AADE-07-NTCE-13

# Proactive Geosteering with Directional Deep Resistivity and Rotary Steerable Tool in Thin Coalbed Methane (CBM) Reservoirs

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**Abstract**

With dwindling reserves in conventional gas and rising wellhead prices, oil majors are shifting their focus to the more unconventional resources of coalbed methane (CBM) and shale-gas. Although CBM is relatively new in western Canada, the United States has been in active production in this arena for the last 20 years.

The Alberta Energy and Utilities board (EUB) estimates that current national reserves are between 150 and 450 trillion cubic feet and six major coal horizons are identified in western Canadian Sedimentary Basin (WCSB) as potential candidates for CBM: (Scollard Formation (Ardley), Mannville Group (both the upper and lower Mannville), Horseshoe Canyon formation, Kootenay Group, Luscar Group and Belly River group). Although most of the plain regions are underlain by coal-bearing formations, the individual coal beds thicken, thin, split, coalesce, pinchout and have locally been truncated in response to depositional, erosional and structural conditions. Typically, these coal seams are buried between depths of 400 to 1500 m TVD while the thickness of these varies between 1-45 ft. [3]

Currently, a typical CBM well is drilled horizontally using conventional measurements like gamma ray (GR) and/or resistivity measurements to position the well in the coal seam. Although this might work in certain applications, this approach has some disadvantages when drilling thin zones (1-10 ft), as conventional measurements used for well placement are shallow reading, nondirectional or both. Operators making use of these measurements frequently discover that by the time shallow measurements indicate proximity to undesired formations or water zones, the well has already been drilled into them, causing issues such as borehole stability problems, side tracks, increased authorization for expenditure (AFE) cost, loss of production, etc.

This paper describes the successful proactive well placement of the first three horizontal wells in the CBM environment with directional deep resistivity logging-while-drilling (DDR-LWD) tool and rotary steerable system (RSS) system. The procedures and processes followed and lessons learned both during planning and execution stage are discussed.

## Introduction

Until recently geosteering in western Canada was performed with a focused GR and/or a resistivity induction tool and conventional motor assemblies. The strategy for geosteering was to build a geological model based on seismic data and offset well logs, and then to correlate real time (RT) LWD measurements in order to forward model the expected geology to change the well's trajectory. These traditional LWD resistivity measurements have confirmed inadequacies in two main areas. The first area of concern is that conventional LWD measurements are not directional. When a measurement changed due to a change in geology it was impossible to determine where this change was occurring relative to the wellbore. This created an issue for determining the direction the reservoir may be dipping, impacting the cost, time and value results when side tracks and additional logging runs used wireline products. The second area of concern is the limited depth of investigation, which is so limited that by the time a change was observed in the real time (RT) data, the reservoir was already exited. This method of geosteering is reactive.

With the introduction of the directional deep resistivity logging while drilling tool (DDR-LWD) into the north American onshore environments clients have the opportunity to choose a tool that overcomes some of the limitations of the past.

The newest generation DDR-LWD tools enable proactive well placement by mapping the distances and direction of one or two geological resistivity boundaries relative to the borehole. In terms of appearance and dimensions, this new tool has the same look as a conventional resistivity tool currently used in the industry. The geometric alignment of the transmitter arrays allows the DDR-LWD tool to penetrate deep into the formation, allowing for the precise positioning of boundaries. [1]

Additional benefits are seen in the new data processing and structure visualization software that is now used to aid the RT decision-making and planning process. Depending on the formation resistivity environment, measurements are able to detect conductive boundaries at distances up to 15 ft. The interpretation software translates measurements into RT structural maps. The data processing is based on a model-based (parametric) inversion algorithm using a simple three-layer model. At each measurement point, data are inverted to obtain distances to nearby boundaries, horizontal and vertical resistivity of the beds, as well as the resistivity of the beds above and below the measurement point. This interpretation enables proactive geosteering decisions and provides important geological insights into the reservoir structure[1] However, the DDR-LWD tools only provide RT guidance during the well placement process and the tool effectiveness diminishes rapidly when the drillstring is not rotated 100% of the time. In cases where conventional steerable motors are used, sliding is required to control the direction of the well; however, 3-D geosteering is not possible while sliding. By utilizing advanced steerable drilling systems in conjunction with the DDR-LWD tool, the well placement and drilling performance can be improved significantly. The next generation of rotary steerables push-the-bit-system is an excellent example of such an advanced steerable drilling system. This tool can be run in combination with measurement-while-drilling (MWD)/LWD with RT communication to the surface with the RT communication between the RSS and the MWD/LWD tools established through an E-mag receiver sub. The RSS controls the wellbore in 3-D, while rotating the drillstring continuously. This tool uses mud-actuated pads to deviate the direction of drilling by pushing against the formation.

Each of the three Case Studies covered by this paper follow an established process for candidate selection. Starting with premodeling, and actual execution of the well, it reports additional optimization decisions, lessons learned and results.

## Geology and Reserves

The potential CBM Reserves present in western Canada Sedimentary Basin have been publicized by the EUB Alberta Geological Survey (AGS) and are referenced herein [5].

The different coal-containing formations are very well mapped in Alberta thanks to the thousands of conventional wells drilled on a yearly basis in western Canada. The coals are distributed throughout the southern plains, foothills and mountains as illustrated in Figure 1 (stratigraphic intervals containing coal zones with potential CBM).

Figure 2 shows a cross section of the different coal seems relative to each other based on TVD. In the plains the younger coals are on top, but due to faulting and folding, the older coals might be on the surface in the foothills and mountains. Coal typically occurs within a ”coal zone”, as discrete coal seam and/or packages with several thin and thick seams interbedded with non-coaly rock layers or beds. A coal zone may be traceable over a large geographic area. Coal zones are found in strata ranging in age from Late Jurassic (approximately 145 million years old) to Tertiary (approximately 65 million years old) Most of the coal zones in Alberta have potential as CBM exploration targets. The wells discussed in this paper are all drilled in the oldest and deepest coals of the Alberta Plains. The Lower Cretaceous Mannville coals are widely distributed across the Alberta Plains (Figure 1). These are thick coals and continuous coals with a high-gas content. Typically six or more seams of coals are present in the Mannville group and the thicknesses of these coals are between 2 to 14 m over a stratigraphic interval of 40 to 100 m. The thickest coals extend from southeast of Grand Prairie in a widening wedge between Edmonton and Calgary to the Coronation area, with coals occurring at depths ranging from about 800 m up to 2800 m.

### *Well Placement*

In the central plains of Alberta the formations are assumed to be layer caked, which should make the placement of the well relatively easy with GR or a resistivity tool. However, reality shows that the formations are not flat at all. Although structural changes are quite small compared to the foothills, staying in a thin coal seam is quite complicated particularly when the zone of interest is thin, and the depth of investigation of the measurements used to place the well is quite shallow. Due to the shallow depth of investigation and the lack of knowing an orientation of the change in geology, it is virtually impossible to stay in the zone. This method of geosteering will affect the overall net pay encountered while drilling a horizontal well. Besides having a low net pay per horizontal section drilled, it is not uncommon to exit the reservoir experiencing geological challenges. This will result in either additional wireline logging to establish a position relative to the zone of interest or pulling back and sidetracking to bring the well back into the pay zone. Eventually due to the low net pay, the overall production rate and economics of the project will be affected. The typical net pay-to-gross footage drilled in the Mannville coals have been ~30%-60%; and at this amount of reservoir, these wells have not been economical to drill.

In addition to using pro-active well placement to remain in the coal, the tools and techniques can enable the wellbore to be placed in a preferential zone within the coal seam. In reservoirs that are vertically heterogeneous it may be advantageous to remain in one portion of the coal seam. These well placement techniques can achieve this goal.

### *Prejob Modeling*

Prejob planning is essential for a well placement candidate selection as it enables the team to identify if the resistivity contrast and bed boundaries are sufficient to attempt a well placement job using DDR-LWD measurements. Data from nearby offset wells are used to model the expected LWD resistivity and directional deep resistivity responses for the laterals, as shown in Figure 5. From the modeled DDR-LWD data, it can be determined based on the resistivity contrast how close the wellbore needs to be in order to reliably determine the distance to a resistivity boundary. If it is the case that the contrast is insufficient, the DDR-LWD tool will add no benefit to the well, rendering it a poor candidate for these services. Prejob modeling is an essential step in any job using DDR-LWD tools to determine if the service will be effective.

## Case Study #1

### *Objective*

EnCana requested to drill a horizontal CBM well targeting the Cretaceous Mannville coals in Central Alberta. The target zone is divided into Mikwan B (upper) and Mikwan A (lower) coal. In between the coals a thin shale section is present of which the thickness is variable. The Mikwan B coal is estimated to be 5 m thick while the Mikwan A coal is expected to be 7 m thick.

When planning a well in the Lower Manville coal, a ranking system was utilized to estimate the structural variance of a planned well. Wells are given a ranking of high, medium and low, wells ranking high in structural variance being the most difficult to drill. To date EnCana has drilled 10 horizontal production wells in the Lower Mannville Coal. Of these 10 wells, three have been consider having high structural variance. Ultimately the results of drilling a high structural variance well with deep-directional resistivity measurements and rotary steerable systems would be compared to the results of drilling high structural variance wells with conventional technology.

The objective is to use the latest drilling and well placement to better understand where it is best to apply this technology. The entire well is to be drilled with Rotary Steerable Systems. In the intermediate hole section, the retrievable resistivity tool will be used to help with the landing of the well. In the horizontal section both the RSS and DDR-LWD tool will be used to place the lateral for 40% in the upper B seam; than go down to drill 60% in the lower A seam coal staying approximately 2.5 m from the top of the seam boundary as illustrated in figure 3.

### *Prejob Modeling*

Drilling plans called for landing the well at the top of Mikwan B using conventional geo-steering. These plans specified the well be landed at 88° deviation in a 222 mm hole where 7-in casing was set. The lateral section (156 mm) was drilled utilizing the DDR-LWD tool to optimize the well placement.

Offset well data were obtained from the client (resistivity, porosity, density, GR and seismic data), and a prejob model was created in RT geosteering software (RTGS) to evaluate the predicted response of DDR-LWD in this field. Log squaring was performed on several offset wells to define bed boundaries from electrolog character (resistivity, porosity, GR and density). The logs show good resistivity contrast of the coals with shoulder beds (shales) making this a good candidate for DDR-LWD prejob forward modeling. The thin Hackett coal marker above the Mikwan coals is expected to be separated (from Mikwan B top) by 40 m TVD of shale/silt /clastic stata of the Mannville Group. Figure 4 illustrate the log response of the markers used to land the well in the intermediate hole section.

The prejob inversion modeling clearly showed that the DDR-LWD tool would be able to identify the upper and lower shale boundaries of Mikwan B (upper coal), but only the lower boundary when in Mikwan A (lower coal). Coal beds have high resistivity and thereby are shaded with lighter colors. Shales and silts are relatively conductive and thereby shaded with darker colors as demonstrated in figure 5. The prejob model showed that the DDR-LWD tool would be able to detect the shale boundary up to 3.5 m away when in the coal.

### *Prejob Well Planning*

Based on the prejob modeling, a good response was expected from the DDR-LWD tool in the lateral section and a full directional technical proposal was prepared for the execution of this well. In case conventional directional equipment would be used to drill the well, the KOP was to be pushed as deep as possible in the intermediate hole section followed by 13.5°/30 m DLS to land the well at 88° in the Mikwan-B coal. Convential planning techniques for rotary steered wells indicate that shallower dog plans will yield to more successful job execution. Offset slide sheets were requested from the client to better understand the bottom hole assembly (BHA) behavior in certain formation types. After careful analysis, the dogleg behavior of a RSS system was predicted for this particular field; and based on this analysis, the well profile could be constructed.

Based on Table 1, the steerable motor with a 1.83° adjustable bend house setting is achieving the theoretical build rates for its setting, except in the Second White Specks (2WS) and Base Fish Scales (BFS). In these particular formation types, the built right (BR) is approximately 70% of the theoretical values.

Table 2 shows the RSS DLS prediction. BHA#1 is a RSS system without a flex joint, whilst BHA#2 is a RSS system with a flex joint incorporated in the BHA design. The theoretical DLS values are calculated with BHA tendency analysis software. Once the theoretical values were established, the DLS were adjusted based on the DLS seen with conventional motors.

The welldesign, figure 6, was adjusted for the RSS system. Rather than kicking off as deep as possible, the KOP was shifted to 900 m TVD. The initial build was at 2.5°/30m, followed by 4.5°/30 m in the Colorado group. 2WS and BFS are renowned for their difficulty of building, thus the DLS was reduced to 1.75°/30 m. Once the Viking sand was tagged, the DLS severity was increased to 3.55°/30 m. The Hackett coal marker was hit at 66° inclination. Once this marker was picked up, the well would be landed in approximately 40 m TVD

Other concerns during this job were the limited standpipe (15,000 kPa) pressure, the availability of only one Gardner Denver PZ8 triplex mud pump, and the limited torque output of the topdrive in high gear. The rig capacity dictated the BHA design. Due to the limited standpipe pressure, RSS in conjunction with a motor could not be utilized. The differential over the motor and the pad actuation pressure of the RSS would exceed the maximum allowable standpipe pressure on the rig. A RSS could be used, but the energy required at the bit had to be supplied by the topdrive. Based on the hydraulics performed on the BHA, the expected flow rate for the 222 mm hole section should be kept between 1.35-

1.45 $m^3$. At this flow rate, the standpipe pressure would not exceed the maximum allowable standpipe pressure while maintaining sufficient pressure over the RSS pads. This flow rate could be supplied by one triplex mud pump using a 152 mm liner. Secondly, this flow rate was above the minimum drill flow of the RSS tool allowing downlinking without jeopardizing the RSS performance. A downlink is accomplished by reducing the drill flow rate by 20% for a certain time interval. During a downlink, the flow rate has to stay above the minimum telemetry flow rate of the tool to ensure the tool is working properly as below this value, downlinking is unreliable.

For the lateral hole section, sufficient pump pressure was available. The RSS system was utilized in combination with the DDR-LWD tool. The 4-in drillpipe that would be used in both the intermediate section and lateral section helped reduce the pressure losses in the system while flowing 1.0 $m^3$. The larger drillpipe also was to assist in the hole cleaning while drilling the horizontal section.

**Job Execution-222mm Hole Section**

At 860 m TVD the rotary BHA was pulled out of hole (POOH) to pick up the RSS/LWD assembly to commence the build section of the intermediate hole section. Table 3 shows the BHA used on the first run:

The RSS system was configured with a low flow impeller. Based on standards calculations and confirmed by flow loop test, the minimum telemetry flow was established. An appropriate internal flow restrictor was used to achieve the recommended pad pressure of around 750 psi. The flow restrictor reduced the overall HSI at the bit to prevent jetting away the formation in a soft drilling environment. The normal drilling flow was around 110 strokes per minute while maintaining the surface rotation between 90-180 rpm. The first BHA drilled to 1532 m MD at an inclination of 71°. The DLS was slightly higher than expected and all downlinks were received. The BHA was POOH for penetration rate. The same BHA was picked up for the second run. The BHA continued to perform as predicted although the penetration rate was low. After 69 m of drilling, the BHA was POOH to pick up a polycrystalline diamond compact (PDC) bit. The bit nozzles were adjusted to ensure that 750-psi pad pressure was achieved. The penetration rate doubled with the PDC bit and the well was landed as per geology's instruction of 86° in the Mikwan-B coal, which came in 3.5 m TVD deeper than expected. Some issues were observed with the MWD signal during this run, and it was noticed the pulsation dampener was leaking. During the PDC bit run, stick-slip was observed and changing surface parameters didn't seem to reduce the stick-slip generated by the bit. Figure 7 shows the actual vs. predicted dogleg severity.

**Job Execution-156mm Hole Section**

After intermediate casing was run and cemented, the BHA for the 156 mm hole section was picked up. Initially some issues arose with the surface testing of the 4[¾]-in RSS and the back-up tool was picked up in combination with a roller cone bit and DDR-LWD/MWD tools. The float collar and shoe had been previously drilled out with slick assembly. The BHA was RIH to just outside the casing; a downlink was sent to put the RSS tool in inclination hold mode. The BHA continued to build and the decision was made to POOH to pick up a motor assembly. At surface it was discovered that the muleshoe angle in the RSS tool was set-up incorrectly, causing the tool to build. The 4[¾]-in RSS system was changed out for a 4[¾]-in 7:8 2.2 stage PDM with a 1.15°ABH. The PDM was run in conjunction with the PDC bit. This BHA managed to bring the well plan back on track, but it had some disadvantages for the DDR-LWD tool. In order to get a 360° view of the wellbore, the tool had to be rotated. In sliding mode, it was not possible to obtain a 360° view; and after each slide, the BHA had to be pulled back to rotate through the slight to establish a position relative to the boundaries. Although it is possible to place the well correctly in combination with a PDM, it is preferred to run the DDR-LWD tool in combination with a RSS tool. Once the well plan was back on track, the BHA was POOH to pick up the 4[¾]-in RSS tool. At surface the third 4[¾]-in RSS tool was picked up. Again, the 4[¾]-in tool failed the shallow hole test. Due to time constraints, it was decided to break the RSS tool between the mechanical and the electronics parts. At this point it was discovered some plastic from the mouse hole was pumped through the tool jamming the impellers. Another RSS tool was shipped from Calgary, which was made up to the DDR-LWD/MWD BHA. This BHA performed very well; the downlinks were received by the tool, although rotation during downlink was required in order to increase the success rate of downlink response partly due to the aerated mud (Polymer mud system). Overall this BHA worked exceptionally well for geosteering requirements with near bit inclination being an invaluable tool for staying inside the Mikwan A and B. Azimuthally LWD measurements also proved helpful for keeping wellbore in the pay.

The DDR-LWD image gave excellent results, showing clearly the upper and lower limits of the formation. Although the resistivity was 9.43 m from the bit, the smooth wellbore trajectory enabled ample time to respond to formation changes at the end of the well coming up in TVD faster than anticipated.

Throughout the 156 mm hole section, the DDR-LWD and MWD system performed exceptionally well. As per prejob modeling, the boundaries of the Milwan B coal could be clearly identified. The inversion canvas demonstrated in figure 8 of the RT geosteering clearly demonstrates the proactive and reactive geosteering decision points as mentioned per Table 5. Bright colors indicate resistive formation and dark colors indicate conductive formations. Distances beyond DDR-LWD tool range show null values (bright or dark). The Mikwan B (upper coal) was thinner than expected in this particular well and a proactive decision avoided going into the base (shale interlayer) of that coal at around 1876 m MD. The interlayer shale between the coals was entered as planned at 2233 m MD (1419.9 m TVD) and exited from the base at 2241 m MD (1420.5 m TVD) .The DDR-LWD saw the interfaces of this 0.6 m thin shale clearly during entry and exit. As predicted by the prejob model, the top of Mikwan A was not seen thereafter, and the steering was done from the base of Mikwan A coal.

Figure 9 shows the top of the Mikwan B coal dipping down. The 4[¾]-in RSS is used to build inclination to 91° (steer up). Thin Interlayer Shale below Mikwan B coal approaches but avoided by steering up (1876 m MD, 1420.3 m TVD). The drop in trajectory before point D may be partly attributed to use of Mud Motor and partly to changes in dip of the lower surface.

The interlayer shale between the coals (positions I and J in the well path – Figure 10) was entered at 2233 m MD (1419.9 m TVD) and exited from base at 2241 m MD (1420.5 m TVD). The DDR-LWD tool saw the interfaces of this 0.6 m thin shale clearly during entry and exit. The curves above the inversion canvas show positive and negative deflection of symmetrized resistivity (SPD4) indicating cutting the interlayer shale. After that the wellbore is geo-steered to stay at the center of Mikwan A (lower) coal. However, soon it is realized that the bottom boundary is coming up at a faster rate than expected. It is decided to build angle, however, the bottom keeps coming up at even faster rate and ultimately the well goes though a “topographic high L” which may be interpreted as one of a series of barrier islands or ancient shorelines (as per later signatures of undulations at positions M and N). A maximum distance from the lower boundary is seen up to 2.5 m (at position N). The lesson learned here was to believe and react to the DDR-LWD measurement.

**Evaluation of Results**

To date EnCana has drilled three wells in the Lower Mannville coal in what are considered to be high structural variance wells. Of these three wells, two have been drilled using conventional technology and one has been drilled using deep-directional resistivity for pro-active well placement. All three well have targeted a wellbore length of 1000 meters in the coal. Figures 11-13 show the results of drilling these three wells in high structural variance environments. Figure 11 shows the well drilled with deep-directional resistivity measurements. Of the 1000 m drilled in the reservoir section, 910 m cut coal, giving a net coal of 91%. Figure 12 shows a well drilled with conventional technology. The net coal drilled in this well was 76%. However, in this well the wellbore exited the coal and drilling was suspended after 604 m, giving a total amount of wellbore in the coal of 462 m, or about half the amount of wellbore in coal as the well drilled using deep-directional resistivity measurements. Figure 13 was the most recent well drilled in a high structural variance environment. Although 1003 m of wellbore was drilled, only 710 m was drilled in the coal, giving a net coal of 71%. On one occasion the wellbore was deliberately steered up into the overlying shale in order to determine when in sequence the wellbore was. This could have been avoided by boundary mapping using deep-directional resistivity measurements.

Of the ten horizontal wells drilled in the Lower Manville coals, four have been drilled in what are considered to be low structural variance environments. The average net coal in these four wells is 92%, all drilled with conventional GR technology. The net coal in the well drilled with DDR-LWD and RSS was 91%. The benefit of drilling with DDR-LWD and RSS systems is that it takes the riskiest wells and allows us to be as successful as if we were drilling in a low risk environment.

**Summary, Lessons Learned & Recommendations**

The first DDR-LWD/RSS runs in western Canada were successful. Although some issues were present with the RSS tool, the well placement by itself was a tremendous success. The lateral was for 91% in the zones of interest despite the complex geology of the Mikwan B and A coals. The basket test performed in the maintenance shop on the BHA components being used in the field helped detect any compatibility issues between the different tools (i.e. software compatibility issues, extender problems, tool defects, etc.). The RT geosteering data was successfully transmitted to the OSC (Operation Support Center) and displayed to the client. The DDR-LWD tool does not generate a quadrant and symmetric measurement while sliding; to overcome this issue, the geosteering software was set in idle mode just prior to the slide. After the slide was completed, the BHA was pulled back to the start of the slide and rotated through the section. This method prevented data gaps in the transmitted geosteering data. Unfortunately, this method of geosteering puts the DDR-LWD tool further back in the string (due to the length of the motor and E-mag receiver of the RSS tool), costs rig time and increases the risk of exiting the pay zone while sliding. Once the motor BHA was replaced for the RSS /DDR-LWD BHA, the through value of this BHA combination could be established. The continuous rotation improved hole cleaning and the DDR-LWD data showed the boundaries as predicted in the prejob modeling. The base of the Mikwan B coals was avoided and the time spent in the interlayer shale between the B and A coal was less than 20 m MD, effectively maximizing the net pay. Finally, the Mikwan A base was drastically different from the offset wells. The DDR-LWD tool thoroughly showed its value by managing to stay in the pay zone despite the complex geology.

**Case Study #2**

***Objective***

MGV Quicksilver elected to pilot test the DDR-LWD and RSS tool for two CBM wells in south central Alberta. The target zone for the lateral section was the Coal Unit #3 (1a) in the Creteous Mannville coal. Besides geosteering the well in RT, and trying to place the well in the pay zone for 100% of the time, it was also expected that the DDR-LWD could give some structural information on the coal unit and eliminate sidetracks caused by geological uncertainties. The RSS would be run in combination with the DDR-LWD tool to allow for continuous rotation of the downhole assembly at all times, which was required for the continuous acquisition of data. The RSS system performance would be monitored and tracked for reducing overall drilling time.

***Prejob Modeling***

The Mannville coal in the area of the planned well is assumed to be continuous and relatively flat, 0.4° regional dip to the south. The Mannville formation has several coal members in this field. The target coal seam, Coal #3, was predicted to be roughly 2.5 m thick at this location. Offset data indicate possible variations in thickness of this coal member.

A prejob model was created in the Schlumberger RTGS to evaluate the predicted response of DDR-LWD tool in this field. Offset well 6-30 was used to model resistivity and GR responses. This vertical well is located a little over a kilometer to the north of the planned well.

From the prejob model, it was determined that the resistivity contrast of the target coal, 40 ohm-m to the shoulder bed, 8 to 10 ohm-m, would be sufficient contrast for DDR-LWD to detect the boundaries of the coal member with a 75 ohm-m conductivity difference between the pay and the shoulder bed. Additionally if the coal member is relativity homogeneous, the DDR-LWD tool should be able to map both boundaries from within the coal member. Predicted response of the DDR-LWD tool was also used to select the optimal set of phase, attenuation, and directional response curves to be used in RT. Figure 14 shows the prejob model based on offset 6-30 well. Both the resistivity model and the inversion curtain are shown.

***Prejob Well Planning***

The prejob modeling of the DDR-LWD tool showed a promising response and a full, directional technical proposal was prepared. The well design, figure 15, would kick off around 900 m TVD into the Colorado at 2.0°/30 m. The dogleg severity would increase by depth from 2.0 all the way to 6.0°/30 m in the Joli Fou. A short tangent was incorporated in the well plan at 60° inclination; and based on the GR markers from the offset well, a decision would be made to land the well at 15.0°/30 m in the Mannville Coal #3 (1a). The intermediate casing string would be set just into the Mannville coal. The estimated length for the horizontal was +/- 1000 m. The intermediate hole section would be drilled with a conventional steerable BHA in combination with a retrievable MWD come with GR. The main bore would be drilled with the 4[¾]-in RSS and DDR-LWD tools for well placement purposes. Torque and drag and hydraulics were run to confirm the rig was capable of supplying the power to run the 4[¾]-in RSS/LWD BHA in the main hole section. This particular rig had access to two 100 HP TSM1000 triplex mud pumps and the topdrive was a Tesco EMIS 400. Based on the specifications of both triplex pumps and topdrive, the rig could deliver the required energy.

**Job Execution-222mm Hole Section**

For the intermediate hole section, the surface casing was drilled out with a rotary slick assembly. Once completed, a conventional extra power low speed PDM was used with a 2.12° ABH with a kick pad. A few slides were required to maintain the well vertical and the kick-off commenced at 890 m TVD. Built with increasing doglegs as planned to 60° inclination, a short tangent of 30 m was drilled till the second KOP was reached. The GR of the MWD tool showed good correlation to the offset 6-30 well until 1280 m MD. From this point forward, there was no clear correlation present. From the last correlation before 1280 m MD, Coal #3 was still on target at the expected depth of 1313 m TVD. The top of the coal didn't come in at 1311 m TVD as previously thought and the landing, figure 16, was cut short to search for the coal as requested by the geologist. About 200 m were drilled and the TVD dropped by an additional 7 m to 1320.2 m TVD. At this point sliding became difficult and the BHA was POOH to change around the HWDP and change out the motor to a standard power section. This BHA landed the well at 1321 m TVD (1721 m MD) and an inclination of 89°.

**Job Execution-156 mm Hole Section**

Casing was stuck at 1569 m and could not be run to the bottom; casing was cemented in place. Cement and the first 10 m past cement retainers were drilled out with a slick BHA assembly. Once the casing shoe was cleaned-out, the 4[¾]-in RSS/MWD/LWD BHA as per table 6 was picked up.

The lateral was drilled in one bit trip from 1669 m till 2720 m MD. This bit and BHA combination could easily drill at 100 m/h, but initially the ROP was held back to 50 m/h until the well was landed in the middle of the coal seam. The DDR-LWD data were analyzed on site by well placement personnel for RT geosteering decisions. Well Placement personnel worked with the well site geologist on well placement decisions.

Eighty-two percent of the well path adjustments for geosteering were preformed through nudge point adjustments with RSS operating in inclination holding mode. Nudge points allow for a half degree inclination adjustment with a minimal downlink signal allowing for minimal time spent communicating with the tool.

RSS demonstrated good response to steering commands and a high ROP through the target coal. ROP was held back to allow for geosteering corrections. ROP was capped at 60 m/h.

Overall, the well path was in the target coal for over 99% of the drilled lateral length. The well path was maintained in the zone except for 9 m exit through the upper boundary between 2043–2052 m MD and the exit was confirmed by cuttings. DDR-LWD tool indicated that this was an abrupt variation in the upper surface. Exit at 2043 m MD was not prevented because the sharp boundary feature coincided with a change in the structural dip. Similar structures were also observed with DDR-LWD tool at 1712 m MD and 2512 m MD. Structure at 2512 m MD was clearly mapped in RT and interpreted as a channel cut feature. Figure 17, shows the final inversion curtain section of the 156mm lateral at the end of the RT geosteering.

Target coal appears to be approximately 3.0 m thick throughout the logged section. DDR-LWD tool was not able to image both coal boundaries from within the target coal because resistivity variations within the coal are observed by the DDR-LWD tool inversion algorithm as a bed boundary, which prevents the mapping of both lithologic boundaries simultaneously. DDR-LWD detects the nearest boundaries both above and below the tool within the depth of investigation. Resistivity variation within the coal were present as seen from the increased resistivity, 55 to 65 ohm-m logged between 1795-1974 m MD while the well path was within the lowest 0.8 m of the coal seam. When the well path is close to either the upper or lower boundaries, the boundary surface is clearly mapped, such as channel features previously mentioned. (.See Figure 17 - Final curtain section.)

Planned TD of the well was originally set at 2360 m MD. As the well progressed, the decision was made to increase the target TD. The well was TD at 2720 m. The total drill time for this lateral section was 55.5 h, which included three wiper trips for hole cleaning purposes. The actual drill time was half of the expected AFE drill time of five days. Overall efficiency while drilling was achieved through the knowledge of where the well was relative to the boundaries and the continuous rotation of the drill string.

**Summary, Lessons Learned & Recommendations**

The post-job processing of the DDR-LWD data set, figure 18 and 19, showed the target coal was approximately 3 m thick throughout the drilled section. Initially the structure dipped down at 1-2° until 1795 m MD. From this point forward the structure started to dip up at 1-2° till 2030 m MD, forming a small, localized syncline structure. From this point forward the structure flattened out. The DDR-LWD/RSS BHA was extremely successful as it stayed in the pay zone. The net pay was estimated to be 99%. The RSS tool improved overall drilling efficiency, the lateral section was drilled in 55.5 h including three wiper trips to the casing shoe. The lateral AFE was five days, effectively cutting the drilling time in half. For future wells Equivalent Circulation Density (ECD) monitoring should be utilized to improve hole cleaning and reduce the amount of wiper trips required to drill this hole section.

**Case Study #3**

***Objective***

In a continuation from Case Study 2, this case study represents the second well from MGV Quicksilvers' pilot test performed with RSS/DDR-LWD services. The objective was to place the well in the Coal Unit #3 of the Cretaceous Mannville coal.

***Prejob Model***

Figure 20 and 21 shows the prejob created in the RTGS based on offset resistivity and GR log. The target coal seam, Medicine River 1B coal (1a), was predicted to be roughly 3 m thick at this location at a TVD of 1235.6 m. Offset data indicate possible variations in thickness of this coal member.

From the prejob model, it was determined that the resistivity contrast of the target coal, 40 ohm-m to the shoulder bed, 8-10 ohm-m, would be sufficient contrast for DDR-LWD tool to detect the boundaries of the coal member with a 75 ohm-m conductivity difference between the pay and the shoulder bed. Additionally, if the coal member is relativity homogeneous, the DDR-LWD tool should be able to map both boundaries from within the coal member. Predicted response of the DDR-LWD tool was also used to select the optimal set of phase, attenuation, and directional response curves to be used in RT. Twenty-two in phase and attenuations were used in RT in place of the 16-in measurements used on Malmo 2-20-44-22, since the shallow 16-in curves showed hole effects on 2-20-44-22.

***Prejob Well Planning***

Based on the prejob modeling, it was decided to geosteer the second well. The well design, figure 22, was kept similar as the previous well. The KOP was in the Colorado formation at 810 m TVD. The dogleg severity increased by depth as per client request from 2.0°/30 m at KOP till 6.0°/30 m in the top of the Joli Fou. A short 30 m tangent second was incorporated in the well design at 60° inclination just below the Hackett coal in the Mannville Group. After the tangent of 30 m, the well was landed at 15°/30 m in the Mannville Medicine River 1B coal (1a) at a TVD of 1236 m. At this point the casing was set and the 1200 m lateral would be geosteered with a RSS/DDR-LWD BHA.

***Landing***

Landing section to 1410 m MD was drilled with MWD and GR tool. The plan was to land the well at 90° inclination at 1235.6 m TVD, 257 m THL (true horizontal length), within the target coal seam. Geologist requested flat landing at 1238 m TVD and well landed at 1237.1 m TVD. Target coal was not detected at the planned landing point. Coal seam was reached at 1369 m MD, 1236.4 m TVD; 1.2 m deeper than expected.

Comparison of the modeled GR response to the RT MWD GR showed reasonable correlation to the offset well 8-29. There is a 1.2 m TVD difference in GR marker TVD's. This is shown in Figure 23. The curtain section was correlated to the RT GR by shifting the TVD 1.2 m and applying a dip down of 0.5° down dip interpreted from RT DDR-LWD data when lateral commenced. This is shown in Figure 24.

**Lateral Section**

The well was landed at the top of coal seam 1236.4 m TVD and drilled to a measured depth of 1410 m. From landing at 1410 to 1745 m MD, the structure appears to be down dipping from 0.5-1.5°. At 1745 m MD a fault was crossed with a ~3.0 m up-throw. Once the fault was crossed, the DDR-LWD tool was able to image the bottom of the coal seam. Inclination was adjusted upward to 93° and at 1845 m MD the coal was re-entered. The well path was out of zone for 100 m.

When the fault was exited, the dip of the structure changed and began to dip up at 0.5 to 1.0°. The well was drilled at 90.5 to 91° inclination to track the up-dip. At 1970 m MD the coal was intersected by a channel cut – this was confirmed from the cutting. The coal top below the channel cut was imaged by the DDR-LWD tool. The well path was adjusted to

87° inclination until the coal was re-entered at 2099 m MD. The well was out of zone for 129 m.

When the coal was re-entered, the trajectory was nudged back towards 90°. Once the bottom of the coal was imaged in RT by the DDR-LWD data, the well trajectory was adjusted to 91°. The trajectory was maintained upward until 245 0 m MD when the top of the coal came down quickly. The top of the coal was not exited but the well path scrapped the upper shale. The inclination was adjusted down to 88.5° and once the center of the coal was achieved, the trajectory was adjusted to 89.5° and held until total depth.

During the intervals when the fault was crossed and the channel cut encountered, the coal boundaries could be seen. When the DDR-LWD tool was in the coal, the RT inversion was only able to image one boundary; either the upper or lower but never both. When the well path was in the center of the coal, the RT inversion could not image any boundaries. The RT inversion is shown in Figure 25.

RT operations support was also provided throughout this job. Satellite communications allowed the data from the rig site to be transmitted RT through a secured network hub to both the client's office and to the service providers Operation Support Center where geosteering decisions were qualified and verified.

The RSS tool allowed for minimizing drilling time through continuous rotation at high ROP while steering. All of the well path adjustments for geosteering were preformed through nudge point adjustments with the RSS tool operating in inclination hold mode. Nudge points allow for a half degree inclination adjustment with a short downlink signal allowing for minimal time spent communicating with the tool. Typical nudge point commands and inclination hold commands were an average 6.5 minutes. After the well was completed, the recorded DDR-LWD data were processed; a correlated curtain section was generated to show structure as mapped by DDR-LWD tool. Target coal seam was observed to be roughly 3.0 m thick throughout the logged section. The recorded data set provided enough information to image the top and bottom of the coal concurrently. The bottom of the coal was consistent in shape whereas the top of the coal undulated considerably. This is shown in Figure 26 along with the interpreted structure.

## Summary, Lessons Learned and Recommendations

The target zone was approximately 3 m thick throughout this section based on the post job processing of the complete data set with the DDR-LWD data set. The recorded data supplied enough data to image the top and bottom of the coal seam. The DDR-LWD tool managed to keep the well in the pay zone; 80.4%; 941 m in the zone and 229 m outside the zone. During the drilling of the lateral, a fault was encountered; but the DDR-LWD tool quickly picked up the bottom of the zone allowing the well to be steered back into the 3 m thick coal seam, which prevented a sidetrack and/or additional logging to detect were the target zone was relative to the borehole. The drilling efficiency of the lateral was improved by 63% due to improved penetration rate, hole cleaning and geosteering. The horizontal well was drilled in 44.5 h versus the planned 120 h. For future wells, ECD management should be incorporated in the well design to further improve hole cleaning and reduce the amount of wiper trips.. The near bit GR can assist in making RT geostopping decisions which is especially useful in cases where the variations in the structure were quite unpredictable.

## Conclusion

There are many critical components necessary in order to achieve a successful horizontal CBM well, some controlled by nature and others by what we do. Production rates and recoverable reserves are a direct result of having the right components. Achieving a good wellbore with maximum cleat exposure is a critical step in yielding a successful horizontal well, therefore, it is important to stay within the coal seam for as many m as operationally possible. DDR-LWD defiantly helps achieve this essential first step, building the foundation for a successful wellbore.

In western Canada, easy or low risk CBM plays can be successfully drilled with conventional technology. The higher risk plays become less economical as less coal will likely be accessed per meter drilled using conventional technology. This paper illustrates that the chances of drilling a successful and economical well are dramatically increased by introducing the latest generation of Logging While Drilling and Directional Drilling technology to a traditionally marginal producing wells like CBM. The continued use pro-active well placement services and measurements will ensure the future success of high risk CBM plays.

## Acknowledgments

The authors wish to thank Quicksilver Resources Canada, Encana and Schlumberger for permission to publish this paper. Special thanks are also due to all office, maintenance staff and field personnel involved in this project and making the first pro-active well placement jobs in western Canada successful.

## Nomenclature

*ABH* =*Adjustable bent housing*
*AFE* =*Authorization For Expenditure*
*AGS* =*Alberta Geological Society*
*BHA* =*Bottomhole assembly*
*BR* =*Build rate*
*CBM* =*Coalbed Methane*
*DDR-LWD*=*Directional Deep Resistivity Logging While Drilling*
*DLS* =*Dogleg Severity*
*DP* =*Drillpipe*
*ECD* =*Equivalent Circulation Density*
*EUB* =*Alberta Energy and Utility Board*
*GR* =*Gamma ray*
*HSI* =*Horsepower per sq inch*
*HWDP* =*Heavy weight drillpipe*
*KOP* =*Kick-off point*
*kPa* =*kilo Pascal*

*Lpm* =*Liter per minute*
*LWD* =*Logging While Drilling*
*MWD* =*Measurement While Drilling*
*OSC* =*Operation Support Center*
*PDC* =*Polycrystalline Diamond Compact*
*PDM* =*Positive Displacement Motor*
*POOH* =*Pull out of hole*
*RIH* =*Run in hole*
*ROP* =*Rate of Penetration*
*RSS* =*Rotary Steerable System*
*RT* =*Real-time*
*RTGS* =*Real-time Geosteering Software*
*SPM* =*Strokes per Minute*
*THL* =*True Horizontal Length*
*TVD* =*True Vertical Depth*
*WCSB* =*Western Canada Sedimentary Basin*

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## Tables

**Table 1: Steerable motor Dogleg capabilities by formation type.**

| Steerable Motor Actual Dogleg Capabilities - Intermediate Hole Section | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Formation Types** | **TVD (m)** | **INC. IN (°)** | **INC. OUT (°)** | **AZI. (°)** | **DLS Min. (°/30m)** | **DLS Max. (°/30m)** | **DLS AVE. (°/30m)** | **%Sliding** | **Theoretical Values (°/30m)** | **100% Sliding Actual (°/30m)** | **% Theoretical Value** |
| Belly river Grp | 732.00 | 0.50 | 1.13 | 138.00 | | | | | | | |
| Lea park Formation | 959.00 | 1.13 | 0.46 | 138.00 | | | | | | | |
| Milk River Formation | 1017.00 | 0.46 | 0.12 | 138.00 | | | | | | | |
| Colorado Group | 1117.00 | 0.12 | 13.76 | 138.00 | 4.77 | 7.91 | 6.66 | 65.0 | 11.20 | 10.25 | 91.48% |
| 2WS | 1382.00 | 13.76 | 35.34 | 138.00 | 4.39 | 9.11 | 6.76 | 82.60 | 11.20 | 8.18 | 73.07% |
| BFS | 1466.00 | 35.34 | 39.54 | 138.00 | 6.61 | 7.44 | 7.03 | 89.20 | 11.20 | 7.88 | 70.37% |
| Viking | 1478.00 | 39.54 | 47.32 | 138.00 | 9.19 | 11.97 | 10.21 | 97.20 | 11.20 | 10.50 | 93.79% |
| Joli Fou | 1496.00 | 47.32 | 58.45 | 138.00 | 6.47 | 11.25 | 9.02 | 80.70 | 11.20 | 11.18 | 99.80% |
| Mannville Group | 1521.00 | 58.45 | 65.47 | 138.00 | 7.97 | 12.89 | 9.47 | 86.20 | 11.20 | 10.99 | 98.09% |
| Coal Marker (Hackett Coal | 1550.00 | 65.47 | 86.89 | 138.00 | 1.73 | 7.75 | 5.36 | 44.90 | 11.20 | 11.94 | 106.59% |
| Landing Point | 1595.00 | 86.89 | 86.89 | 138.00 | | | | | | | |

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**Table 2: RSS DLS Prediction**

| Rotary Steerable Dogleg Prediction - Intermediate Hole Section | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Formation Types** | **TVD (m)** | **INC. IN (°)** | **INC. OUT (°)** | **AZI. (°)** | **Req. DLS Min. (°/30m)** | **Req. DLS Max. (°/30m)** | **Theoretical Values BHA#1 (°/30m)** | **Theoretical Values BHA#2 (°/30m)** | **DLS Prediction BHA#1 (°/30m)** | **DLS Prediction BHA#2 (°/30m)** | **BHA to be Used by Depth** |
| | | | | | | | | | | | |
| Belly river Grp | 548.50 | 0.00 | 0.00 | 140.89 | 0.00 | 0.00 | N/A | N/A | N/A | N/A | |
| Lea park Formation | 775.50 | 0.00 | 0.00 | 140.89 | 0.00 | 0.00 | N/A | N/A | N/A | N/A | |
| Milk River Formation | 833.50 | 0.00 | 2.79 | 140.89 | 0.00 | 2.50 | N/A | N/A | N/A | N/A | |
| Colorado Group | 933.50 | 2.79 | 41.72 | 140.89 | 2.50 | 4.50 | 3.50 | 5.65 | 3.20 | 5.17 | |
| 2WS | 1198.50 | 41.72 | 48.68 | 140.89 | 1.75 | 1.75 | 3.15 | 5.47 | 2.30 | 4.00 | |
| BFS | 1282.50 | 48.68 | 49.75 | 140.89 | 1.75 | 1.75 | 3.08 | 5.35 | 2.17 | 3.76 | |
| Viking | 1294.50 | 49.75 | 52.63 | 140.89 | 1.75 | 3.55 | 2.96 | 5.26 | 2.78 | 4.93 | |
| Joli Fou | 1312.50 | 52.63 | 57.82 | 140.89 | 3.55 | 3.55 | 2.91 | 5.10 | 2.90 | 5.09 | |
| Mannville Group | 1337.50 | 57.82 | 65.01 | 140.89 | 3.55 | 3.55 | 2.76 | 4.90 | 2.71 | 4.81 | |
| Coal Marker (Hackett Coal | 1366.50 | 65.01 | 88.00 | 140.89 | 3.55 | 3.55 | 2.51 | 4.57 | 2.68 | 4.87 | |
| Landing Point | 1411.50 | 88.00 | 88.00 | 140.89 | 3.55 | 3.55 | 2.51 | 4.57 | N/A | N/A | |

**Table 3: BHA used on the first run.**

| *Element* | *Length (m)* |
|---|---|
| Bit - GX11 (16, 2 x 20) | 0.25 |
| RSS c/w 8 5/8” sleeve | 4.15 |
| E-mag Receiver for RSS | 1.72 |
| Inline Flex Collar | 2.89 |
| Contingences mud wave MWD system (high data rate) | 8.20 |
| Retrievable Resistivity Tool | 7.65 |
| 2 x NM Flex collar | 18.94 |
| X/O | 0.66 |
| Jar | 6.67 |
| 4 x 4” HWDP | 37.46 |
| X/O | 0.34 |
| 40 jnts of 4’ DP | 382.33 |
| X/O | 0.34 |
| 44 jnts of 4” HWDP | 410.02 |
| X/O and DP to surface | |

**Table 4: Proactive and reactive geosteering decision points.**

| *Element* | *Length (m)* |
|---|---|
| 6 1/8" Bit – MX09 (3 x 20) | 0.20 |
| 4 ¾" RSS c/w 6" sleeve | 4.05 |
| Float X/O | 0.50 |
| E-mag Receiver for RSS | 2.22 |
| DDR-LWD Tool | 7.62 |
| MWD/Resistivity tool | 11.08 |
| 2 x NM Flex collar | 18.65 |
| X/O | 0.51 |
| 4 x 4" HWDP | 37.46 |
| X/O | 0.34 |
| 102 jnts of 4" DP | 974.44 |
| Jar | 4.82 |
| X/O | 0.34 |
| 44 jnts of 4" HWDP | 410.85 |
| X/O and DP to surface | |

**Table 5: Steering Decisions**

| | MD | Comment |
|---|---|---|
| A | 1768 | Exit casing shoe - observe clear boundary 0.7 m above |
| B | 1820 | Steering decision: drop inclination to reach bed (Mikwan B coal ) center |
| C | 1850 | Trip & change to RSS |
| D | 1860- 1876 | Observed approach of lower boundary: Steered to avoid |
| E | 1920 | RSS build inclination to 91° |
| F | 2070 | Level inclination to 90°: hold at bed center |
| G | 2180 | Increase in standpipe pressure. Mechanical sticking. |
| H | 2200 | Planned down-turn to Mikwan "A" |
| I | 2233 | Exit Mikwan B 2233 m MD: 0.6 m Shale |
| J | 2241 | Enter Mikwan A - steer down to target 1435.2 m TVD |
| K | 2360 | Lower boundary, 0.3° up dip. Steer to 1425.0 m TVD |
| L | 2522 | Crossed undulation (barrier island?) in lower boundary: steering up |
| M | 2590 | Steer up from increasing up-dip lower boundary |
| N | 2756 | TD well - Mikwan A (TVD 1418.5 m, MD 2765 m ) |

**Table 6:**

| *Element* | *Length (m)* |
|---|---|
| 6 1/8" Bit – FMX2641 (3 x 12, 3 x 14) | 0.20 |
| 4 ¾" RSS c/w 6" sleeve | 4.07 |
| Float X/O | 0.48 |
| E-mag Receiver for RSS | 2.23 |
| DDR-LWD Tool | 7.63 |
| MWD/Resistivity tool | 10.32 |
| NM Flex collar | 9.5 |
| X/O | 0.45 |
| 6 x 4" DP | 56.79 |
| Jar | 7.33 |
| 102 jnts of 4" DP | 966.01 |
| 60 jnt HWDP | 548.92 |

**Table 7: Log of geosteering commands.**

| Geosteering Log | | | | |
|---|---|---|---|---|
| | Displ | MD | Observation | Geosteering Decision |
| 1 | 499 | 1665 | Start Rotating | |
| 2 | 529 | 1695 | Well path right at the upper boundary of the coal seam. | From 180°-20% to 180°-40% |
| 3 | 581 | 1747 | DDR-LWD shows well path to be at center point of coal | Downlink to 20% and limit ROP to 60m/hr |
| 4 | 587 | 1753 | Well path in lower than mid-point of coal | 0-80% |
| 5 | 598 | 1764 | DDR-LWD Imaging lower boundary 0.5 m from well path | 0-100% - TVD Target 1322.5 m |
| 6 | 620 | 1786 | DDR-LWD dir. Curves level off - still 0.5 m from bottom | Inclination hold - nudge 0.5° |
| 7 | 639 | 1805 | DDR-LWD lower boundary, 0.8 m from well path -2° ap. dip | Nudge twice - Hold at 89.5° |
| 8 | 646 | 1812 | Small fault at 1797 - GR & Resistivity horns show boundary. | Increase inc to 91.5° |
| 9 | 653 | 1820 | Well path approaching boundary | Conferred with geos, target is 1322 m-1321.5 m |
| 10 | 674 | 1841 | RSS not responding fully - trying to build angle | PDINC dropping to 89.8° |
| 11 | 680 | 1847 | GR increase ROP drop | 100% build - Adjust TVD target to 1321.5 m |
| 12 | 728 | 1895 | GR increase. Dip estimated at 0.5° t0 1.2° | Hold current well path |
| 13 | 750 | 1917 | Target 1321 m TVD - confirmed with geologist | Continue drilling - inclination 91.5° |
| 14 | 800 | 1967 | DDR-LWD - lower boundary approaching, GR increasing | Inclination from 92.0° to 92.4° |
| 15 | 813 | 1980 | Drifting up in section | Skip next planned inc increase - hold at 92.0° |
| 16 | 856 | 2023 | Bed center | Nudge inclination down - 91.5° |
| 17 | 870 | 2037 | DDR-LWD indicated nearing upper boundary | Nudge down inclination 91.2° to 90.8° |
| 18 | 876 | 2043 | Intersect top boundary | Down link to 180°-60% |
| 19 | 886 | 2053 | At upper boundary of coal - GR/ROP indicate bit back in coal | 89° inc hold |
| 20 | 907 | 2075 | Bit nearing bed center | PD inclination to 88° |
| 21 | 938 | 2106 | Bit nearing bed center | 0.5° Nudge up |
| 22 | 954 | 2122 | DDR-LWD indicates well path nearing lower boundary | Inclination from 88.8° to 89.3° |
| 23 | 975 | 2143 | GR increasing | PD inclination to 90° |
| 24 | 983 | 2151 | GR back to coal base line | Hold 90.2° and evaluate |
| 25 | 1009 | 2177 | Staying low in section | Increase 0.5° |
| 26 | 1032 | 2200 | DDR-LWD imaging upper boundary | Decrease inclination 0.5 degree |
| 27 | 1051 | 2219 | Top of formation rapidly approaching | Steer at down at 89° - Geol. target 1322.5 m TVD |
| 28 | 1070 | 2238 | Bit nearing bed center | Hold target at 1322.5 m TVD from geos |
| 29 | 1107 | 2275 | Wiper Trip 9:30 - 13:10 | Revised target from geologist to 1321.5 m |
| 30 | 1125 | 2293 | DDR-LWD indicated lower boundary approaching | Downlink - hold inc at 90.5° - Geol. Target 1321 m |
| 31 | 1182 | 2350 | Bed center | Target 1320.5 m -1321.0 m |
| 32 | 1250 | 2419 | DDR-LWD indicating well path nearing upper boundary | Holding inclination 90.2° |
| 33 | 1338 | 2507 | Upper boundary rapidly nearing | Drop inclination to 89.5° |
| 34 | 1357 | 2526 | GR dropping off | Hold course |
| 35 | 1373 | 2542 | Upper boundary 1.0 m from well path | Nudge up to 89.6° inclination to level off |
| 36 | 1399 | 2568 | Wiper Trip 0:15 - 4:45 | |
| 37 | 1443 | 2612 | Bed center | Inclination hold 90° |
| 38 | 1527 | 2696 | Lower Boundary detected | Could not send steering command - well flowing |
| 39 | 1551 | 2720 | Lower boundary 0.5 m from trajectory | TD at 2720 m MD. Inclination 90°. |

## Figures

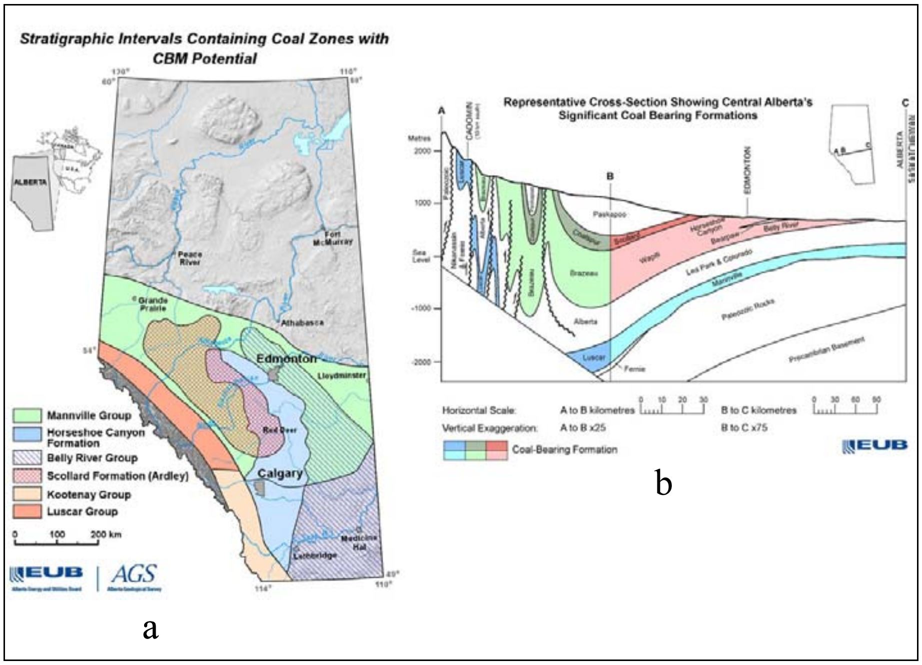


Figure 1: (a) Stratigraphic intervals containing coal zones with potential CBM; (b) cross section of the different coal seams relative to each other based on TVD.

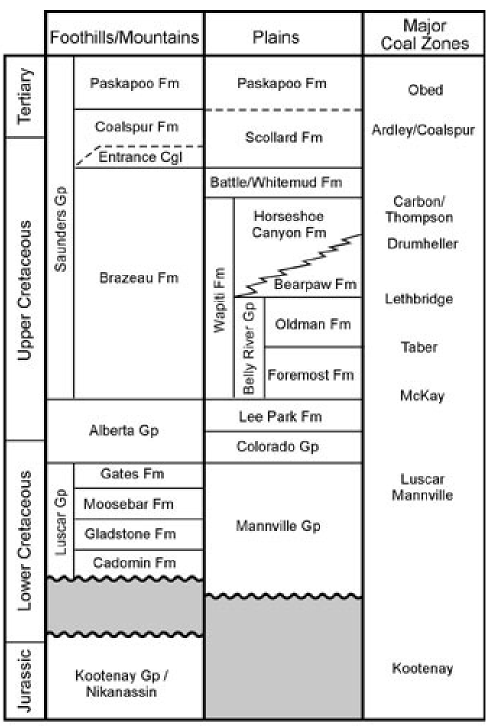


Figure 2: Coal zones in Alberta have potential CBM exploration targets.

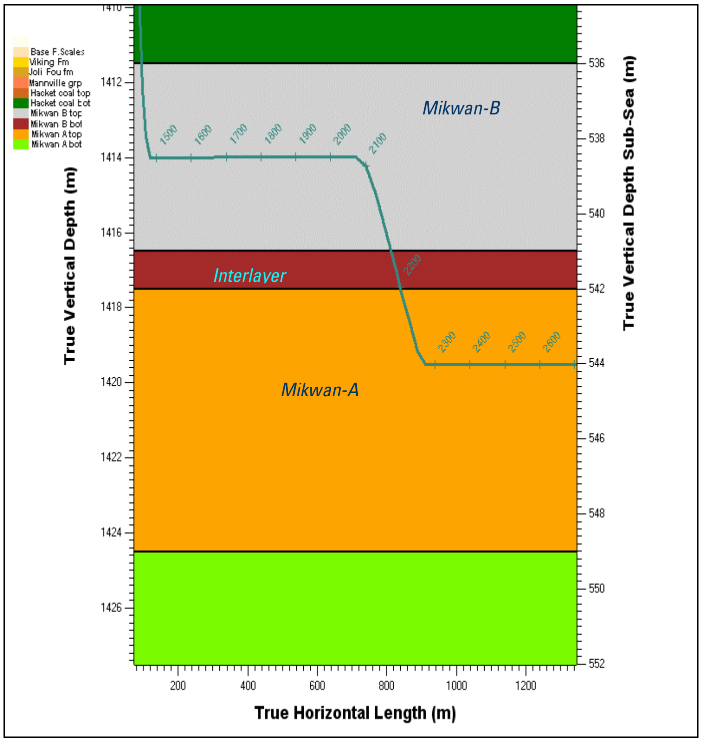


**Figure 3: Vertically exaggerated diagram of planned well trajectory and expected coal, interlayer shale and shoulder beds in TVD.**

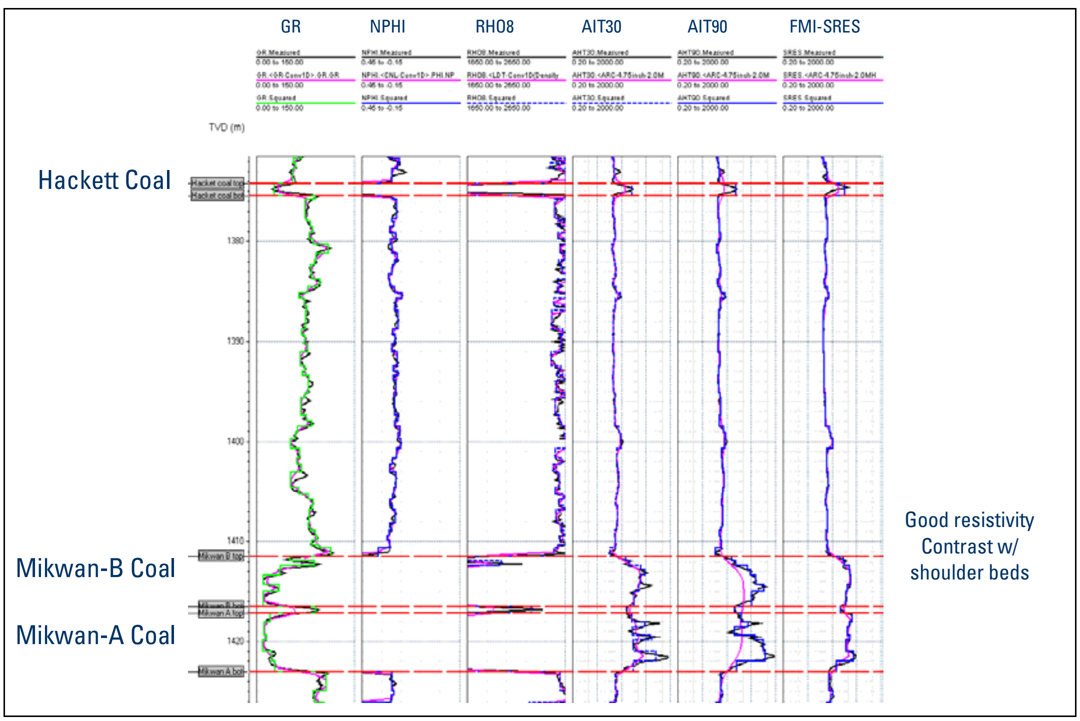


**Figure 4: Log squaring to define bed boundaries.**

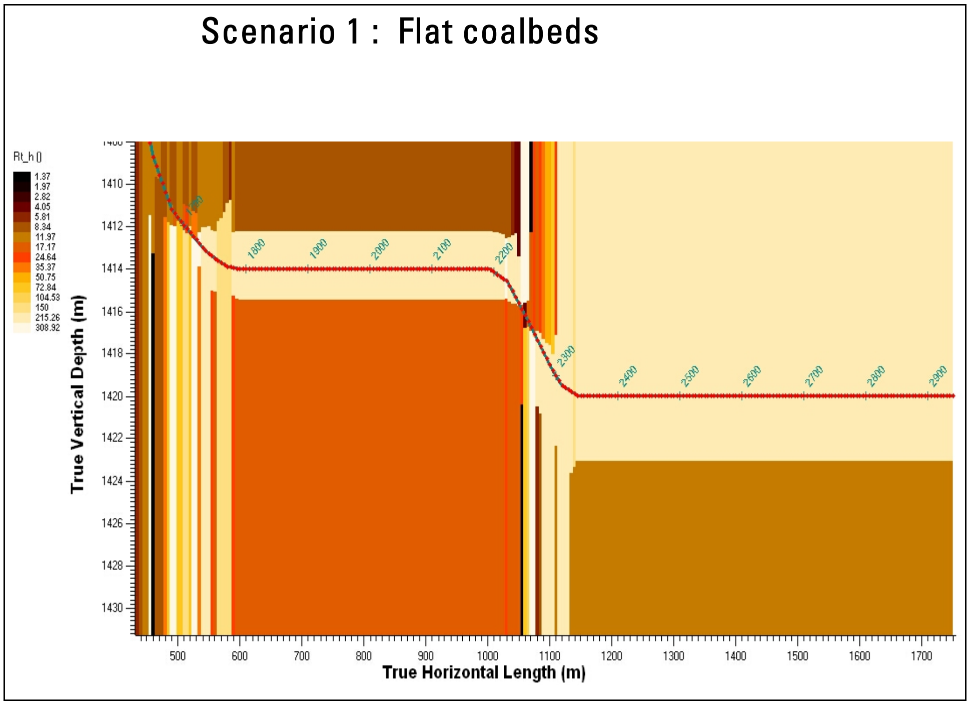


**Figure 5: Scenario 1 – Flat coal beds (resistive – bright color, conductive – dark color)**

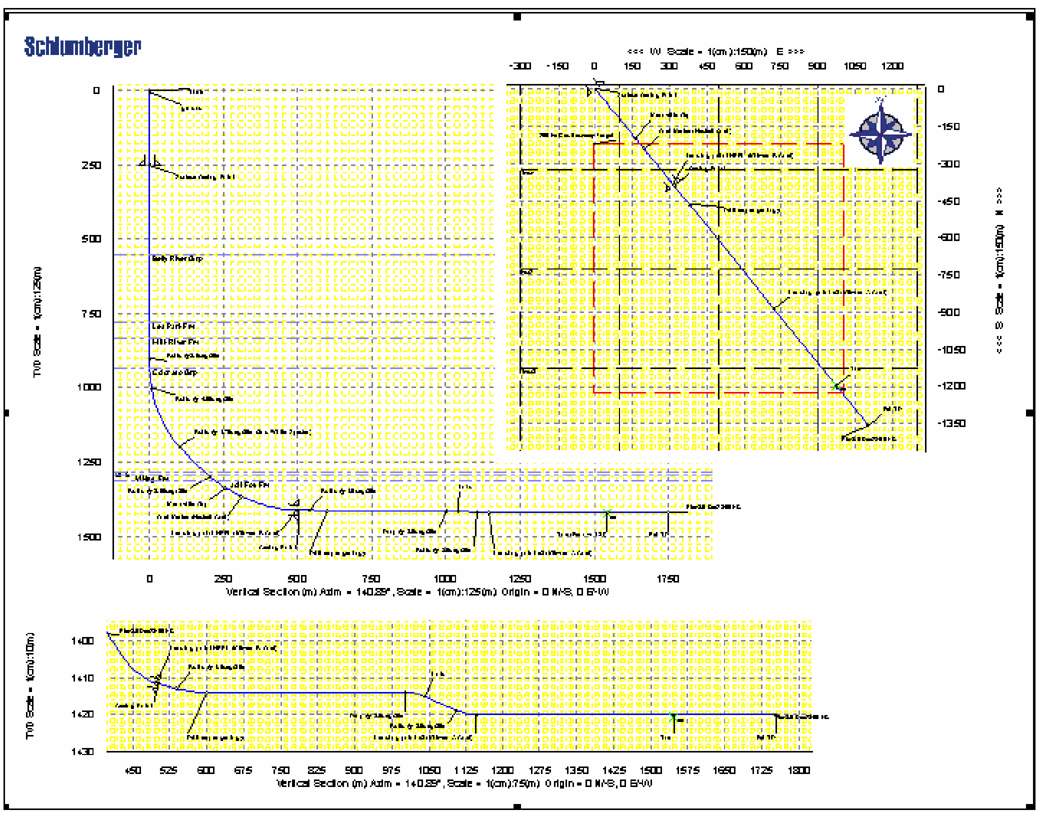


**Figure 6: Well Design**

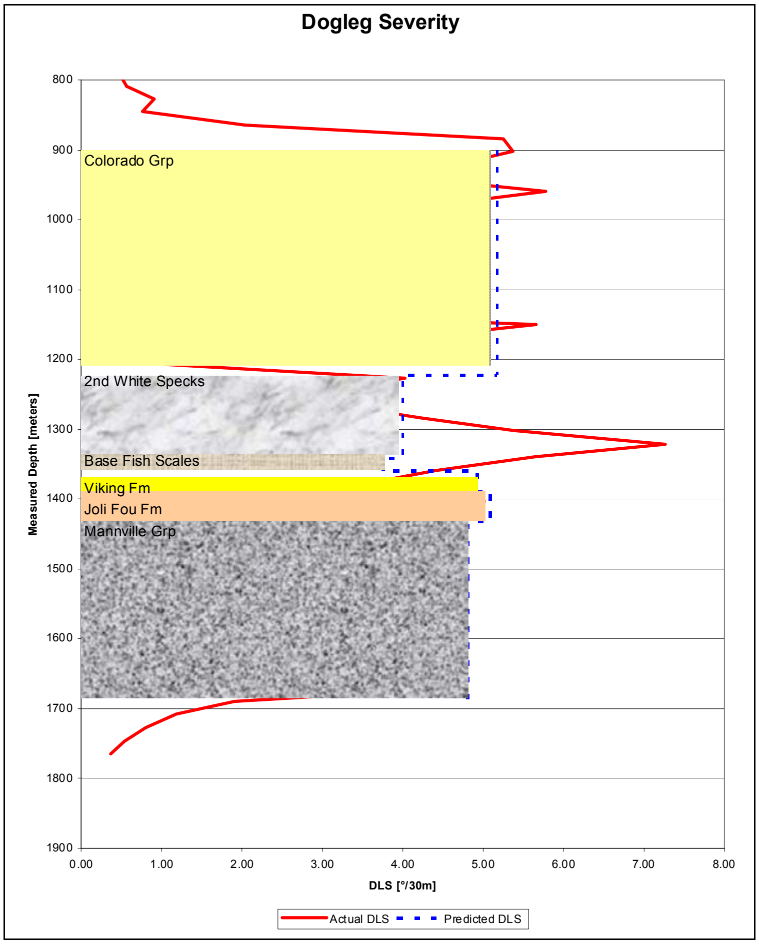


**Figure 7: Dogleg Severity**

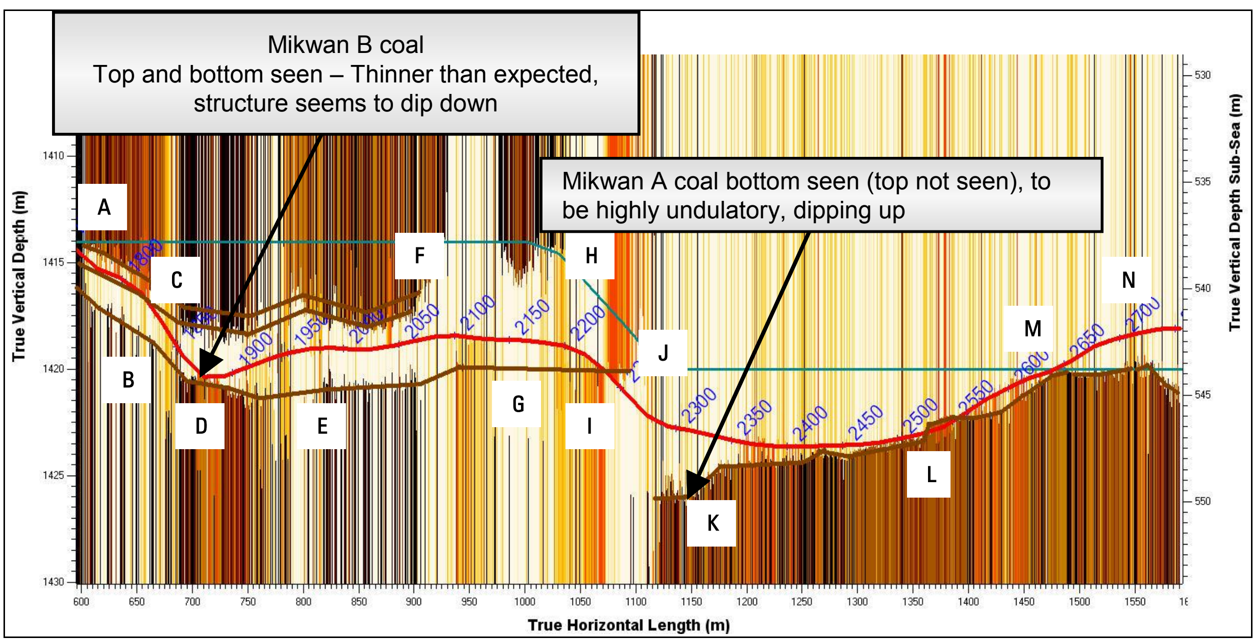


**Figure 8: Mikwan A and B Coal**

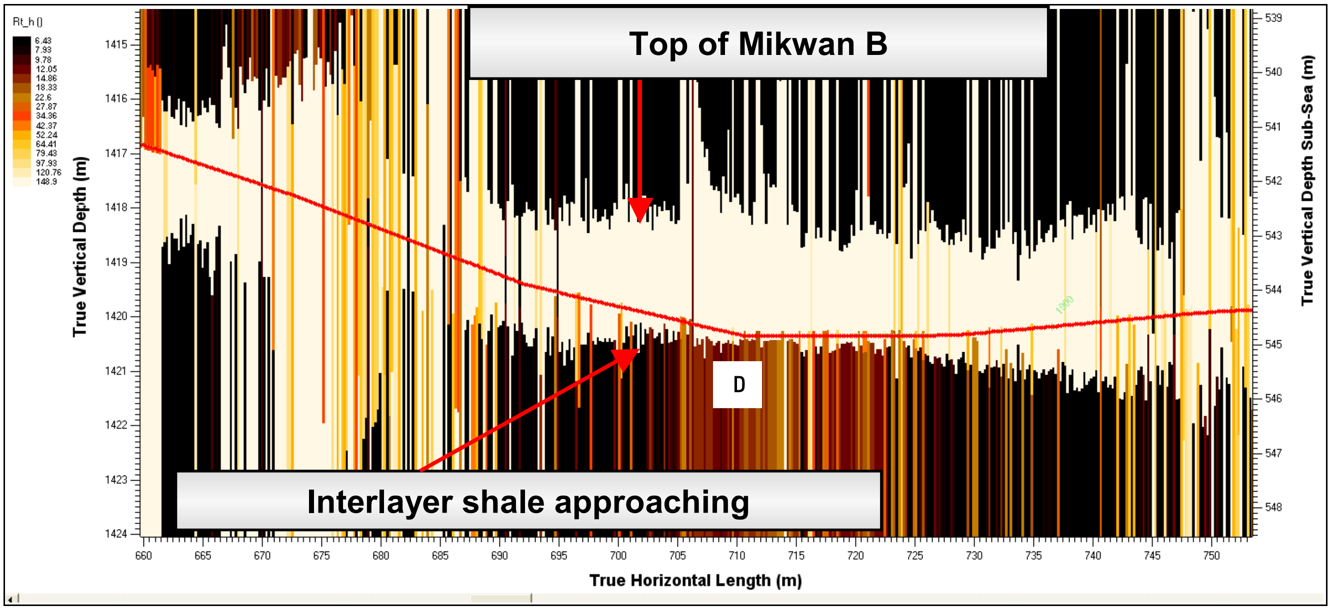


**Figure 9: Interlayer shale between the coals.**

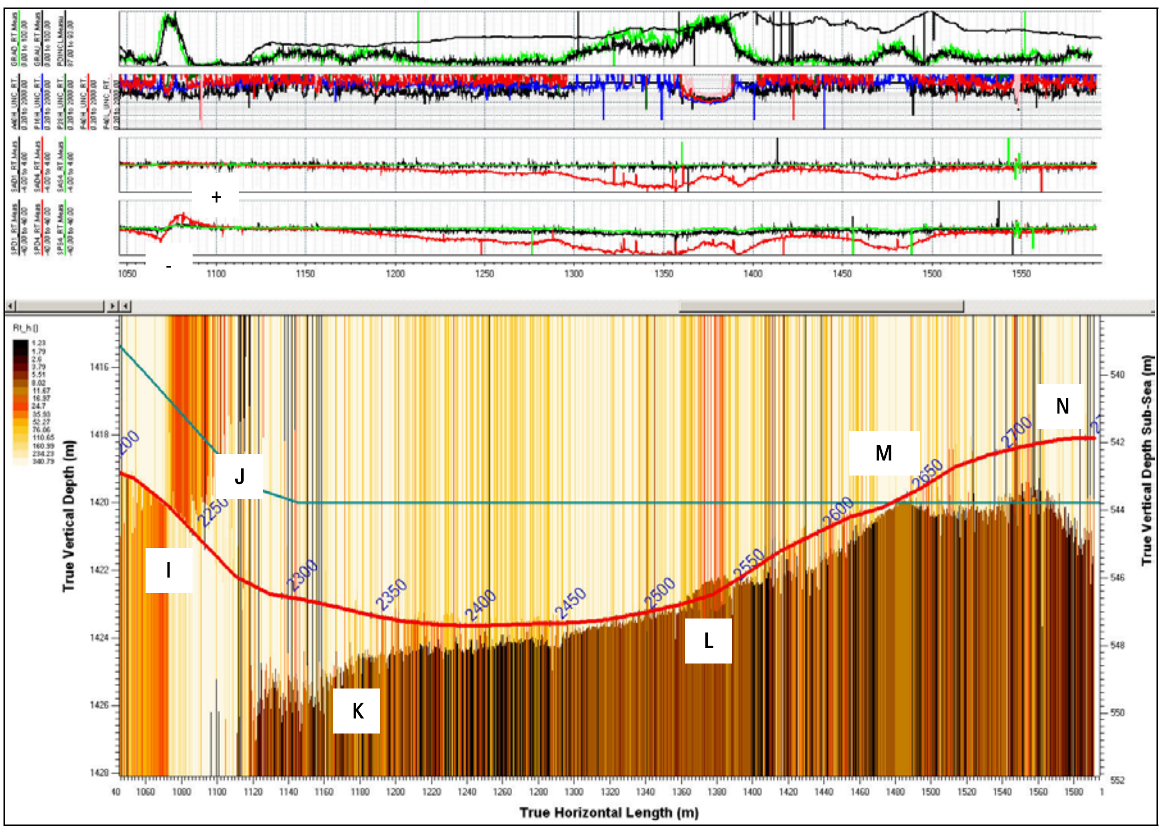


**Figure 10: DDR Boundary Measurement**

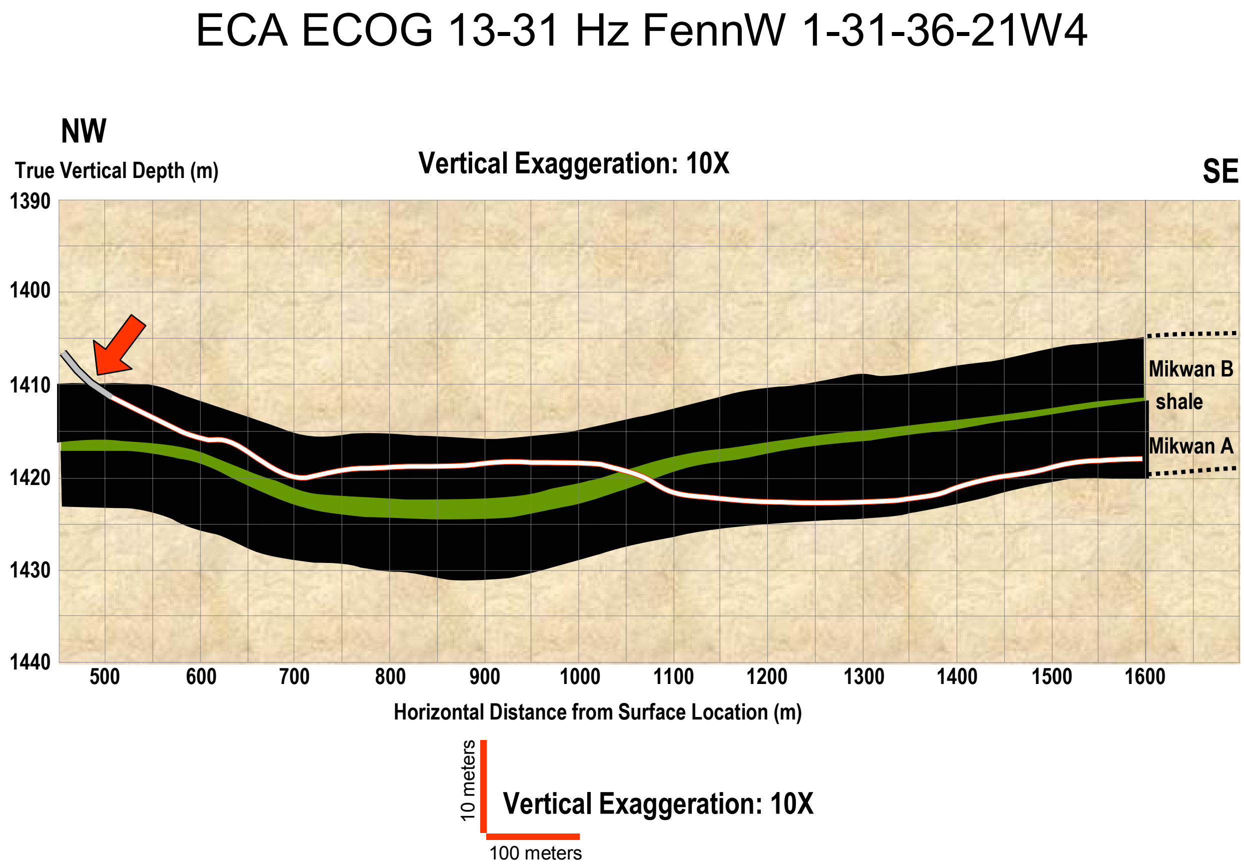


**Figure 11: High structural variance well drilled using DDR-LWD and RSS systems.**

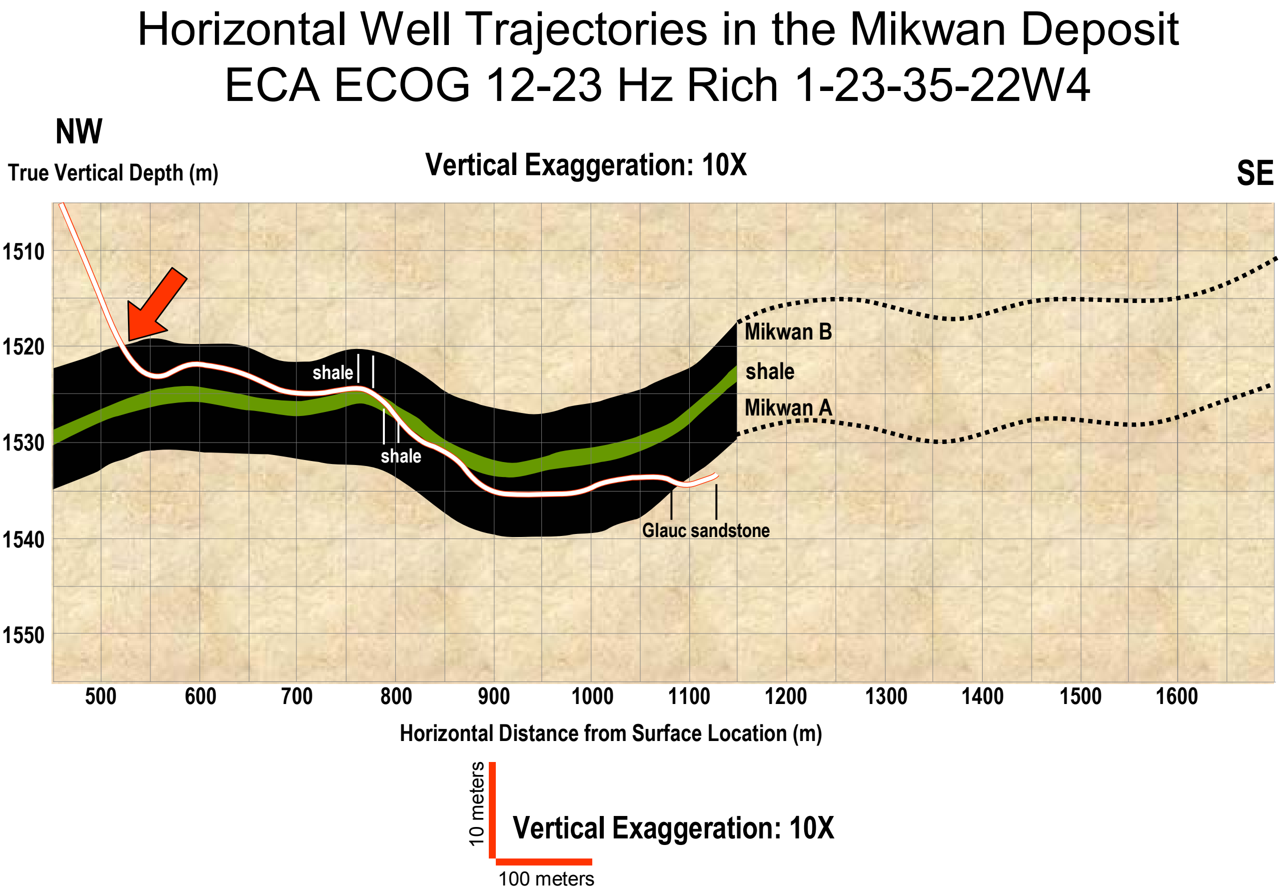


**Figure 12: High structural variance well drilled using conventional technology. Well TD'd early due to coal exit.**

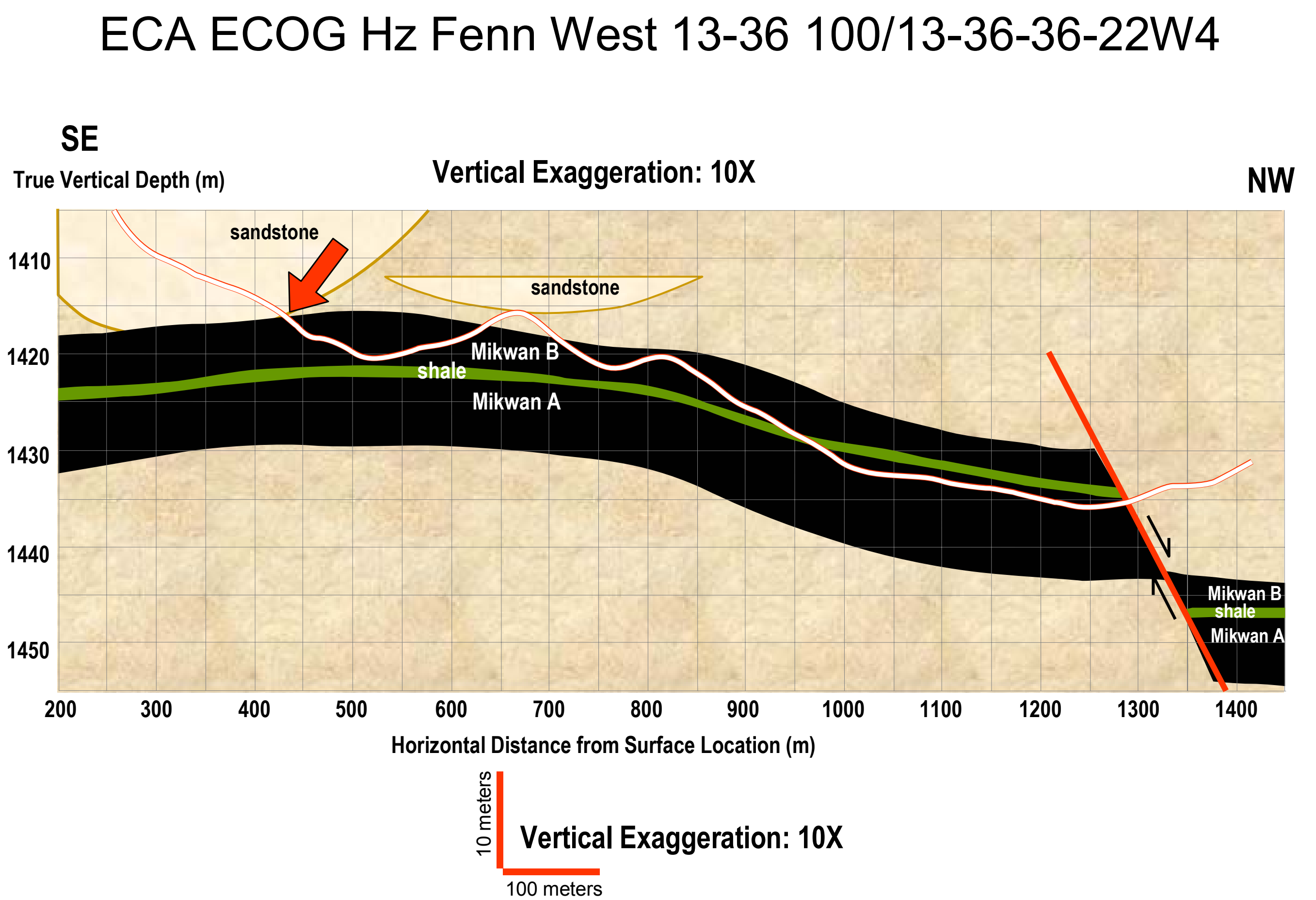


**Figure 13: High structural variance well drilled using conventional technology. Unable to find coal after crossing fault.**

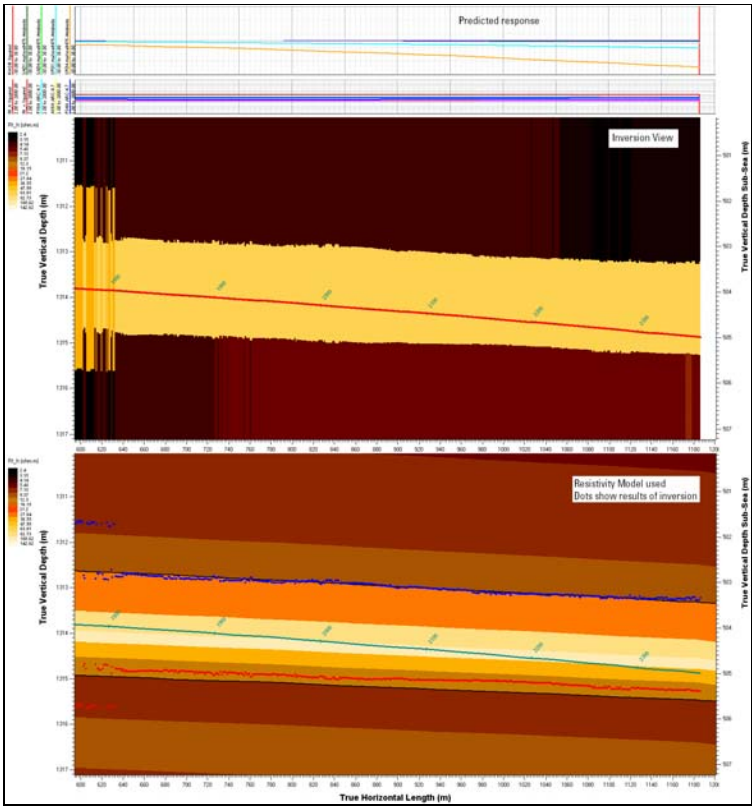


**Figure 14: Prejob Model based on the offset 6-30 well.**

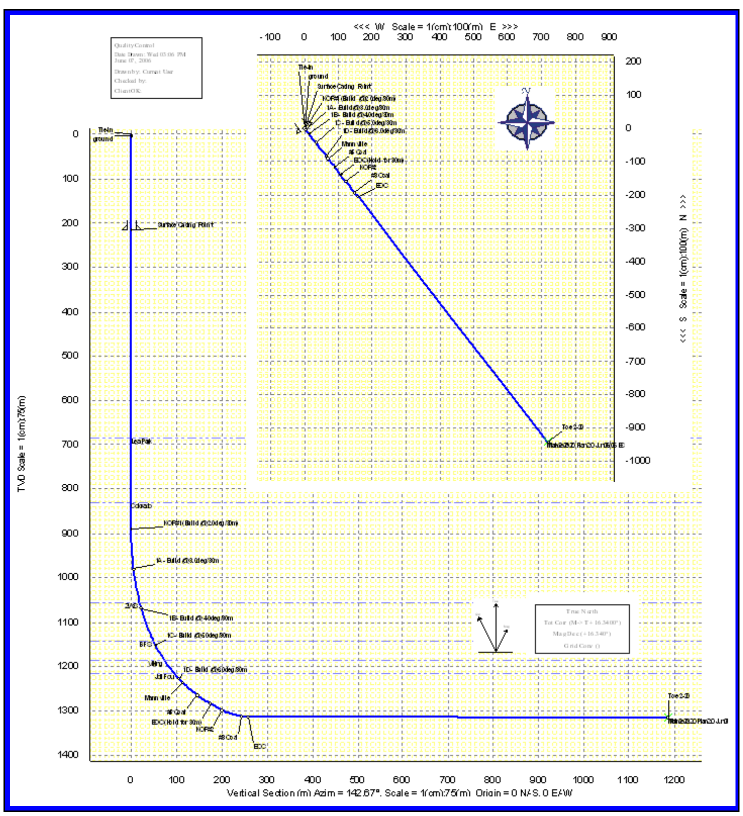


**Figure 15: Wellplan used for Prejob Modeling of the DDR tool**

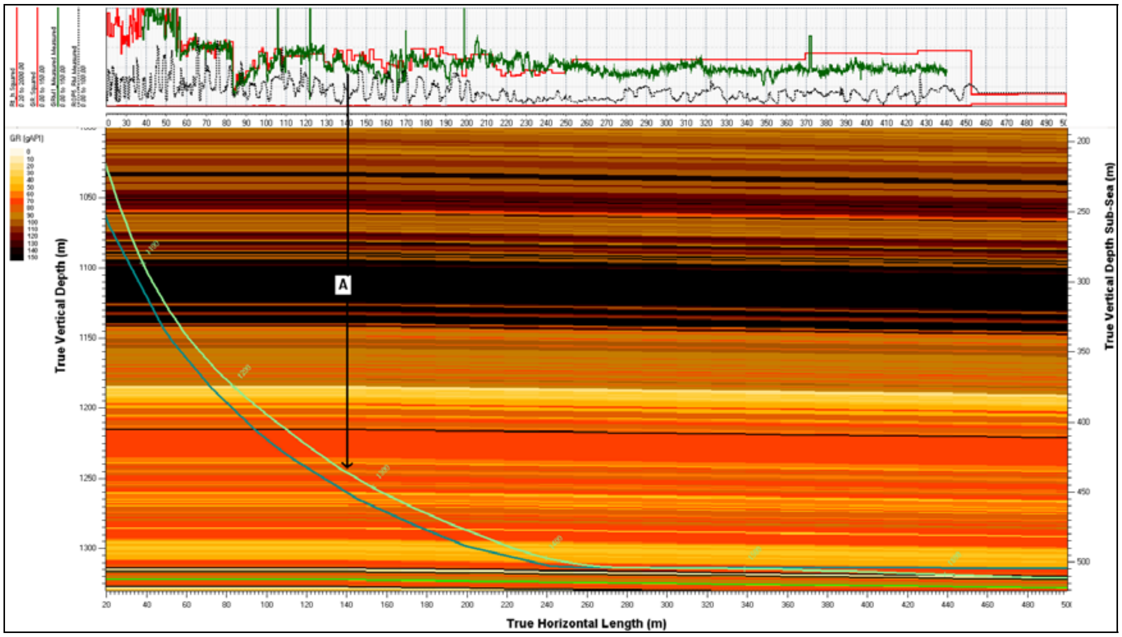


**Figure 16: Landing section shown in RTGS window. Note: good correlation between predicted GR (red) and measured GR (dark green till 1280 MD point "A".**

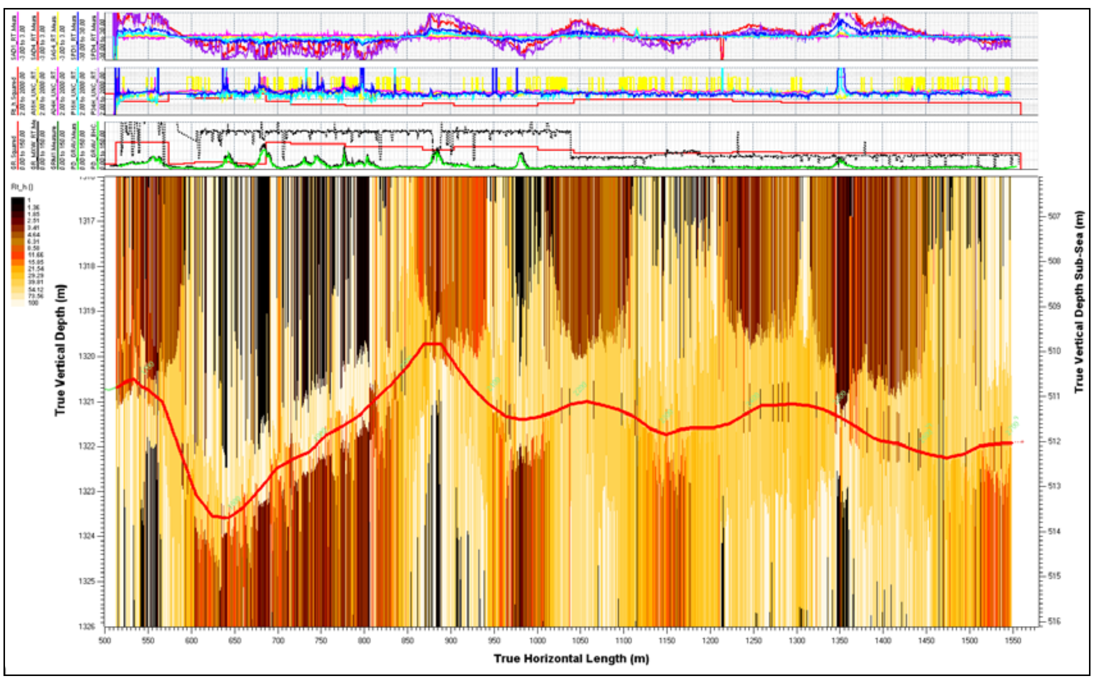


**Figure 17: Final inversion curtain section from end of RT geosteering.**

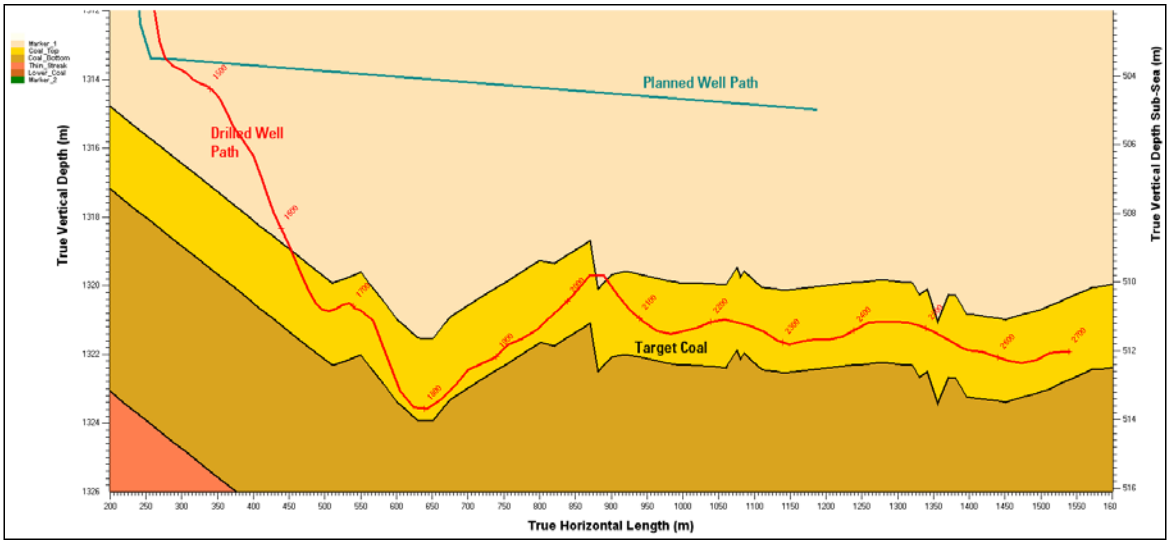


**Figure 18: Cartoon cross section, X100 vertical exaggerations, showing structure as observed from DDR-LWD. Note deviation from planned well path and increase in lateral length.**

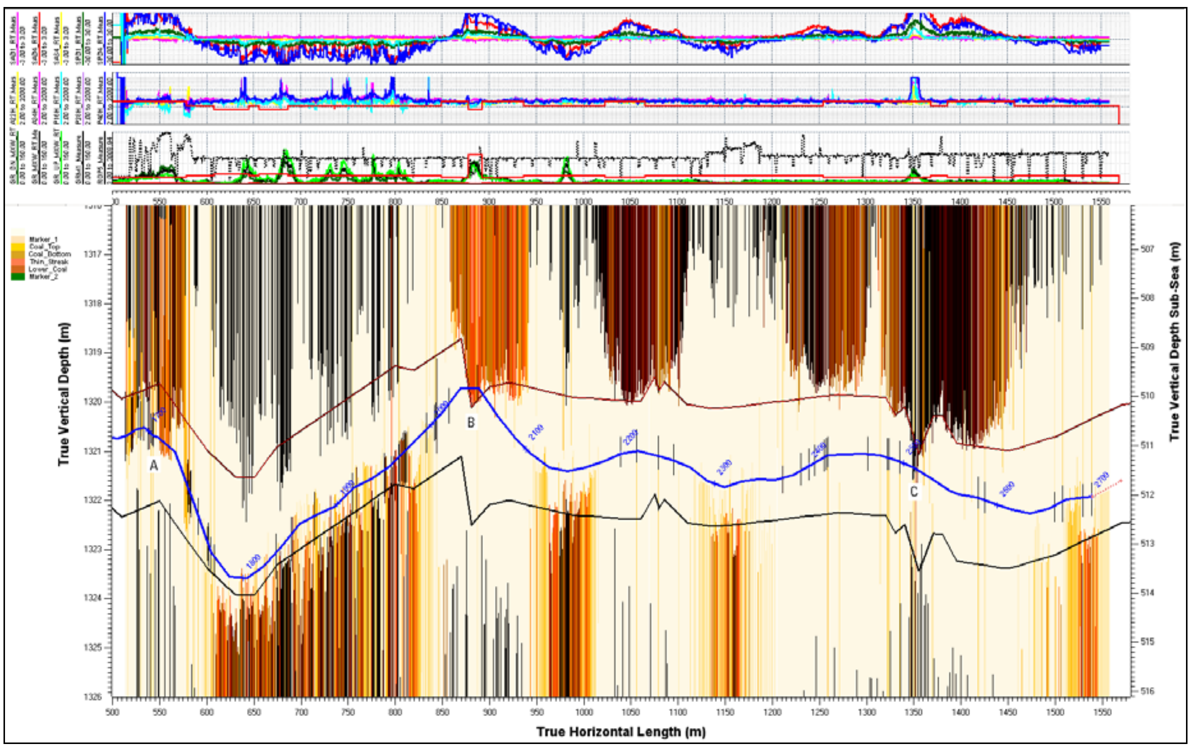


**Figure 19: Final inversion section re-processed with recorded mode data from DDR-LWD. Overlain with correlated boundaries. Sharp features in upper boundary shown at points A, B, C.**

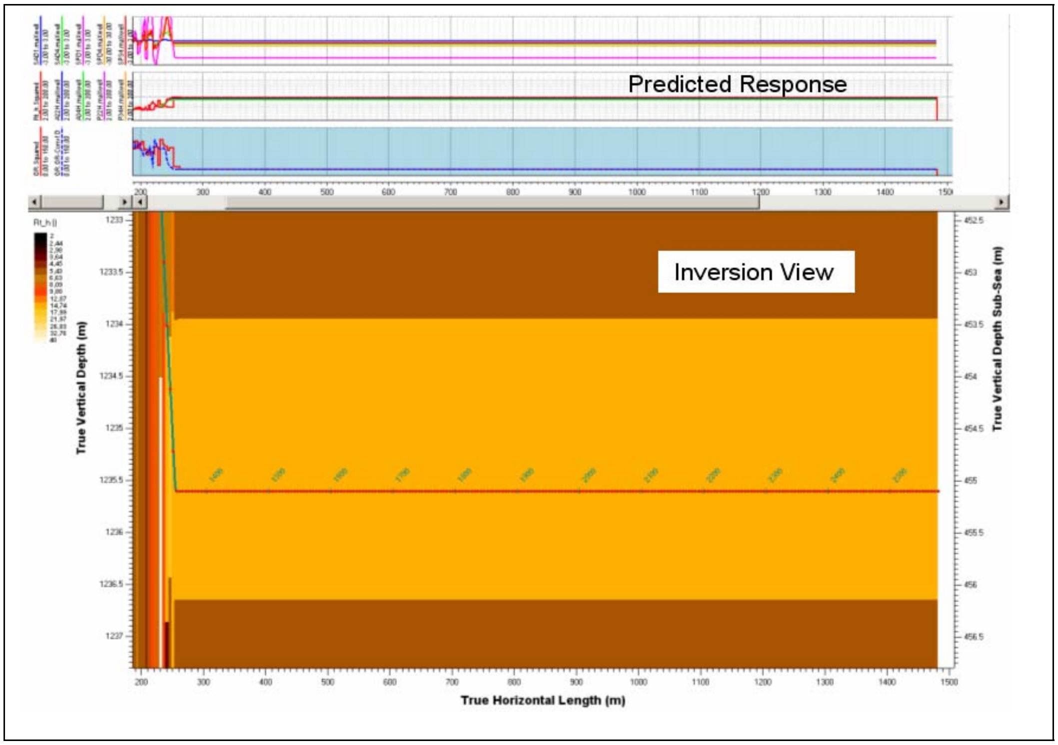


**Figure 20: Prejob RTGS model showing the inversion curtain of expected response in the zone based on the offset well.**

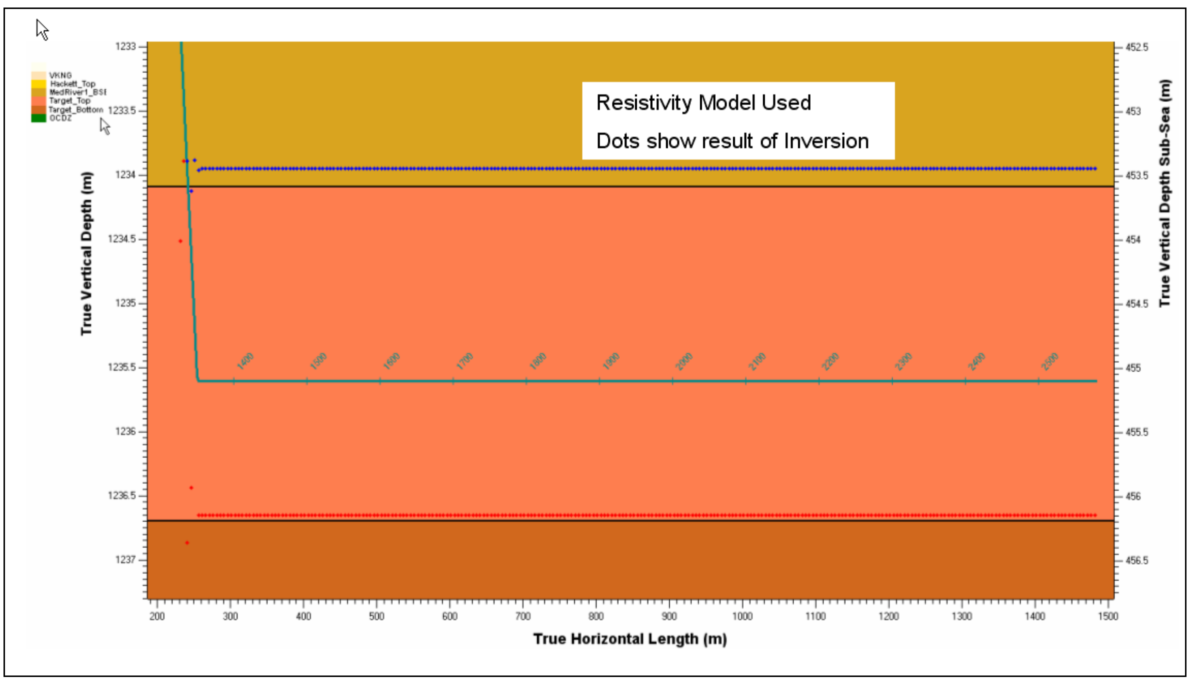


**Figure 21: Prejob RTGS model showing expected response in zone from offset well. Resistivity model is shown.**

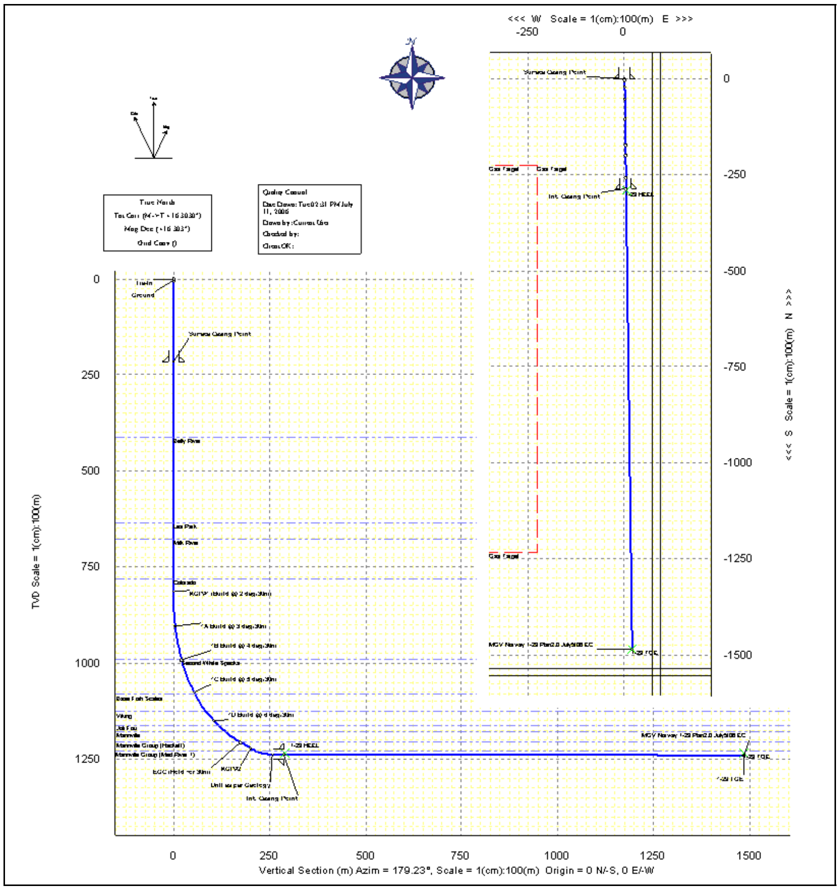


**Figure 22: Landing**

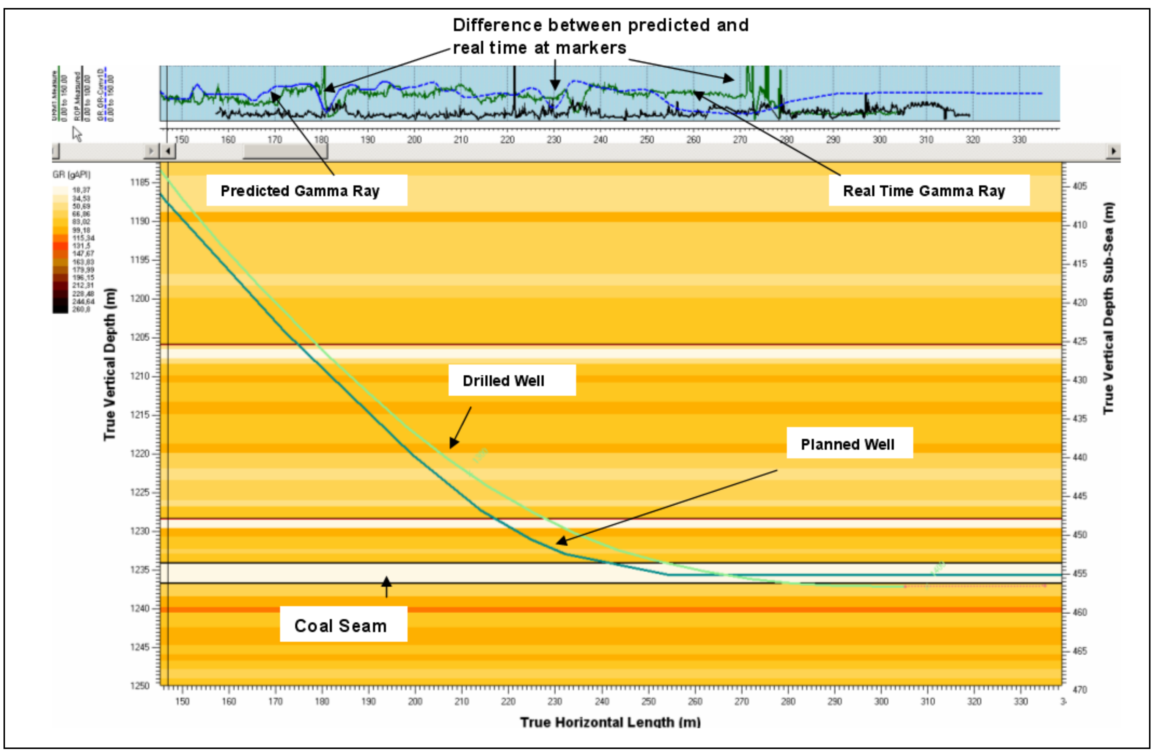


**Figure 23: Landing Section shown in RTGS Window.**

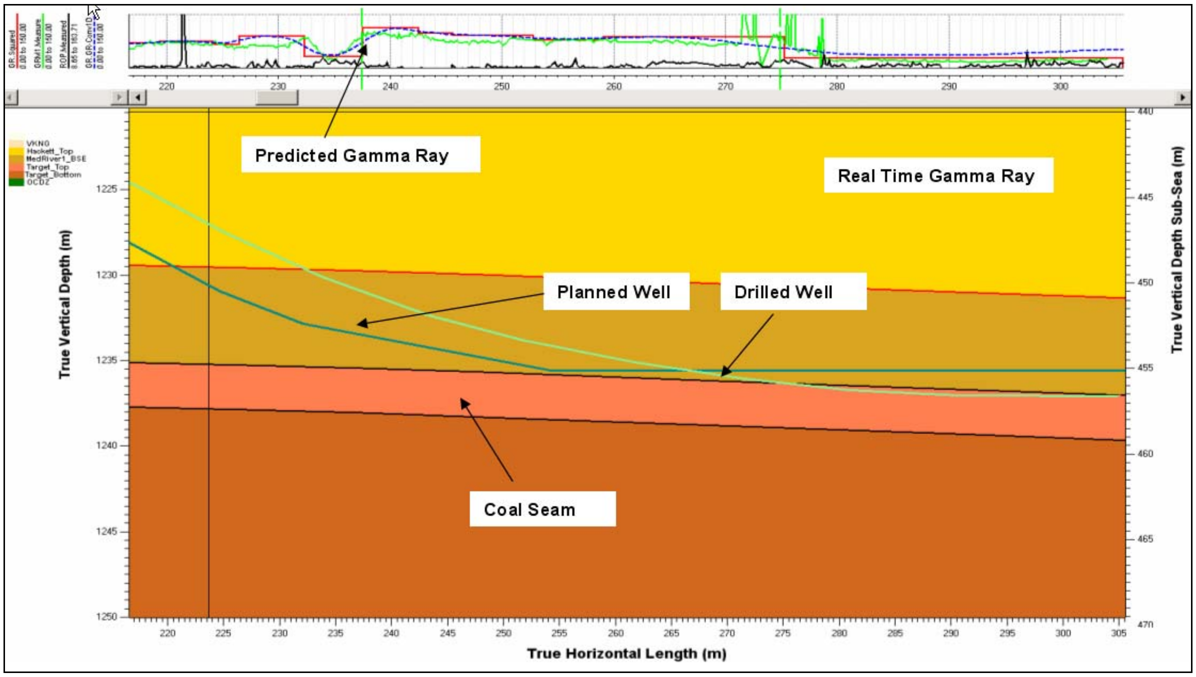


**Figure 24: Correlated curtain section shown in RTGS Windows.**

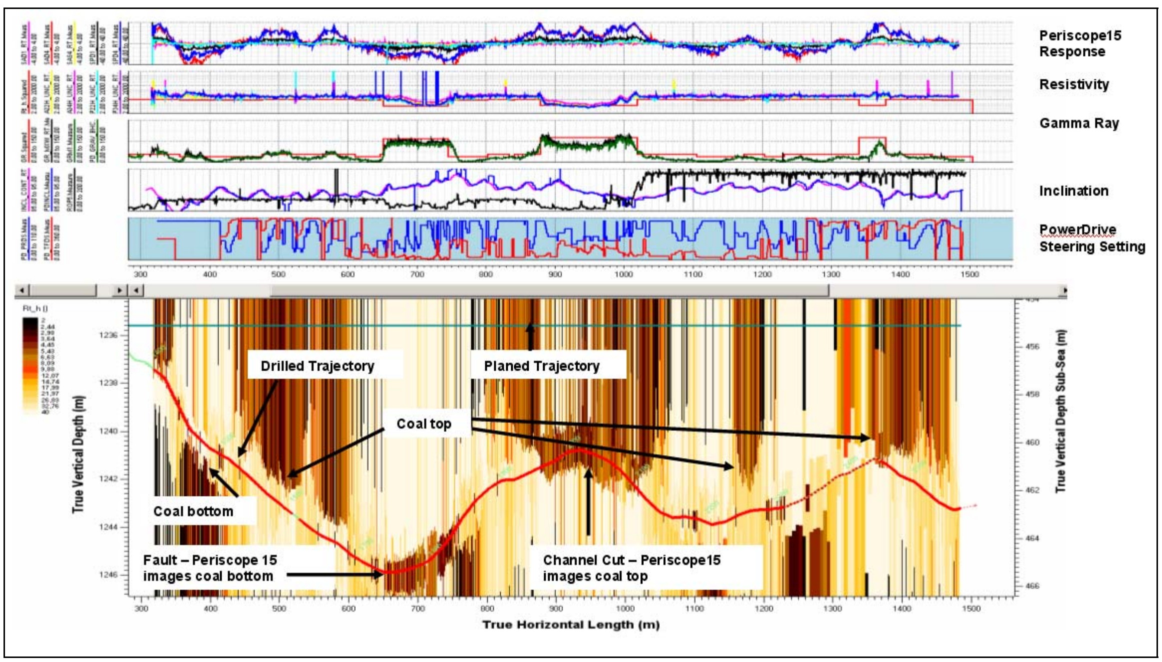


**Figure 25: RT RTGS Inversion**

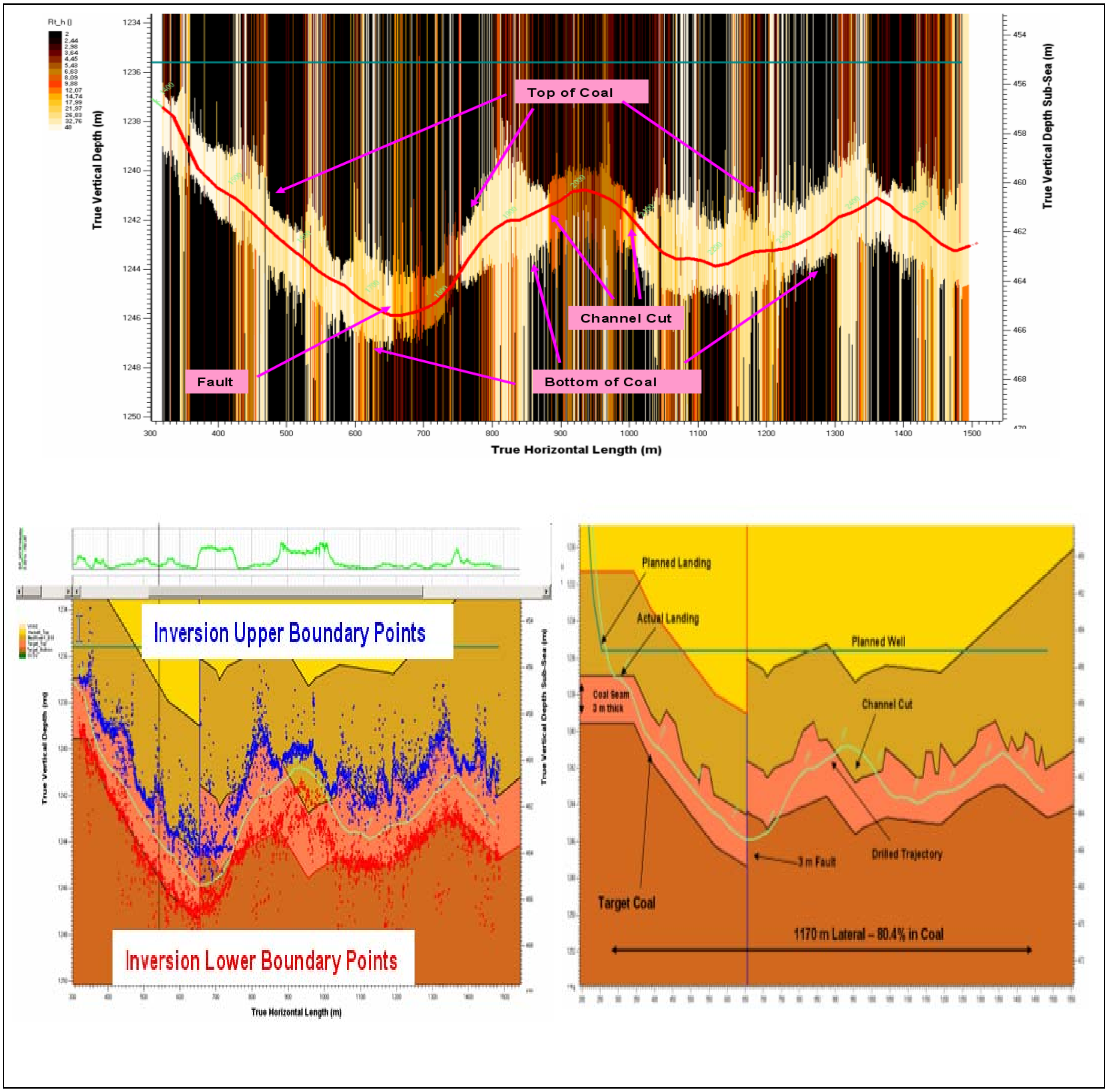


**Figure 26: RTGS Recorded Mode Inversion and Structure Interpretation.**