, and cross about 19 CDP bins on the seismic map.

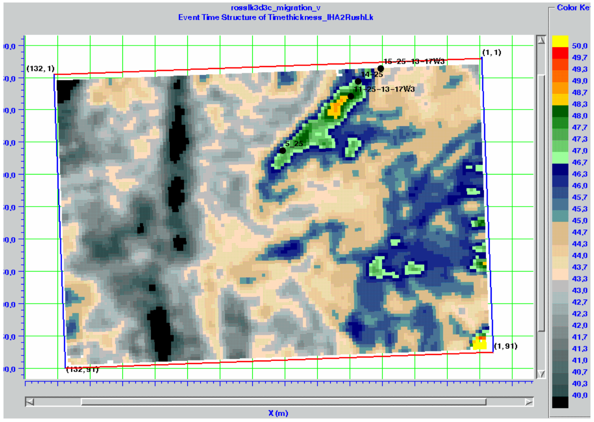

FIG.1. PP time thickness map from the 3C-3D seismic survey.

In the same way as the PP data, the PS time thickness map between the IHACM and Rush-Lake is then calculated (Fig.2). Comparing with PP, the PS time thickness map has larger time variation: 60 – 84 ms (40% change) versus 40 – 50 ms (25% change), but lower horizontal resolution.

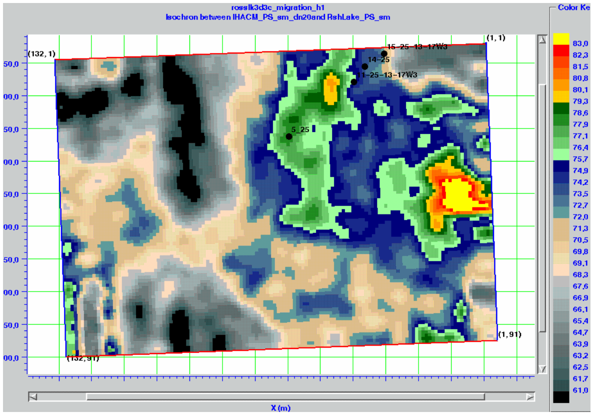

FIG.2. PS time thickness map for the IHACM and Rush-Lake horizons.

Combining the PP and PS horizon time structure maps creates the apparent average interval V_p/V_s map between the IHACM and Rush-Lake horizons. The V_p/V_s shows higher resolution than PP or PS time thickness maps (Fig.3.). Very low V_p/V_s value (1.7 ~ 2.0, bright yellow color) with north-south trend at the left half and upper right corner may be thick, good, tight sands, in which the P-wave travels fast. Possibly, they may be other incised features not belonging to the Dimmock Creek Member. The upper right half grey part seems to be a closure feature. The PP time anomaly (previously interpreted as the reservoir sand body) has split into two parts with V_p/V_s about 2.15 ~ 2.25 by a horizontal stripe with V_p/V_s about 2.3 ~ 2.4, which suggests there is a shale-cut or shaly part within the target sand body. This interpretation is supported by the existing horizontal well.

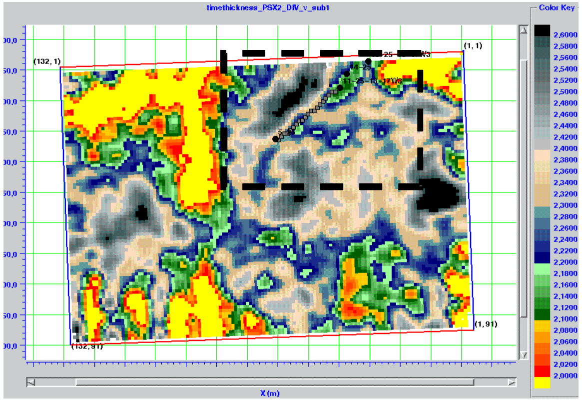

FIG.3. V_p/V_s map between the IHACM and Rush-Lake horizon.

The expanded V_p/V_s map shows another anomaly with V_p/V_s about 2.15 ~ 2.25 which is the target of our new horizontal well (Fig.4). Our goal is to design a horizontal well through this sand body in order to enhance the production in the pool. The rest of the paper covers the designing process and different formulas which help us.

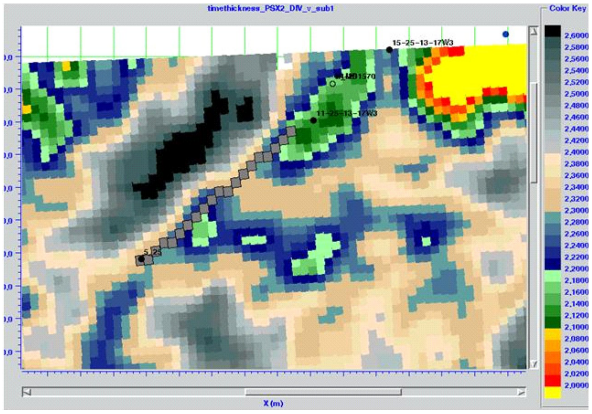

FIG.4. Expanded V_p/V_s map, highlighted with the drilled horizontal well trajectory.

WELL DESIGN

There is a horizontal well in the pool and the drilling information from this well has been used to design the new horizontal well. Figure 5 shows BUR vs. True Vertical Depth (TVD) of the horizontal well. It can be clearly seen that below the Kick Off Point (KOP) at 940m most of the path have been drilled with BUR around 8 deg/30m, while they were approaching the target at 1150m they enhanced the BUR to even about 12 deg/30m in order to hit the target, when they reached the target they decreased the BUR from 10 to 2 or 0 deg/30m very rapidly. This well has about a 600 m long horizontal reach staying within the Dimmock Creek Member sand, and crosses about 19 CDP bins on the seismic map. Figure 5 helps us to estimate the BURs as: Maximum actual BUR=10 deg/30m, Minimum actual BUR=6 deg/30 m and actual BUR=8 deg/30m.

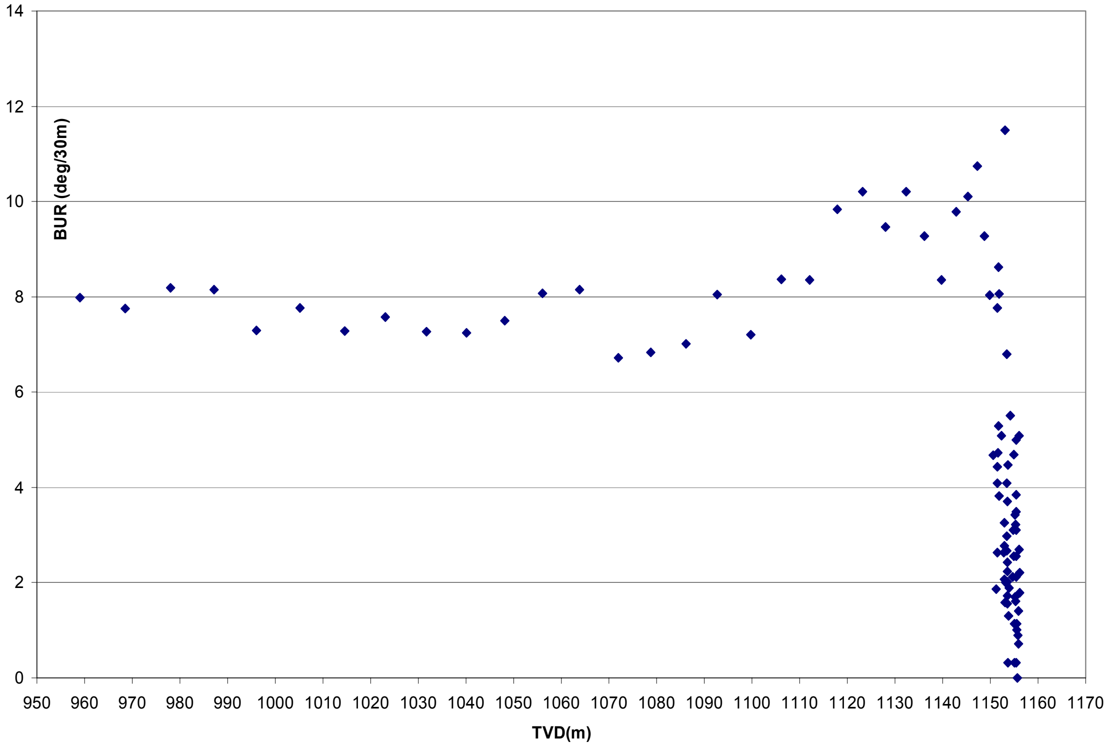

FIG.5. BUR vs. TVD for the horizontal well.

We designed three different horizontal wells with different paths and different surface locations, but with the same BURs. The design BUR must be no greater than the actual BUR for the angle-build motor selected; therefore, we used the actual BUR (8 deg/30m) to design our wells. This BUR is very conservative; that is, we can design the wells with higher BUR like 10 deg/30m then we would get less horizontal displacement but for designing purpose it is better to assume the lower value. Different authors suggested different formulas to design a well; each of them used the same concept, although, final results are equal.

First proposed well

An advantage of selecting a high BUR is the relative change in TVD variation with a given variation in BUR. The BUR will always vary from theoretical design due to formation interaction and drilling conditions. A 1° increase in BUR at 19 deg/30m decreases the TVD by 4.5m; a 1° increase in BUR at 12 deg/30m decreases the TVD by 11m. In this Pool, the BUR is low so the possibility of hitting the target would be much lower; therefore, it is better to design a tangent section in which the variations in BUR can be corrected, while the drilling conditions don't let us increase the BUR. If the actual BUR in the field exceeds the planned rate, the length of the tangent interval is adjusted so that the second build curve reaches the target if it builds at the same rate as the first curve.

Therefore our new well consists of three sections: first build curve, tangent section or slant hole, and second build curve. Appendix A gives the step by step formulas used to calculate the dimensions of first proposed well.

The well starts with a vertical section down to 874m (KOP), and then with 215m curvature it reaches 1070m with 66° as tangent angle. Selecting the appropriate tangent length is important since few tangent drilling assemblies drill at constant angle. However, it is not necessary to drill at constant angle provided one has good idea of the final angle at the bit. The minimum recommended length of tangent interval is 36m based on the typical MWD survey intervals and desirability of minimizing the slant hole. But here we utilize the observed first build curvature to calculate the height of the second build curve and from there the required length of the tangent section and depth of the second kick off point. This decreases the error in hitting the target to the relatively small differences between the actual and planned heights of the second build curve. Therefore, the length of the tangent section estimated 160m with 65m vertical displacement and 146m horizontal displacement. One of the main reasons we proposed this well is that we can adjust the well path using the marker beds. About 8m above the Cantuar formation or approximately 22m above the Dimmock Creek Sandstone is a marker bed called IHACM (abbreviation for Index Horizon Above Cantuar Marker) which can be used to adjust the tangent section; therefore, we place our second Kick Off Point at 1135m which is somewhere near the Cantuar formation TVD. Finally the well hits the target at 1154m at 90° with 87m horizontal displacement and at least 19m vertical displacement. Selection of the horizontal section of the well and its surface location will be discussed in different section.

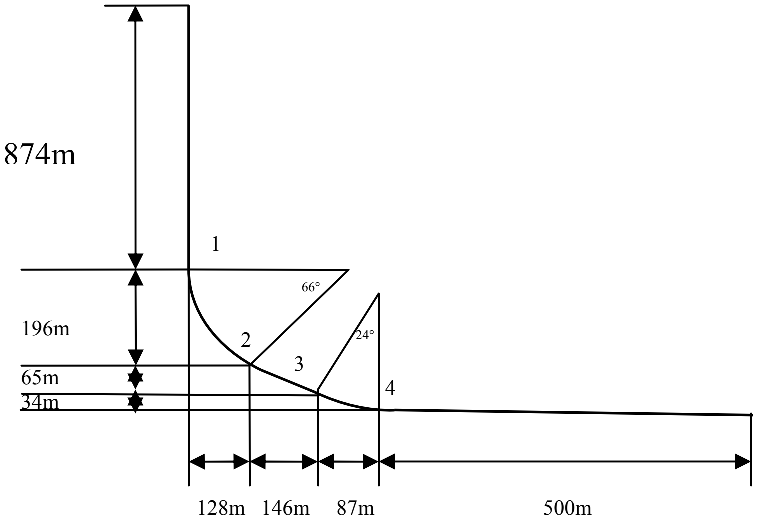

FIG.6. First proposed well using tangent section.

Second proposed well

The horizontal well in the pool has no tangent interval and it was drilled with one build curve to hit the target. Initially, it starts with a vertical section and below KOP at 940m with BUR around 8 deg/30m it approaches the target. With higher BUR the well reaches the pay zone (Dimmock Creek Sandstone) at 1150m depth. As mentioned before the possibility of hitting the target with this kind of design would be lower since unpredictable variations of BUR due to drilling conditions can not be corrected. However, the results of several horizontal wells in the area show little changes in BUR; therefore, single build curve would be reasonable in this pool (Fig.7). Figure 5 shows little variation from actual BUR for the horizontal well in the pool, as an example.

This well kicks off at 940m with a single 215m radius of curvature and hits the target at 1155m with 90ºangle. Both vertical and horizontal displacements are 215m. The well passes IHACM marker bed at about 8m above the Cantaur formation at about 1127m depth. Later we bring the discussion about the horizontal part of this well.

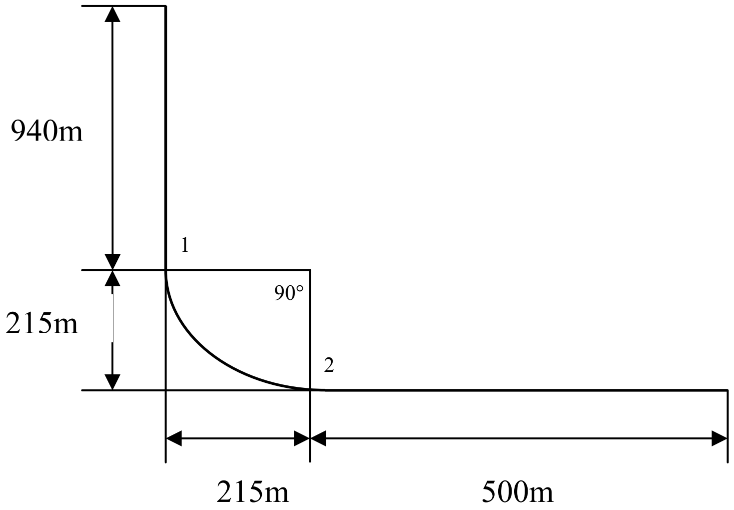

FIG.7. Second proposed well using single build curve.

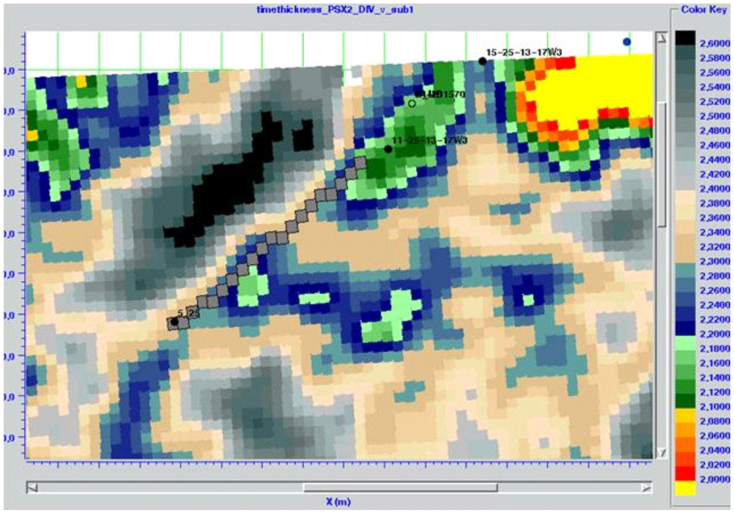

FIG.8. Expanded Vp/Vs map highlighted with the horizontal wells surface locations.

Horizontal hole for the wells

The Vp/Vs map shows the sand channel, in which we designed our new well, expands east to west about 775m on the Crossline 25. The target zone has three sand bars with high thickness in the right side of the actual horizontal well in the pool. There was a discussion whether the horizontal well should pass the sand bar in the eastern part of the target zone or not. Therefore, we have to calculate the oil in place and recoverable oil in this part of the target zone and compare that to the extra drilling cost that is used to drill this part which at first looks a small anomaly. The well logs of the four vertical wells (15-25, 14-25, 11-25, and 10-25) are available and there is only one core analysis in the whole pool, for well 14-25. The well 10-25 is dry. We estimated the oil saturations and pay zone thickness from the logs; however, oil saturation for the well 25-14 doesn't match with its core data. Therefore, we evaluated the total oil in place and recoverable oil with both logs and core results. Original oil in place (OIP) can be obtained from the following equation:

$$OIP = \frac{A_h \cdot h \cdot \phi \cdot S_{oi}}{5.615 \cdot B_o}, \tag{1}$$

Table 2 summarizes the information obtained from well 25-14 core analysis which are assumed to be constant throughout the target sand body. We calculated the OIP for the eastern sand body and for the whole area of target zone. Assuming recovery factor equal to 1/3 and constant $\$_{oil}$ =Can\$55.00 the recoverable oils for the small part of the reservoir and the total sand target estimated about \$6,293,375 and \$26,640,735 respectively.

Table 2. Reservoir estimation using core data

ϕ=34%	OIP=343,273 bbl (Eastern sand bar)
h=42.65ft	R_{oil}=114,425 bbl (Eastern sand bar)
B_o=1.02 RB/STB	R_{oil}=\$6,293,375 (Eastern sand bar)
S_{oi}=41%	
A_h=329,645 ft^2 (Eastern sand bar)	OIP=1,453,130 bbl (Whole target)
A_h=1,379,126 ft^2 (Whole target)	R_{oil}=484,377 bbl (Whole target)
$\$_{oil}$ =Can\$55.00	R_{oil}=\$26,640,735 (Whole target)

In the same way, we estimated the recoverable oil for both the eastern sand bar and the whole target zone as \$9,223,940 and \$40,424,780, respectively. Here we used the information obtained from the well logs available in the pool. The porosity, oil saturation and thickness are averaged values for different part of the sand bars in terms of thickness and are correlated with V_p/V_s values showing different colors on V_p/V_s map. In both cases, core data and well logs, A_h estimated from the V_p/V_s map which roughly shows the sand bars boundaries.

Table 3. Reservoir estimation using well data

ϕ=30% (Thinner part)

ϕ=34.5% (Thicker part)

h=42.65ft (Thinner part)

h=49.21ft (Thicker part)

B_o=1.02 RB/STB

S_{oi}=65%

A_h=329,645 ft^2 (Eastern sand bar)

A_h=1,379,126 ft^2 (Whole target)

$\$_{oil}$ =Can\$55.00

OIP=503,122bbl (Eastern sand bar)

R_{oil}=167,708bbl (Eastern sand bar)

R_{oil}=\$9,223,940 (Eastern sand bar)

OIP=2,204,988 bbl (Whole target)

R_{oil}=734,996 bbl (Whole target)

R_{oil}=\$40,424,780 (Whole target)

Figure 9 shows that, in order to drill the whole sand bars we need a well with approximately maximum 775m horizontal section passes about 30 bins on the seismic map. Assuming average Rate of Penetration (ROP) of 10m/hour in the field with all mechanical problems gives us at least drilling 200m/day. Also, assuming the total cost for drilling a well in southern Saskatchewan as \$66,200/day gives us the total cost to drill the well in the pool. Tables 4 and 5 summarize the total costs for drilling the pool for our two different proposed wells with different lengths.

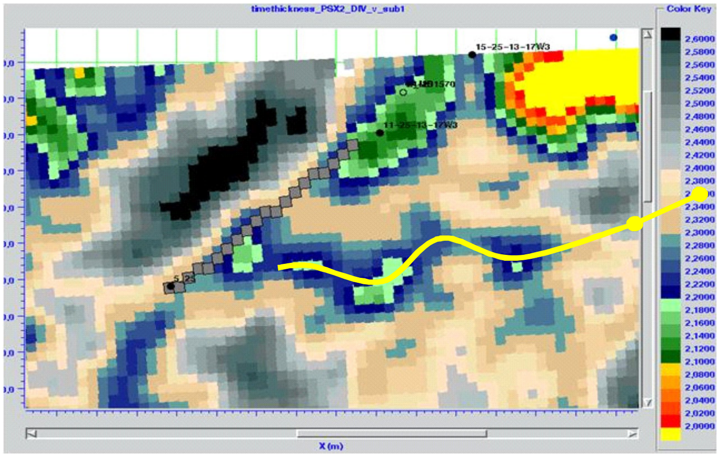

FIG.9. Expanded V_p/V_s map highlighted with the new horizontal wells surface locations and path.

Table 4. Costs for the first proposed well

Drainage area	Measured depth (m)	Days needed (day)	Total cost ($)
Total area	1371+775=2,146m	11	728,200
Without the eastern sand bar	1371+550=1,921m	10	662,000

Table 5. Costs for the second proposed well

Target	Measured depth (m)	Days needed (day)	Total cost ($)
Total area	1278+775=2,053m	10	679,543
Without the eastern sand bar	1278+550=1,828m	9	605,068

To access the recoverable oil for the small sand channel in the eastern part of the pool, we would need an extra day extra drilling (200m more) and total cost of about $70,000; as a result, we recommend that, the surface location of the well has to be located much further in the east to drill and drain the whole sand bars.

The mechanical limits for horizontal section have to be considered. The primarily limits are related to torque and drag. In a given hole, the maximum horizontal length is reached or perhaps exceeded when we can no longer rotate the pipe or sufficiently load the drillstring to drill. To reach the maximum length, we need to reduce the torque and drag forces. Since buckling and gravity forces dominate the torque and drag effects in the horizontal part, the best design is to select the lightest possible drillstring. Table 6 shows the record horizontal lengths as a function of hole size and BUR. Although we do not know how close these record lengths are to the limits, certainly the limit is not less than these lengths. We assume these values to be the minimum lengths for the horizontal part, since new developments in horizontal technology allow drillers to drill horizontal holes up to 4500m for 6in. diameter medium radius horizontal wells or up to 2500m for 8-1/2in. diameter medium radius horizontal wells.

Table 6. Record Horizontal well lengths

Type 	Size in.	Radius m	Length m
Short	4-3/4 6	9 11	130 270
Medium	4-1/2 6 8-1/2	90 90 120-240	400 670 1020
Long	8-1/2 12-1/4	300-760 700	1220 2000

Considering our well as medium type with 215m radius, shows that the horizontal lengths of maximum 775m for both proposed wells are much lower than the record limits (Table 1). Therefore it is assuring that there should be no mechanical problems with the horizontal sections of both suggested wells to drain the whole sand channels.

Comparison

About 8m above the Cantuar formation or approximately 22m above the Dimmock Creek Sandstone is the IHACM marker bed which can be used to adjust the tangent section in the first proposed well, since the length and inclination of this section is site specific. It is assuring that about 8m below the marker bed at 1135 we would place our second Kick Off Point which is somewhere near the Cantuar formation TVD. Therefore one of the advantages of the first proposed well is to use the IHACM as the marker bed. Additionally, as mentioned before, in case the actual BUR in the field exceeds the planned rate, the length of the tangent interval is adjusted so that the second build curve reaches the target if it builds at the same rate as the first curve.

On the other hand, this well has about 160m tangent section with 66º inclination which has 65m vertical displacement through 146m horizontal displacement. The first well has more total measured depth compare to the second well which increases the drilling cost to about $50,000 more.

Generally, placing the tangent interval at angles greater than 45º increases the length of the hole and displacement of the end of the curve; moreover, it makes the length and displacement sensitive to the actual curvatures in the first and second curves. These considerations make tangent angles above 60º unacceptable. Therefore drilling, the sand channel with single curve would be more reasonable.

ACKNOWLEDGMENTS

We would like to thank Tingge Wang from iCenter at University of Calgary who handled all the software requirements. Indeed, his help was indispensable. Larry Mewhort and Angela Ricci provided all the horizontal well data at Ross Lake. Finally, we greatly appreciate the consultations with Bob Sanregret and Dushan Putnik from Precision Drilling.

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APPENDIX A

Calculations of the first proposed well

<u>Assumptions</u>

Expected angle build (BUR_{Exp}), 8 deg/30m.

Maximum expected angle build (BUR_{Max}), 10 deg/30m.

Minimum expected angle build (BUR_{Min}), 6 deg/30m

$I =$ Well inclination (deg).

Initial angle, $I_i = 0°$.

Target angle, $I_f = 90°$ at 1154m TVD.

Tangent length, L_2.

True vertical depth at target base, $T_b = 1160m$.

$MD =$ Measured depth (m).

$T =$ True Vertical Depth (m).

$T_{kop} =$ True vertical depth at Kick Off Point (m).

$D =$ Horizontal displacement (m).

Solution

We use the minimum expected BUR to calculate the Kick Off Point (KOP) as the formula suggests.

$$T_{kop} = T_b - \frac{1719}{BUR_{Min}} \cdot (\sin I_f - \sin I_i) = \quad 1160 - \frac{1719}{6} \cdot (\sin 90 - \sin 0)$$

$$T_{kop} = 874m = T_1 = MD_1$$

Optimum tangent angle,

$$I_{\tan} = \sin^{-1}[\sin I_f - \frac{BUR_{\max} \cdot BUR_{\min} \cdot (T_b - T_t)}{1719 \cdot (BUR_{\max} - BUR_{\min})}]$$

$$I_{\tan} == \sin^{-1}[\sin 90 - \frac{10 \cdot 6 \cdot (1160 - 1150)}{1719 \cdot (10 - 6)}] = 66^{\circ}$$

The corresponding TVD (T_{tgt}) within the zone is then calculated,

$$T_{tgt} = T_t + 1719 \cdot (\frac{1}{BUR_{Exp}} - \frac{1}{BUR_{Max}}) \cdot (\sin I_f - \sin I_{\tan})$$

$$T_{tgt} = 1150 + 1719 \cdot (\frac{1}{8} - \frac{1}{10}) \cdot (\sin 90 - \sin 66) = 1154\,\mathrm{m}$$

We use the actual expected BUR to design the first and second build curves.

Radius of curvatures, $R_1 = R_2 = \frac{1719}{BUR_{Exp}} = \frac{1719}{8} = 215\,\mathrm{m}$

First curve,

$$T_2 = T_1 + R_1 \cdot (\sin I_2 - \sin I_i) = 874 + 215 \cdot (\sin 66 - \sin 0) = 1070\,\mathrm{m}$$

$$MD_2 = MD_1 + R_1 \cdot (\frac{\pi}{180}) \cdot (I_2 - I_i) = 874 + 215 \cdot (\frac{\pi}{180}) \cdot (66 - 0) = 1121\,\mathrm{m}$$

$$D_2 = D_1 + R_1 \cdot (\cos I_i - \cos I_2) = 0 + 215 \cdot (\cos 0 - \cos 66) = 128\,\mathrm{m}$$

Tangent section,

With the reverse calculation the tangent length estimated about 160m.

$$T_3 = T_2 + L_2 \cdot \cos I_{\tan} = 1070 + 160 \cdot \cos 66 = 1135\,\mathrm{m}$$

$$T_3 = T_{kop} = 1135\,\mathrm{m}$$

$$MD_3 = MD_2 + L_2 = 1121 + 160 = 1281\,\mathrm{m}$$

$$D_3 = D_2 + L_2 \cdot \sin I_{\tan} = 128 + 160 \cdot \sin 66 = 274\,\mathrm{m}$$

Second curve,

$$T_4 = T_3 + R_2 \cdot (\sin I_f - \sin I_{\tan}) = 1135 + 215 \cdot (\sin 90 - \sin 66) = 1154\,\mathrm{m}$$

$$MD_4 = MD_3 + R_1 \cdot (\frac{\pi}{180}) \cdot (I_f - I_{\tan}) = 1281 + 215 \cdot (\frac{\pi}{180}) \cdot (90 - 66) = 1371\,\mathrm{m}$$

$$D_4 = D_3 + R_2 \cdot (\cos I_{\tan} - \cos I_f) = 274 + 215 \cdot (\cos 66 - \cos 90) = 361\,\mathrm{m}$$

Calculations of the second proposed well

Assumptions

Expected build rates (BUR), 8 to 10 deg/30m.

$I =$ Well inclination (deg).

Initial angle, $I_i = 0\,^{\mathrm{o}}$.

Target angle, $I_f = 90^{\mathrm{o}}$ at 1155m TVD

True vertical depth at target base, $T_b = 1155m$.

$MD =$ Measured depth (m).

$T =$ True Vertical Depth (m).

$T_{kop} =$ True vertical depth at Kick Off Point (m).

$D =$ Horizontal displacement (m).

Solution

Same as the first suggested well we use the expected BUR (8 deg/30m) to design the build curve, but first the Kick Off Point:

$$T_{kop} = T_b - \frac{1719}{BUR_{Exp}} \cdot (\sin I_f - \sin I_i) = 1155 - \frac{1719}{8} \cdot (\sin 90 - \sin 0)$$

$$T_{kop} = 940m = T_1 = MD_1$$

Radius of curvature, $R = \frac{1719}{BUR_{Exp}} = \frac{1719}{8} = 215 \text{ m}$

$$T_2 = T_1 + R_1 \cdot (\sin I_2 - \sin I_i) = 940 + 215 \cdot (\sin 90 - \sin 0) = 1155 \text{ m}$$

$$MD_2 = MD_1 + R_1 \cdot (\frac{\pi}{180}) \cdot (I_2 - I_i) = 940 + 215 \cdot (\frac{\pi}{180}) \cdot (90 - 0) = 1278 \text{ m}$$

$$D_2 = D_1 + R_1 \cdot (\cos I_i - \cos I_2) = 0 + 215 \cdot (\cos 0 - \cos 90) = 215 \text{ m}$$