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PS Geological Challenges in the Development of a Colombian Waterflood Using Horizontal Wells*

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Abstract

La Cira Infantas Field is a mature field undergoing waterflood to increase the reservoir pressure and oil recovery factor. In 2013 and 2014, horizontal wells were proposed to develop the C zone (Mugrosa Formation) in the lower part of the structure, where the thickness of the pay zone is reduced due to its proximity to the oil/water contact. The geological complexity, which includes lateral variations due to the fluvial environment, azimuth variations, a high formation dip of nearly 35°, a thin target zone, and low resistivity contrast between sandstones and mudstones, proved to be a big challenge during the planning and drilling of these horizontal wells.

The planning stage involved: (1) building a geological sector model of structural and stratigraphic complexity, (2) designing a directional well plan with negative section due to surface platform restrictions, (3) adjusting the horizontal section of the plan to fit the model, and (4) prejob simulations using offset wells properties to define the appropriate steering method.

To ensure the horizontal wells landed in the narrow target zone, azimuth was carefully maintained with respect to the plan, and a complex correlation was developed that required the inclusion of additional formation tops. Running deep directional resistivity logs with density images plus gamma ray at the bit was crucial to steering these horizontal wells. Additionally, the structural model had to be adjusted in real time to follow the strike of the beds.

The horizontal wells were steered through 8-15 ft TVD of net pay thickness for distances of 2,500 to 2,800 ft, resulting in a productivity index 3-5 times greater than a vertical well in the same sandstone.

Introduction

Since 2005, Occidental Andina and Ecopetrol have been redeveloping the La Cira Infantas Field, the oldest oilfield in Colombia, as a waterflood to increase the reservoir pressure and oil recovery factor. As part of this redevelopment, 766 producers and 438 injectors have been drilled, resulting in a significant increase in the oil production profile. La Cira Infantas Field is a mature field with high potential in the lowest part of the structure, although the pay zone is thinner there due to its proximity to the oil/water contact; therefore, it is necessary to implement technologies to optimize the oil extraction process and make it economically viable.

Drilling horizontal wells emerged as a good alternative to drain oil in thin pay zones where vertical wells are not economically attractive. Horizontal wells could increase the drainage area, productivity index, and recovery factor. The preliminary assessment was that one horizontal well could recover the equivalent reserves of three vertical wells.

The selected area to implement horizontal drilling technology in La Cira Infantas Field had a significant oil volume potential according to the analytical volumetric calculations. In addition, the sand bodies selected have good quality rock, and a water injection process was in its initial phase. However, the high structural complexity and the stratigraphic heterogeneity due to the fluvial depositional environment were the biggest challenges for horizontal well placement.

To achieve the project objective and work cooperatively with the service company, a detailed geological sector model was created using electrical well logs, but not the seismic data volume, due to the low resolution, in order to represent the structure and rock properties in the target zone. Also, a model prediction was done using offset wells data to see the potential response of two techniques, Laterolog images and deep directional resistivity tool, which would be used to steer the horizontal wells. Based on these models, the appropriate technology was selected to land and navigate horizontal wells.

Geological Settings

La Cira Infantas Field is located in the central section of Middle Magdalena Valley Basin (MMVB) about 250 km north of Bogotá, near to Barrancabermeja, Colombia, South America. The MMVB is an intermontane basin tilted toward the east with a homocline tendency, affected by some folds and faults (Perez and Valencia, 1977), along the Magdalena River valley between the Central and Eastern Andean Cordilleras in Colombia (Figure 1).

The La Cira and Infantas anticlines are located in the Cachira paleohigh, a structurally controlled topographic high, which was active between the late Cretaceous and late Eocene (Olaya, 1997). The La Cira Anticline is an asymmetric fold that plunges N-S parallel to the La Cira Fault, a high-angle reverse fault with east-vergence and N-S azimuth. The Infantas fold, the principal structural feature in the La Cira Infantas Oil Field, is a narrow and elongated antiform whose axis also trends N-S. The crest line is broken by the Infantas fault system, causing the uplift and partial erosion of the east flank. The Infantas fault system is comprised of a set of low-angle, west-vergent reverse faults that generally strike from north to south to N30°E (Gutierrez, 2001).

The La Cira and Infantas anticlines are compartmentalized by many normal faults into an assemblage of reservoir blocks. The normal faults show oblique and longitudinal patterns when seen in plan view. The longitudinal faults are high-angle normal faults striking E-W with variable north or south vergence. The oblique faults are high-angle normal faults with variable strike and dip orientation. In general, these faults strike between 0° and 30° on either side of dominant E-W azimuth of the longitudinal set (Gutierrez, 2001).

La Cira Infantas reservoir is constituted by the Colorado Formation (Zone A), Mugrosa Formation (Zones B and C) and Esmeraldas Formation (Zone D). The C sands are the main target of the development program in La Cira Infantas Field.

The Mugrosa Formation is a predominantly muddy unit (Caballero, 2010), consisting of gray to grayish-green fine- to medium-grained sandstones, with interbedded bluish-gray mudstones and some conglomeratic beds in the lower part. The middle part consists of blue and brown massive mottled mudstones with interbeds of fine sandstone. The upper part consists of grey fine- to coarse-grained sandstones, sometimes pebbly (Dickey, 1992). The top contains fossiliferous mudstones. This Formation corresponds to a depositional environment of meandering rivers, with a marked lateral migration channels, middle sinuosity, with presence of alternating bars, and repetitive presence of crevasse splay and crevasse channel, where the development of paleosols is little, but the floodplain deposits are strong (Fonseca et al., 2009).

The C zone in the study area (Infantas South) contains gray to greenish-gray sandstones, medium-to fine- grained, semi consolidated, moderate sorting, with interbedded greenish-gray siltstone and claystone beds, and reddish, brown and reddish-yellow paleosols. The average thickness of the C zone in Infantas South is about 750 ft. The Upper C zone contains deposits of meandering channel, which consist predominantly of cut-and-fill macroforms composed of amalgamated through cross-bedded to massive sandstones (Ramon and Cross, 1997), creating interconnected channel sandstone belts. In the Lower C zone (in contrast with Upper C zone), the proportion of floodplain increases and the channel and crevasse splay amalgamated sandstones are thinner and separated by thick, laterally continuous mudstone packages.

The sandstones are classified compositionally according to Folk (1974), as feldspathic litharenite that varies from subarkose to sublitharenite. Primary porosity is intergranular, between 6% and 22%, caused by dissolution processes affecting matrix sectors, lithic and feldspar, especially plagioclase feldspars, followed by others with less impact. Absolute permeability ranges from 50 mD to 4 D. Occasional intragranular microcracks interconnects the remaining pores, increasing permeability.

Planning Stage Geological Challenges

The study area selected for the proposed horizontal wells is located on the west flank of the Infantas Anticline, in the low structural part of Infantas South (see left of Figure 3). The horizontal wells were proposed for the Lower C zone, which has a good oil potential and an immature water injection process, unlike the Upper C in this area, which has a high water saturation.

After identifying the best operational units, detailed chronostratigraphics correlations were generated in the offset wells. The correlations showed stratigraphic variations in geometry, architecture, and continuity of facies, which were related to the cannibalization, amalgamation, and preservation of the original macroforms deposited. Due to the depositional environment features, it was possible to define three laterally continuous channel belts, but no single channels. Two sandstone bodies were identified for the first well and only one sandstone body was

identified for the second horizontal well (see Figure 2). The thickness of the target sandstones varied from 6 ft to 18 ft, accordingly it had a thickness average of 12 ft to 15 ft to maneuver the drill bit through the beds during geosteering.

A geological sector model (Figure 3) was constructed from electrical log interpretations of wells in the area to represent the structural setting and rock properties. This model was used to estimate the oil volume that will be contacted by the horizontal wells and to generate a synthetic log of the petrophysical properties expected along the horizontal wells path. The seismic volume was not used as input to build the geological model, because the resolution was too low to follow thin individual channel belts. Also, this sector is affected by the Infantas fault system, so the velocity model is not reliable.

The formation dip angle in the flank of this particular area averages 35° and the dip azimuth is 260°, with variations in the dip and the azimuth of 5° and 7°, respectively, along the path of the horizontal wells. The area has little folds generating local changes in dip angle and azimuth on the beds (Figure 3).

Because of the steeply dipping beds, this reservoir has a limited lateral distance between the top and the base of the target sandstone. Therefore, the horizontal wells would steer parallel to the azimuth of the stratum, and it would be necessary to maintain strict control of the distance between base, top, left, and right. Changes in bed azimuth as little as 1 ft represent approximately 0.7 ft of vertical displacement, so trajectory must be controlled by inclination, because is not possible do large or rapid azimuth changes.

The directional plans design was limited by the very short horizontal distance between the only available surface platforms and the landing point. This resulted in a well plan with a negative section. The planned horizontal section utilized many control points to adjust the plan to the model as much as possible to follow the azimuth of the beds. The path of the first horizontal well was S-N and the path of the second horizontal well was N-S (see left side of Figure 3). To optimize the drawdown of the horizontal well, it was necessary design a tangent of 180 ft to place the electrical submersible pump 80 ft TVD closer to the entry point. This would represent a high degree of uncertainty during drilling due to the possibility of encountering formation tops above the prognosis depth.

During the simulation, two techniques were selected - the deep directional resistivity tool (PeriScope), and MicroScope for dip picking purposes. The simulation model utilized offset wells logs data, and similar to the geological model, included both structural and properties data to create a properties model, which is shown in a cross-section in Figure 4. This properties model allowed us to predict the forward distance to layer boundaries, identifying the conductive and resistive zones. In this way, the horizontal well can be steered maintaining its track in the sandstone.

According to the results of this simulation, the PeriScope was better than the MicroScope dip picking technique for offset sensor distances (Figure 4). However, a very little resistivity contrast was found between sandstones and mudstones. The PeriScope tool had a range of response around 5 ft TVD in the first well and 2-3 ft TVD for the second horizontal well. Some offset wells showed low properties, and the base will be identified using measurements of low depth of investigation. The azimuthal component of both well trajectories will help to identify dip angle and verify it from the geological model.

As part of engineering assessment, the pressures throughout the reservoir zone were analyzed, using pressure points taken while drilling offset wells. Also, the connectivity between injectors and producers was improved to ensure good performance of the waterflooding process in the target area.

Geological Challenges in Well Placement Execution

Landing Section

The main objective was to keep the azimuth constant (with respect to the plan) to avoid changes in the observed thickness of the layers and lose the sand target. The horizontal wells were drilled with LWD so we could correlate them with the offset wells, using the unit tops to adjust the horizontal wells. This required the inclusion of additional tops to ensure the wells were landed in the narrow target zone.

During construction of the tangent of the first horizontal well, the readings showed the well differed from the directional plan by 15-18 ft toward the high part of the structure. According to the geometry of the beds, this alteration in the horizontal well azimuth resulted in the formation tops being encountered 15-30 ft TVD shallower than the geological model predicted, which accelerated landing. In order to land in the target sandstone at the appropriate inclination, it would be necessary to increase dog leg severity up to nearly 6° before reaching the landing point. Using the gamma-ray and resistivity log correlations in the offset wells, the well was landed successfully at the base of the first sandstone with 84.3° inclination (Figure 5).

For the second horizontal well, drilled 100 ft below the first one, after the second stratigraphic marker, the formation tops were encountered 13-24 ft TVD below the geological model. For this case, the tangent was longer than in the first horizontal well to try to maintain the 80 ft distance in TVD from the tangent to the planned entry point. Correlating carefully the last 50 ft TVD in the second horizontal well, the main target sandstone was found to be amalgamated in the upper part, but the well did not have the suitable inclination to land there without creating a high dog leg right at the landing point; so finally, the well was landed with 87.7° inclination at the top of the target sandstone, as identified by correlation (Figure 6).

Horizontal Section

Accurate horizontal well placement in such a geologically complex scenario is difficult to achieve using conventional geostering techniques. The geosteering decisions were made based on the interpretation of real-time measurements of azimuthal gamma ray, resistivity, azimuthal response of PeriScope curves (Phase and Attenuation), and neutron-density. Also, inclination at the bit was monitored carefully to respond properly to the changes observed while geosteering. The geosteering model had to be updated rapidly in real time based on the responses of the complete set of logs in order to steer the wells along the strike of the target beds.

The first horizontal well, which was drilled S-N, was done in two stages, according to the tendencies of the channel belts and the properties of the first target. The first stage was drilled inside the upper sandstone for a total of 1,023 ft MD and 15 ft TVD. The second stage was steered in the second target (HD_2). The horizontal well crossed the interbedded mudstone for about 190 ft MD between both targets.

During the first part of this well, due to the low resistivity contrast, the PeriScope was nor very helpful; however, geosteering was done based on correlations and the inversion from PeriScope on eXpandGST. During the middle part, the contrast increased and PeriScope performance was much better. During the last part of the well, the resistivity contrast was again poor (Figure 7).

In the second part of the well, after geosteering 390 ft MD and 8 ft TVD inside the HD_2 sandstone, very poor quality in the petrophysical properties was observed. With the intention of finding a quick way back to the upper sandstone, we continued drilling until the bit reached an inclination of 93° with a constant azimuth of 353°. During this operation, the well crossed a sandstone package for about 60 ft MD, and the remainder, was just mudstone.

The second horizontal well, which was steered N-S, represented a challenge from the beginning, because after landing and casing operations, the inclination was 2.5° below the projected inclination for the landing. Additionally, the formation had a tendency to turn this well to the left 8-9 ft, which means toward the base of the target sandstone.

For a short section at the beginning and in the middle part of the horizontal section, the resistivity contrast was good and the inversion of the PeriScope allowed successfully navigated (Figure 8). However, at around 2,000 ft MD in the horizontal section, the resistivity contrast was really poor and the PeriScope was not helpful. The azimuthal gamma ray close to the bit (6.5 ft) was used to continue drilling the well, but it was not used until the middle of this section. In addition, some little folds were encountered that affected the geometry of the horizontal trajectory.

The initial concept when we began drilling this horizontal well, was to keep the azimuth with respect to the plan. Due to the data obtained while drilling the well, small modifications were made to the azimuth and inclination within short intervals for the purpose of moving quickly and finding the best properties along the trajectory. This well shows better properties inside a thickness around 4 ft TST (5 ft TVD).

Results

Openhole logs, gamma ray, resistivity and neutron density, were run in the horizontal wells and used to generate the petrophysical interpretations. Vclay, porosity, saturation, and permeability properties were estimated from the interpretation of these logs using the petrophysical model of the C zone in the La Cira Infantas field. Figure 9 shows raw data and interpreted data in both horizontal wells.

The first horizontal well had a total length of 2,835 ft in the horizontal section, contacting 802 ft of net pay with an average porosity of 14%, average permeability of 530 mD and average water saturation of 33%. The second horizontal well had 2,591 ft, of horizontal section, contacting 463 ft of net pay with an average porosity of 17%, average permeability of 1,128 mD, and average water saturation of 20.6%.

The productivity index estimated for the horizontal wells was around 3-5 BFPD/psi for a thickness of 14-18 ft TVD of horizontal section with a maximum length of 2,600 ft. In contrast, a vertical well (or a deviated well) in a regular injection pattern with 120 to 180 ft TVD perforated is estimated to have a productivity index between 0.5 and 1.5 BFPD/psi.

The horizontal wells drilled in the low part of the structure close to the oil/water contact, which steered through 8-15 ft TVD of net pay thickness and 2,500 to 2,800 ft of horizontal length represented the initial production and reserves of three vertical wells, as planned.

Conclusions

Despite the structural and stratigraphic complexity in the zone and the operational difficulties that happened concerning the planned entry point, the landing was done successfully based on both the geological correlation with the offset wells and the cross-section from the eXpandGST.

The formation geometry represented a big challenge, as did the thickness of the target units (less than 15 ft) while drilling the horizontal wells. To stay in the zone, it was essential to maintain the azimuth close to the plan; however, to move quickly once inside the beds, variations in the trajectory azimuth were made, but these were too aggressive for the first well and more conservative in the second well to maintain the trajectory inside the target bed. The important thing is to be aware of the implications of these azimuthal changes in a highly complex structural configuration.

During geosteering, more variations than expected were observed in both the structure and the stratigraphy. Localized changes in the azimuth of the beds and folds were found and these required modification of the geometry of the horizontal section. In addition to the high stratigraphic heterogeneity, characteristic of this fluvial environment, zones with very poor quality rocks were found. This complicated the navigation in some sections of the horizontal wells.

Despite the low resistivity contrast between the sandstones and mudstones of the Mugrosa Formation and the resulting low usefulness of the PeriScope in some parts of the horizontal section, these wells were successfully geosteered using the azimuthal gamma ray tool placed close to the bit (6.5 ft), enabling us to react as quickly as possible and effectively address all unexpected formation conditions that showed up during the horizontal drilling.

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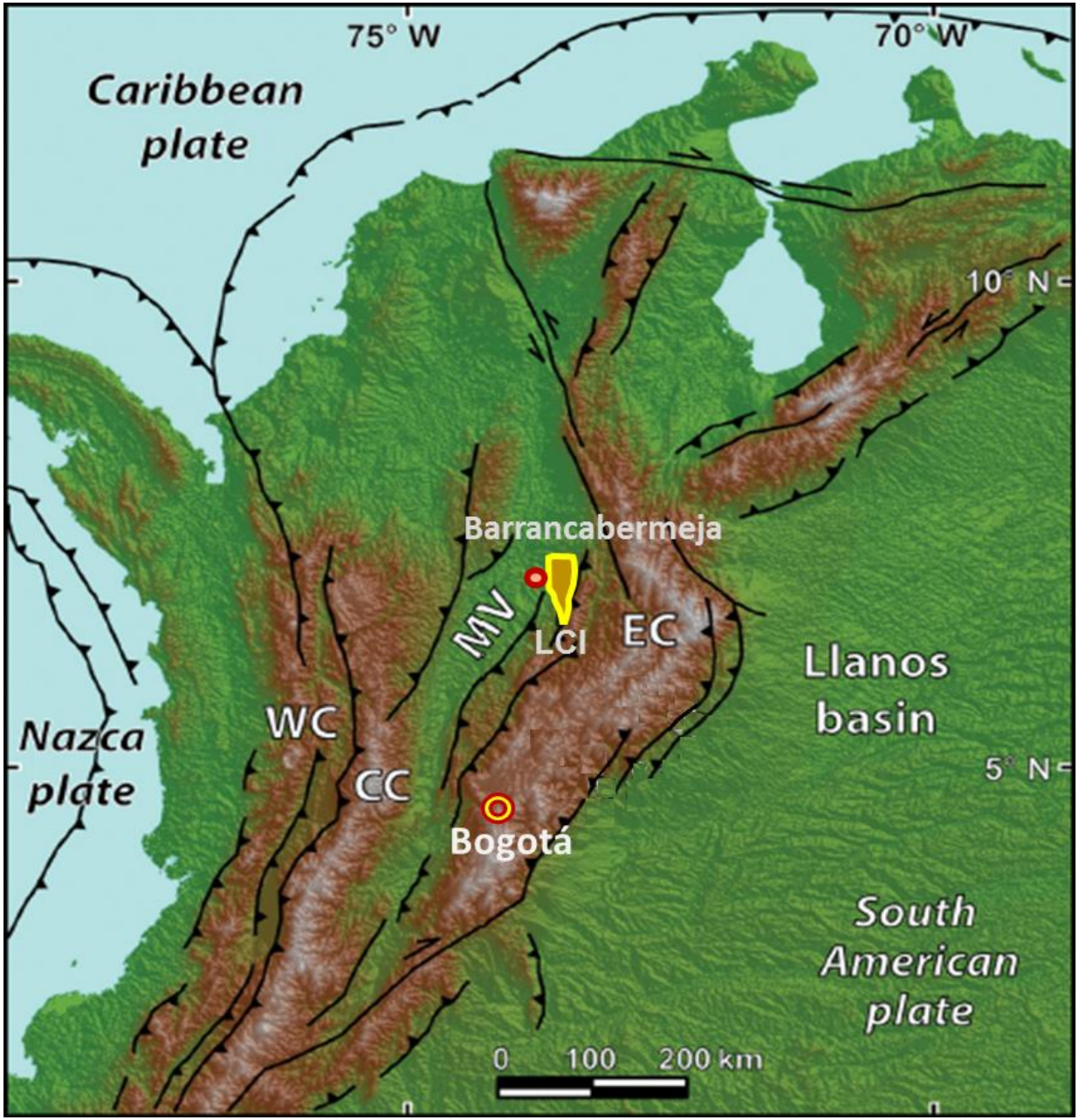

Figure 1. La Cira Infantas Field location map (adapted from Horton et al., 2010). CC - Central Cordillera; EC - Eastern Cordillera; MV - Magdalena Valley; WC - Western Cordillera; LCI - La Cira Infantas.

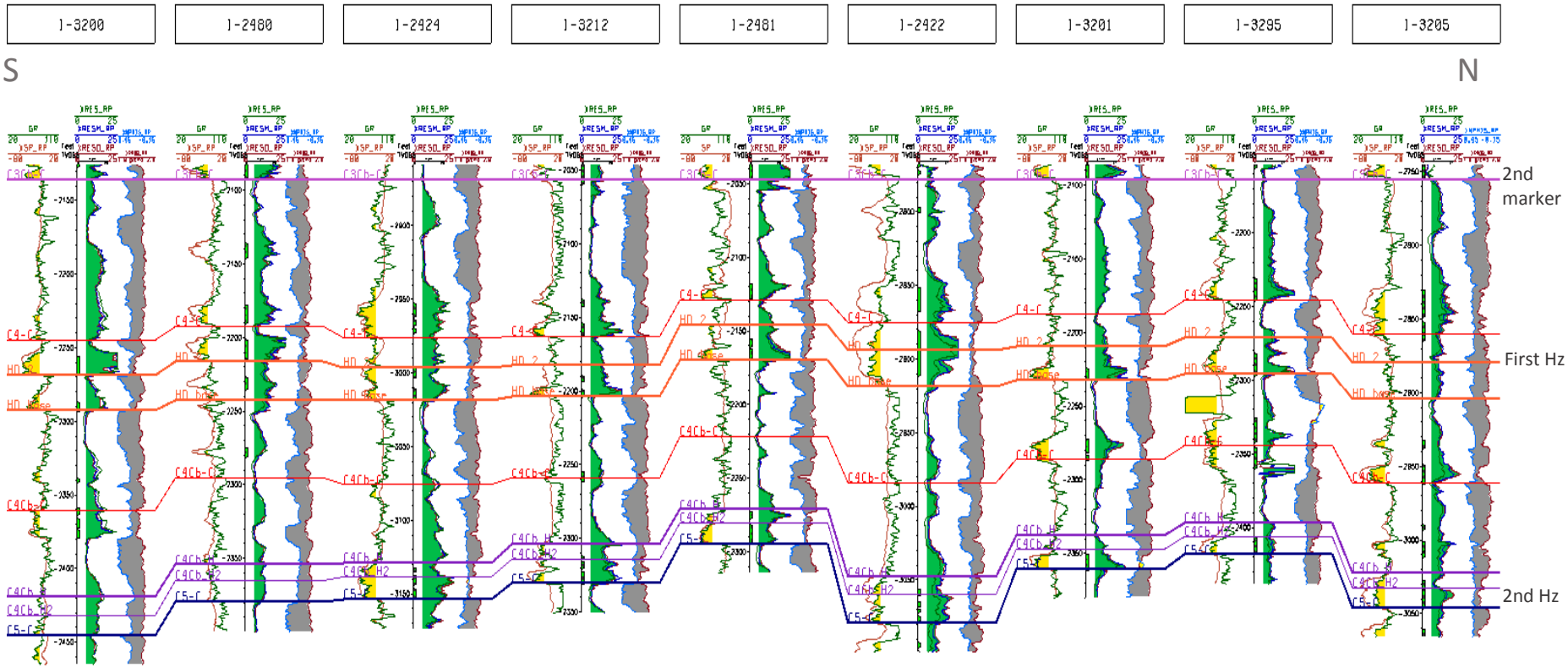

Figure 2. Stratigraphic correlation (TVDSS) using offset wells showing the target sandstones for each horizontal well.

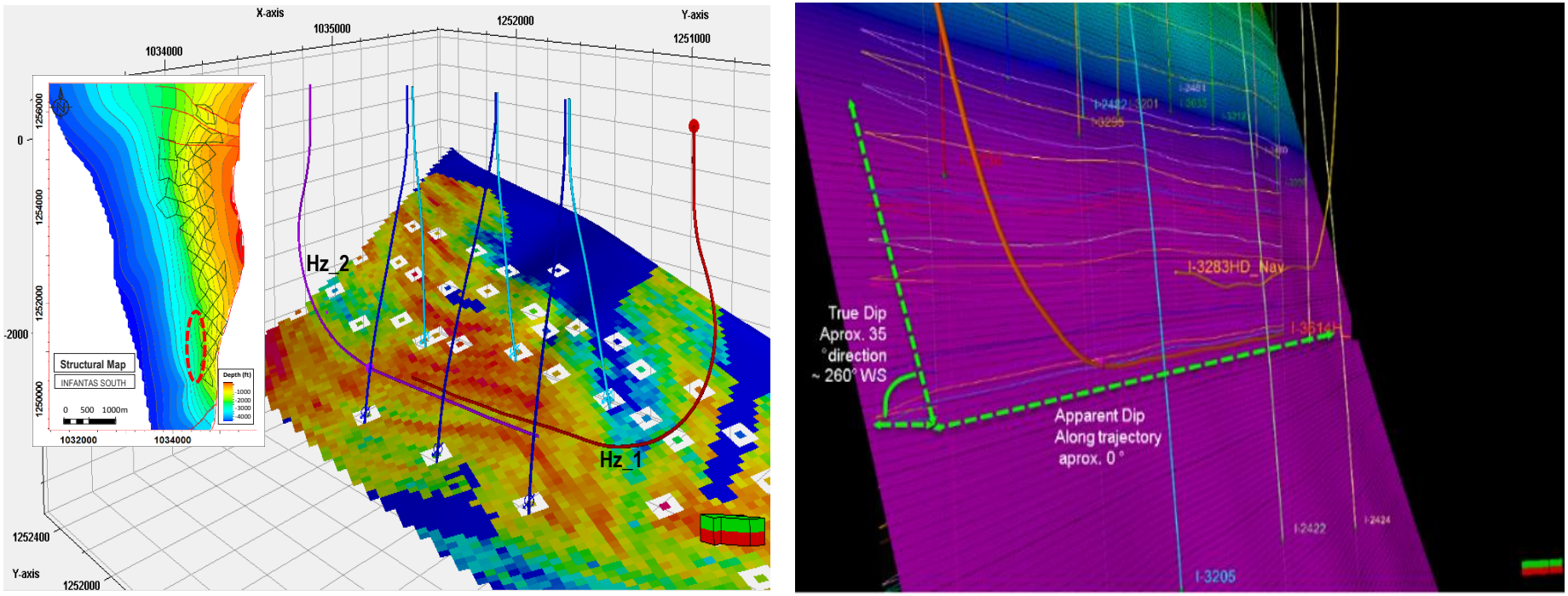

Figure 3. Left: 3D geological model, permeability property. Right: 3D view of layer structural modeling for the second horizontal well, in the N-S direction.

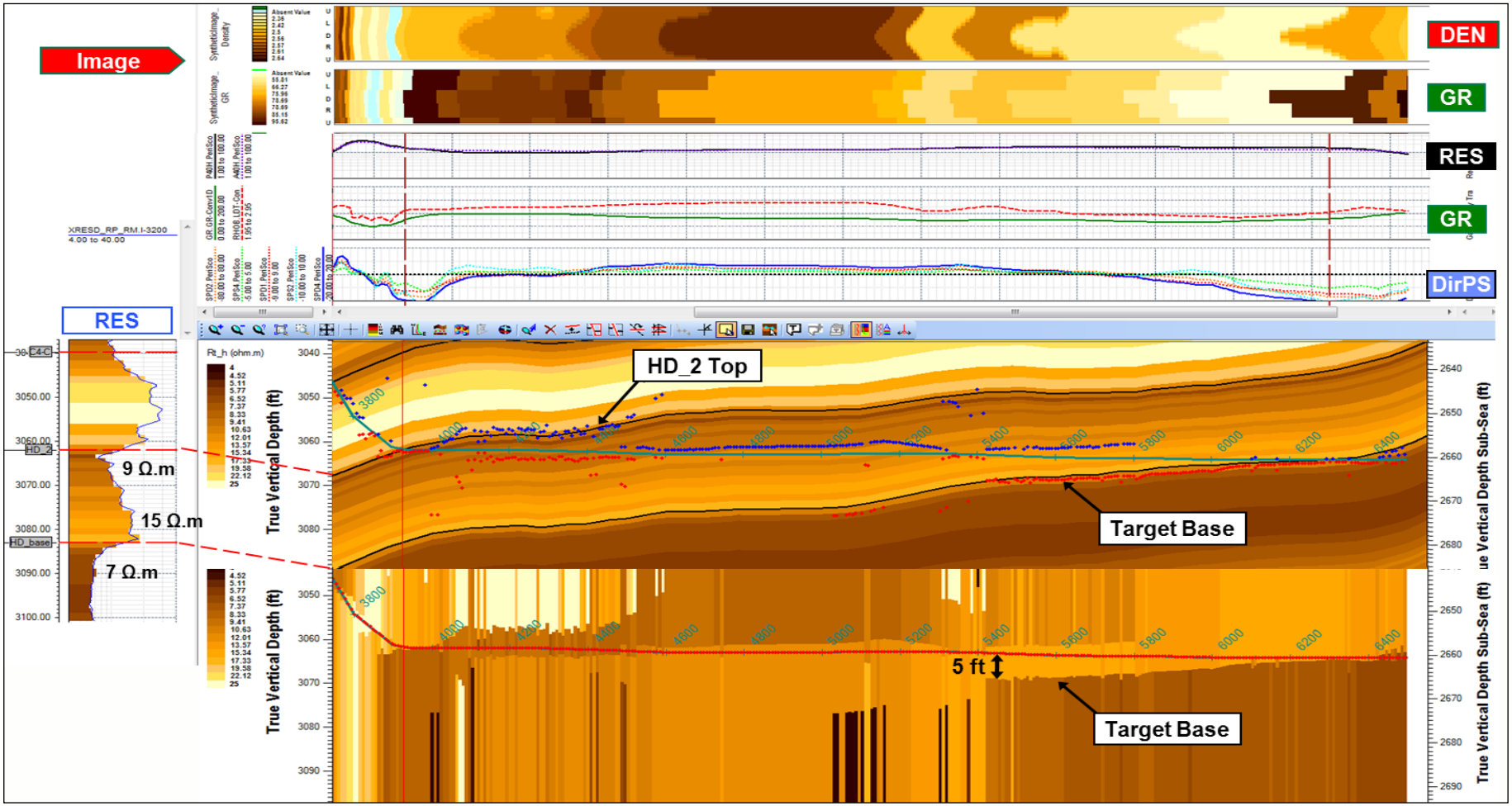

Figure 4. Simulation response using properties from offset well.

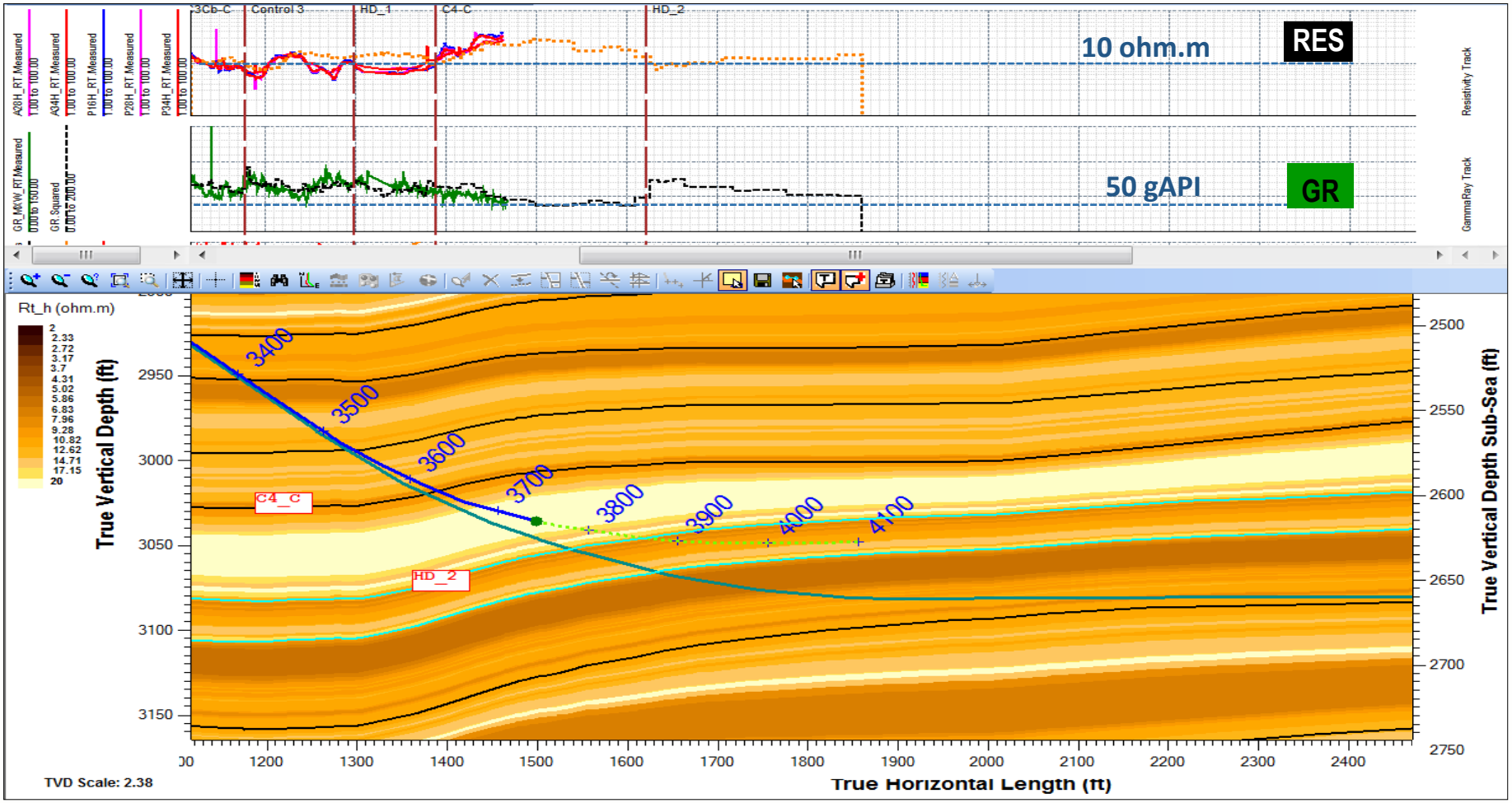

Figure 5. Landing first horizontal well, from eXpandGST.

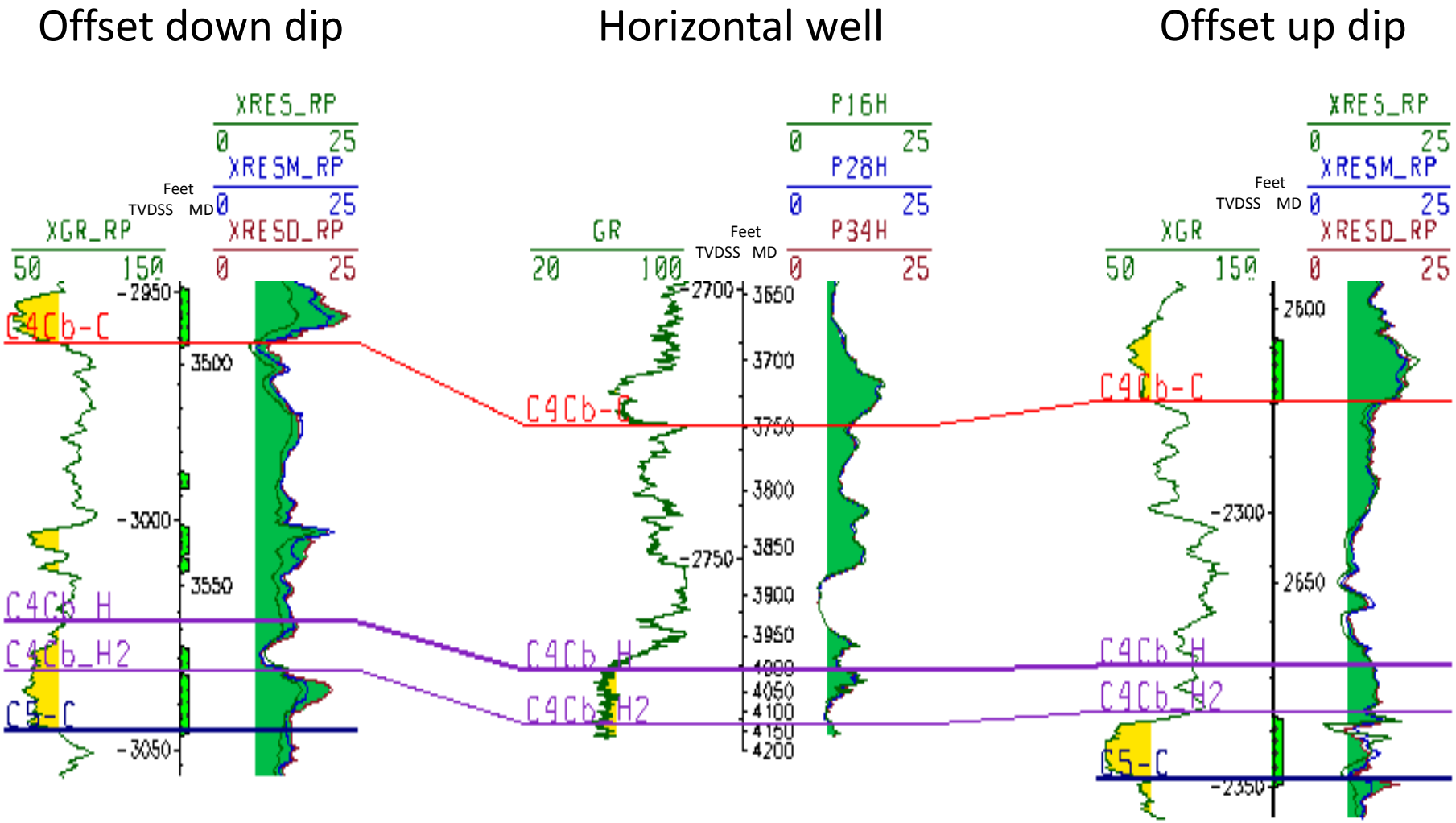

Figure 6. Landing correlation of the second horizontal well (TVDSS).

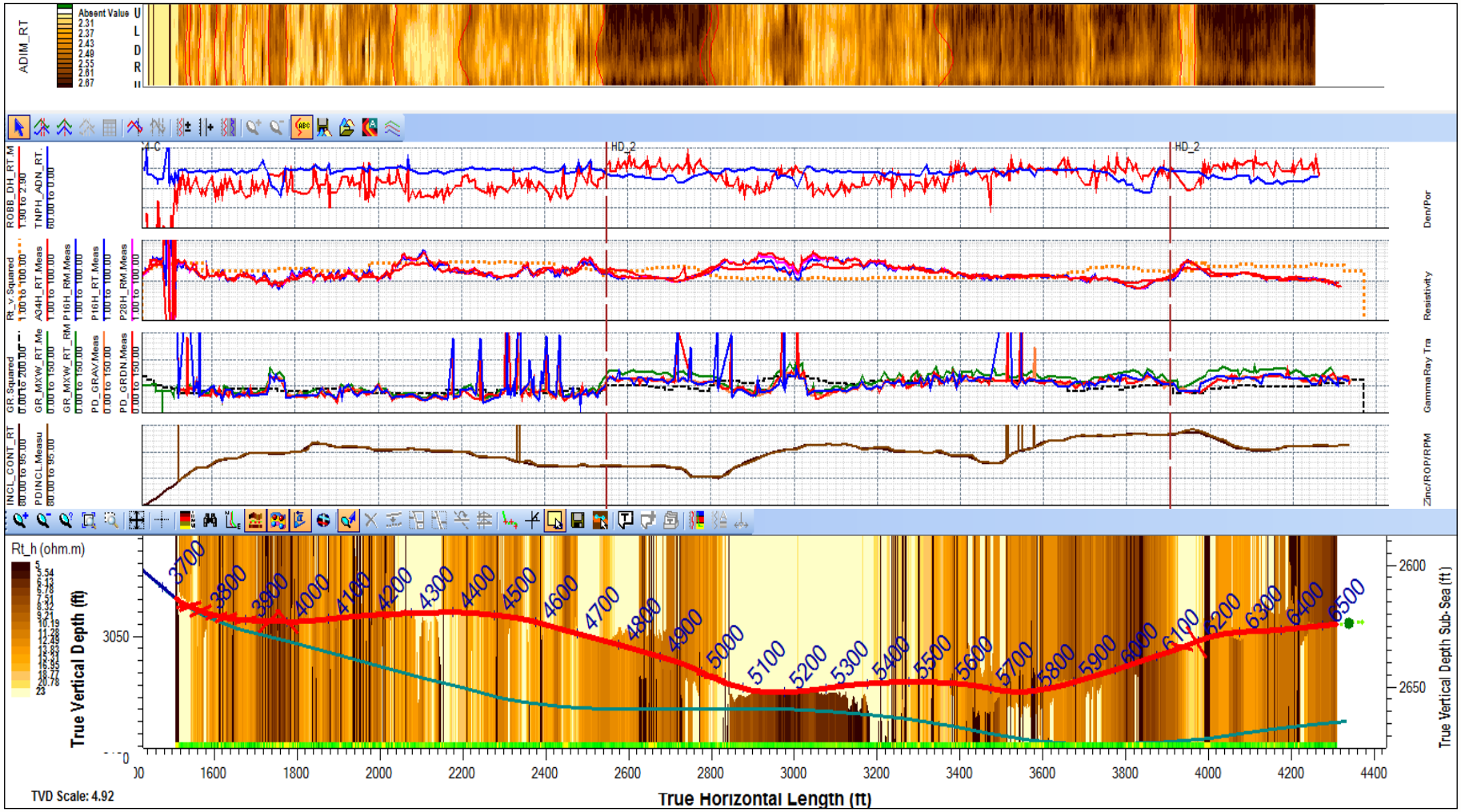

Figure 7. Inversion from PeriScope on eXpandGST first horizontal well.

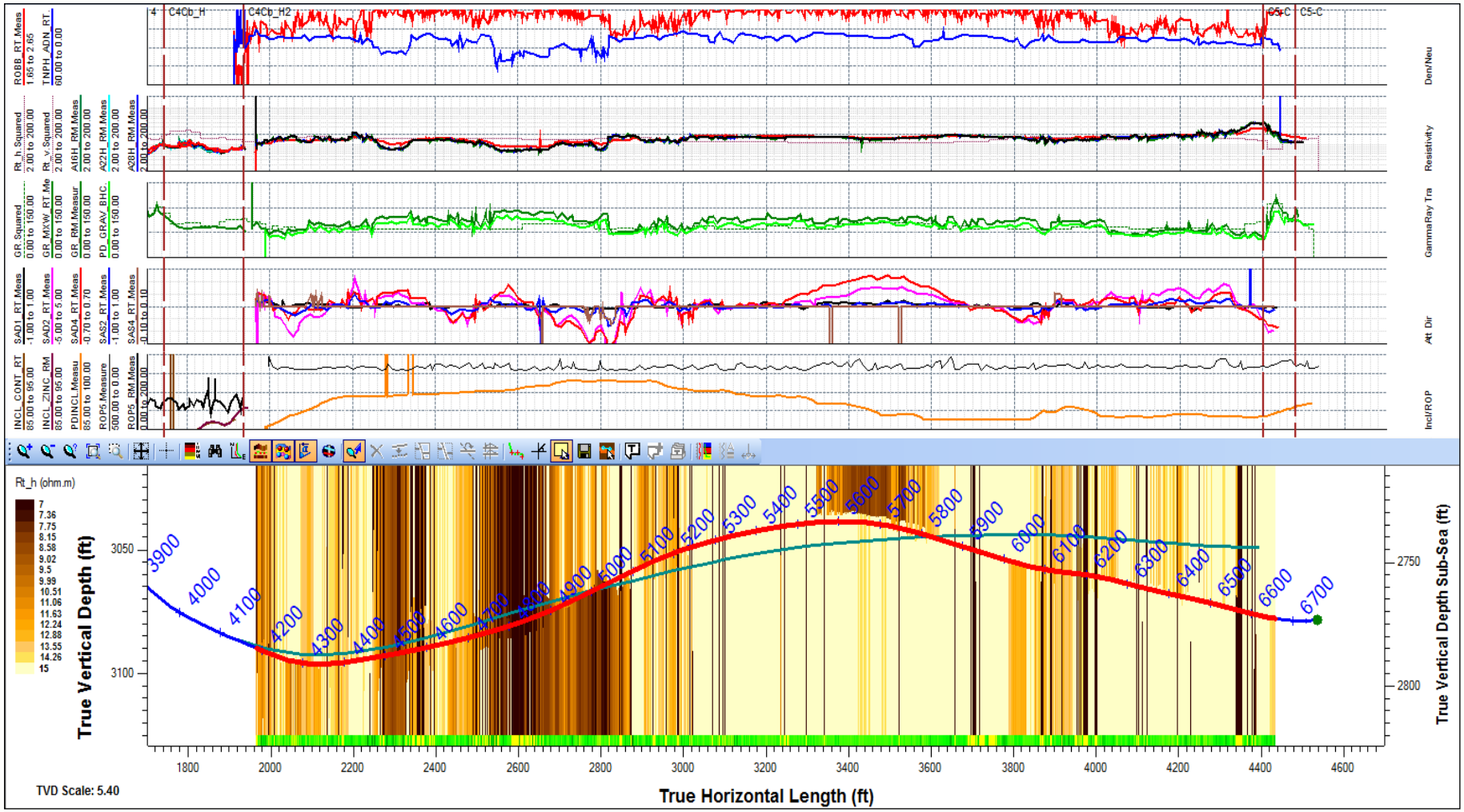

Figure 8. Inversion from periScope on the eXpandedGST second horizontal well.

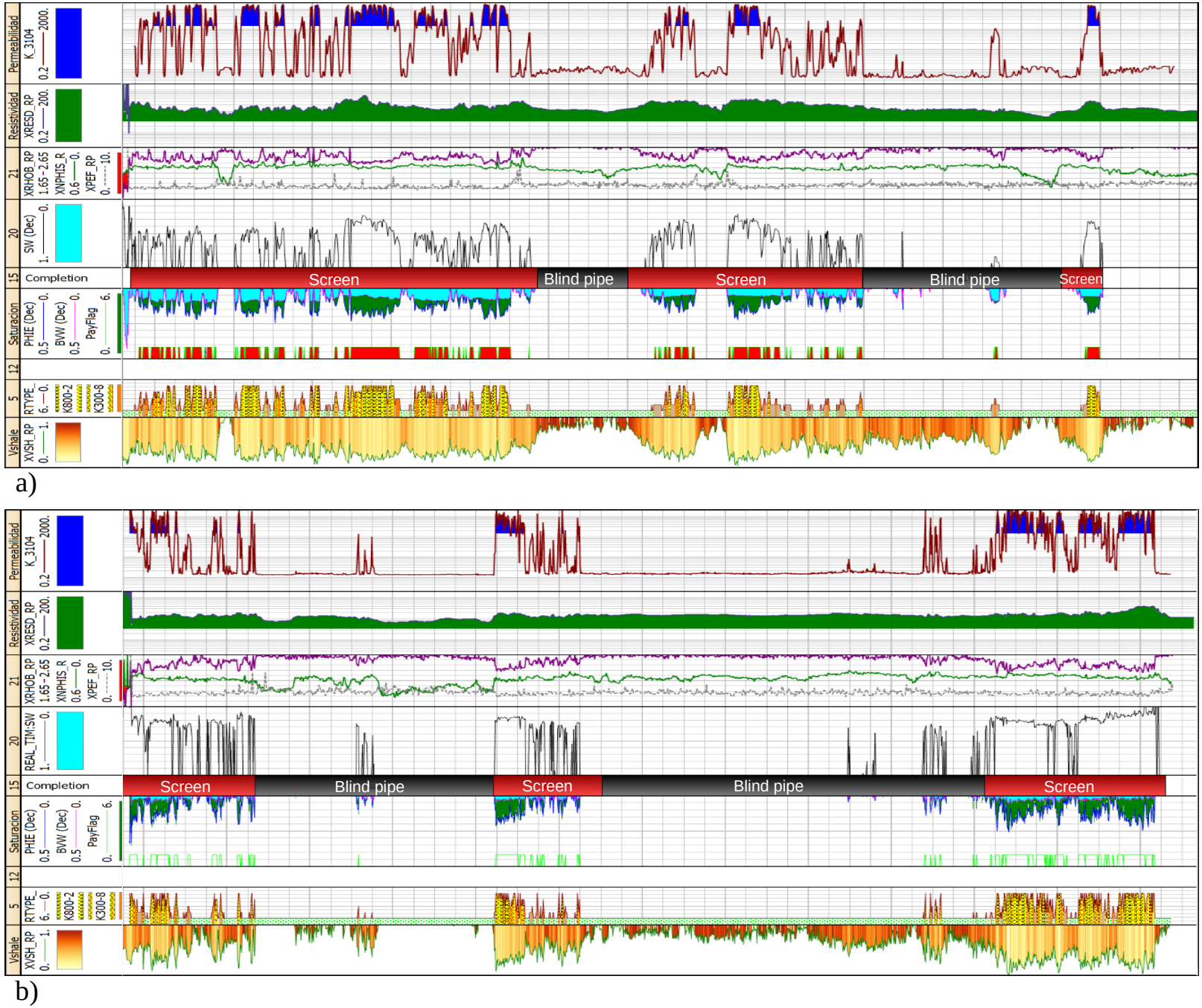

Figure 9. Petrophysical interpretation of horizontal wells. (a) First horizontal well. (b) Second horizontal well.