

# **Integrated Application of Logging-While-Drilling (LWD) Electrical Images to Drilling, Geosteering, and Real-Time Formation Evaluation: A Case Study from the Precambrian Dengying Formation, Central Sichuan Basin of China\***

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Search and Discovery Article #41939 (2016)\*\*

Posted November 14, 2016

\*Adapted from extended abstract based on oral presentation given at AAPG/SEG International Conference & Exhibition, Cancun, Mexico, September 6-9, 2016

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## **Abstract**

A logging-while-drilling (LWD) electrical image tool combined with a rotary steerable system (RSS) was used to drill a horizontal well in the Precambrian Dengying Formation, Central Sichuan basin, China. Drilling the horizontal well was as an experiment to increase gas production from a single well in the complex heterogeneous carbonate formation. Usually vertical wells were drilled to develop the carbonate gas reservoirs in the field. Drilling a horizontal well in the formation presents various challenges, including a large amount of mud loss caused by natural fractures and solution caves, low drilling rate of penetration (ROP) due to the hard and abrasive tight carbonate formation, wellbore instability, and inadvertent sidetracks in the deep-landing target zone. There is also a high risk of gas influx events and measurement-while-drilling (MWD) failure due to high temperatures and mud plugging materials.

The LWD electrical images in the horizontal well revealed the depth of mud loss and low ROP, presented the abnormal geological structure dips that could cause inadvertent sidetracks, and showed the borehole breakout on the borehole wall, which aided in further analyzing wellbore instability while drilling. As a result of the processing of the electrical images while drilling, effective geosteering was performed in the horizontal section of 649 m, of which about 216 m were associated with dissolution vugs - possibly carbonate gas reservoir storage sections. The drilling events that occurred in the horizontal section included 14 bit replacements due to roller bit wear from hard and abrasive rock, 7 MWD replacements due to MWD failure at temperatures greater than 149° C and mud plugging materials, and one key drilling directional control discussion because of abnormal geological structure dip. This case study demonstrates an integrated application of LWD electrical images to drilling, geosteering, and real-time formation evaluation in a horizontal well and presents the significance and value of LWD electrical images when developing a horizontal well in the Precambrian Dengying Carbonate Formation.

## Introduction

The Dengying Formation formed in the Late Precambrian marine carbonate depositional environments of platform margin and mound shoal (Zou et al. 2014). The lithologies of the Dengying Formation are mainly algal dolomite and crystalline dolomite, with occasional saddle dolomite. The Dengying Formation is one of the oldest reservoirs in the world. A long period of deep burial and diagenesis made the reservoir very compact and very tight. The diagenetic processes included penecontemporaneous dolomitization and burial dolomitization as well as hydrothermal dolomitization. The silicification process, however, was the main factor in making the Dengying Formation so tight (Ma et al., 2014; Liu et al. 2007; Shi et al., 2013).

The structural trap area of the Dengying Formation covers up to 7,500 km<sup>2</sup>. The area is associated with 130 normal faults with 10 to 400 m of throw, including 6 faults more than 20 km long. The faults strike south/north, northeast-east/southwest-west, northwest-west/southeast-east, and east/west (Wei et al., 2015).

A long period karst weathering and erosion caused locally well-developed solution vugs and caves in the Dengying Formation. The target reservoirs of the Dengying Formation are fracture-vug reservoirs and vug reservoirs. The average porosity of the target reservoirs is 2.2% to 3.9%, and the average permeability is 0.59 mD (Wei et al., 2015).

The tight formation, complex faults, natural fractures, and secondary solution vugs and caves are challenging for a horizontal well drilling in the Dengying Formation. The potential risks while drilling a horizontal section in the formation were unpredictable mud loss, measurement-while-drilling (MWD) tool jamming, and roller bit wear. This case study demonstrates the integrated application of logging-while-drilling (LWD) electrical images to drilling, geosteering and real-time formation evaluation in a horizontal well in the Dengying Formation. Drilling this well provided good experience and lessons for handling the drilling risks.

## Horizontal Target Location

The horizontal well was planned at a depth 35 m from the top of the Dengying Formation ([Figure 1](#)). The closure azimuth is 5°, the directional azimuth is 23°, and the pre-target displacement is about 645 m. The borehole deviation angle at the entry point (A) is planned as greater than or equal to 85°, and the horizontal section length was planned as 1,000 m from the entry point (A) to the end point (B). The thickness of the target was estimated as 25 m. In fact, due to complex drilling problems in the Dengying Formation, the completed horizontal section is only 649 m in length.

[Figure 1](#) shows seismic data associated with the plan trajectory. The structure is an anticline. The structure of the target layer is 1.4° updip before the entry point (A), and the structure dip increases downdip with an average 1.9° between A and B without fault and structural dip variation.

Two vertical offset wells were used to construct the formation model of the well placement with both the structural information and the properties of the target layer, as shown in [Figure 2](#) and [Figure 3](#). Based on the structural dips of the overlying formations, the structural dip of

the Dengying Formation between wells 2 and 3 is estimated as 0 to 10 degrees, the thickness and depth of the target layer in the horizontal well are estimated as almost the same as the offset well 3, and 35 to 40 m from the top of the Dengying Formation. The gamma ray reading of the target layer is estimated as 10 to 15 g API, the resistivity is 1,000 to 50,000 ohm-m, neutron porosity is 2 to 3.5%, and density is 2.74 to 2.8 g/cm<sup>3</sup>. Compared to the surrounding layers, the gamma ray reading of the target layer is similar to that of the surrounding layers, the resistivity is lower than the surrounding layers, and the bulk density is almost constant, showing little variation.

A horizontal target location is generally planned based on the structural information derived from seismic data and well-to-well log correlation. However, due to the limited vertical resolution of surface seismic data and the assumptions made during the well-to-well log correlation, the actual subsurface structure is often different from that indicated by the plan. LWD real-time data is indispensable for adjusting the planned target location for geosteering. A rotary steerable system (RSS) is required for hole cleaning and closed-loop steering control. It is also advantageous for well placement because the continuous rotation of the bottom-hole assembly (BHA) ensures that LWD image logs are acquired over the entire length of the well.

The gentle structure and medium gas reservoir quality interpreted from the seismic data and well-to-well log correlation indicate this reservoir could be a good candidate for horizontal drilling. It appears that the drilling risk will come only from the greater than 149°C formation temperatures in the Dengying Formation.

### **Drilling Events**

Horizontal well 2 was the first successful high-pressure/high-temperature (HPHT) horizontal well in the Dengying Formation. Eighteen runs from x189 to x838 m were performed in the 5 7/8-in. horizontal section. For seven runs, POOH occurred due to tool failure caused by high circulating temperature greater than 149° C (maximum circulating temperature is 154° C), including lost signal and MWD electrodes burned and jamming. For six runs, POOH occurred due to low rate of penetration (ROP), PDC bit damage and ring out, and tricone bit loss cone. For two runs, POOH occurred due to hole loss and kick. One key drilling directional control discussion was held because of abnormal geological structure dip.

Total footage is 649 m in the horizontal well. The footage in run 3 was 199 m, and other runs were less than 100 m. The drilling efficiency was a very low 18%, and the average daily footage was 11 m. However, the RSS increased ROP by 21% compared to conventional motor.

A summary of the runs is given below:

- Run 1, depth out x194 m, pumping time 53.9 hours, footage 5 m; the reason for POOH was hole loss.
- Run 2, run in hole (RIH) with wiper trip BHA and drilling 5 m.
- Run 3, depth out x398 m, pumping time 137.5 hours, footage 199 m; the reason for POOH was hole loss.
- Run 4, RIH with wiper trip BHA and drilling 17 m.
- Run 5, depth out x450 m, pumping time 43.3 hours, footage 33 m; the reason for POOH was PDC ring out ([Figure 4](#)).
- Run 6, depth out x504 m, pumping time 38.6 hours, footage 54 m; the reason for POOH was PDC ring out ([Figure 4](#)).

- Run 7, depth out x563 m, pumping time 60.3 hours, footage 59 m; the reason for POOH was roller lost cone and lost signal.
- Run 8 and 9, run fishing and clearing out BHA.
- Run 10, depth out x569 m, pumping time 50.8 hours, footage 99 m; the reason for POOH was MWD lost signal.
- Run 11, depth out x569 m, pumping time 0.6 hours, footage 0 m; the reason for POOH was MWD jamming during a shallow hole test.
- Run 12, depth out x716 m, pumping time 51.0 hours, footage 47 m; the reason for POOH was MWD lost signal.
- Run 13, depth out x716 m, pumping time 8.9 hours, footage 0 m; the reason for POOH was abnormal stand pipe pressure (SPPA).
- Run 14, depth out x730 m, pumping time 19.9 hours, footage 15 m; the reason for POOH was low ROP and LWD failure.
- Run 15, depth out x753 m, pumping time 53.8 hours, footage 23 m; the reason for POOH was low ROP and MWD failure to take survey.
- Run 16, RIH with wiper trip BHA.
- Run 17, depth out x799 m, pumping time 116.5 hours, footage 46 m; the reason for POOH was MWD failure to take survey.
- Run 18, Motor BHA drill to total depth x838 m, pumping time 120 hours, footage 39 m.

Note that real-time LWD electrical image logging was performed only in the first 14 runs of the 18 runs. Conventional motor drilling was used in the last 4 runs.

### **Geosteering and Quicklook Formation Evaluation**

Real-time LWD electrical image logs present the geological features, vugs, caves, and fractures, as well as the artificial drilling event, breakout. The cumulative thickness of the vugs in the horizontal section is 216 m, including two solution caves. One cave at depth x215 m is about 1 m in height; another cave at depth x499 m is about 2.5 m in height. The vugs and caves mainly occur in the sections x189 to x240 m and x360 to x540 m. The drilling breakouts occur in the section x560 to x720 m, as shown in [Figure 5](#). The 14 drilling events and the low drilling ROP occurred only in the vug and the breakout sections ([Figure 5](#) and [Figure 6](#)).

In general, a low drilling ROP is typical of drilling in hard and abrasive rock in a tight formation with low porosity, wellbore instability, and inadvertent sidetracks in the deep landing target zone. However, the low ROP in the horizontal section of well 2 occurred in the vug and cave sections – the carbonate gas reservoir sections. From the core photographs ([Figure 7](#)), the reason is clear. The roller bit wears in the horizontal section drilling, and this is most likely caused by euhedral quartz fill in the vugs and caves.

Particularly after run 14 at the depth x730 m, drilling was stopped to discuss if drilling ahead would cut through a high-resistivity layer. The formation with high-resistivity log reading was considered as a hard and abrasive rock, which could cause drilling events, roller bit wear, or breakout. Based on the structural dips from LWD electrical image logs, the decision was made to make runs 15, 16, 17, and 18; build inclination up towards 90° drilling a total footage of 108 m; and POOH to the depth x838 m where the inclination was 90.5°.

The 3-D model indicates that run 14 drills through the high-resistivity layer, as shown in [Figure 8](#). However, no roller bit wear event occurred. This suggests that the high-resistivity layer is not an essential factor for a drilling event, i.e. bit replacements due to roller bit wear. The geological structural dips from LWD image logs indicate that the well trajectory is cutting down from x189 to x578 m, cutting up from x578 to

x653 m, and then cutting down again from x653 to x799 m. [Figure 8](#) shows that the lower-resistivity sections correspond to the sections with vugs and caves (i.e. gas reservoir storage).

### **Conclusions**

Real-time LWD electrical image logs reveal that it is the vugs and caves in the horizontal section that cause a low drilling ROP rather than the low-porosity tight formation. Core data further indicate that euhedral quartz fill in the vugs and caves could be a major factor resulting in low ROP and roller bit wear.

Structural dips from real-time LWD electrical image logs improve the structural model of the well placement from the seismic data and well-to-well log correlation, which is the key for geosteering. The combination of the LWD electrical image tool and RSS improves ROP in horizontal section drilling.

High-temperature and high-pressure in the Dengying Formation is a big challenge for MWD tools during horizontal section drilling. Due to a large amount of mud loss caused by caves and fractures in the Dengying Formation, mud plugging materials are another negative factor for MWD tools.

This case study presents that LWD borehole image logs were visualized in real time and revealed the intervals with good reservoir quality in the form of vugs and caves. This secondary porosity is believed to be the primary mechanism for gas storage in the Dengying Formation. These image logs also allowed geologists and drilling engineers to collaborate and better explain drilling issues such as low ROP, bit wear, etc. Borehole image analysis suggests that lower ROP and bit wear issues correlated to intervals having vuggy porosity and borehole breakout. And surprisingly, intervals having lower porosity were drilled efficiently.

### **Acknowledgements**

The authors would like to thank PetroChina SWOGC Shunan for supporting the LWD data acquisition. We also thank PetroChina SWOGC Shunan for permission to publish this article and release the data.

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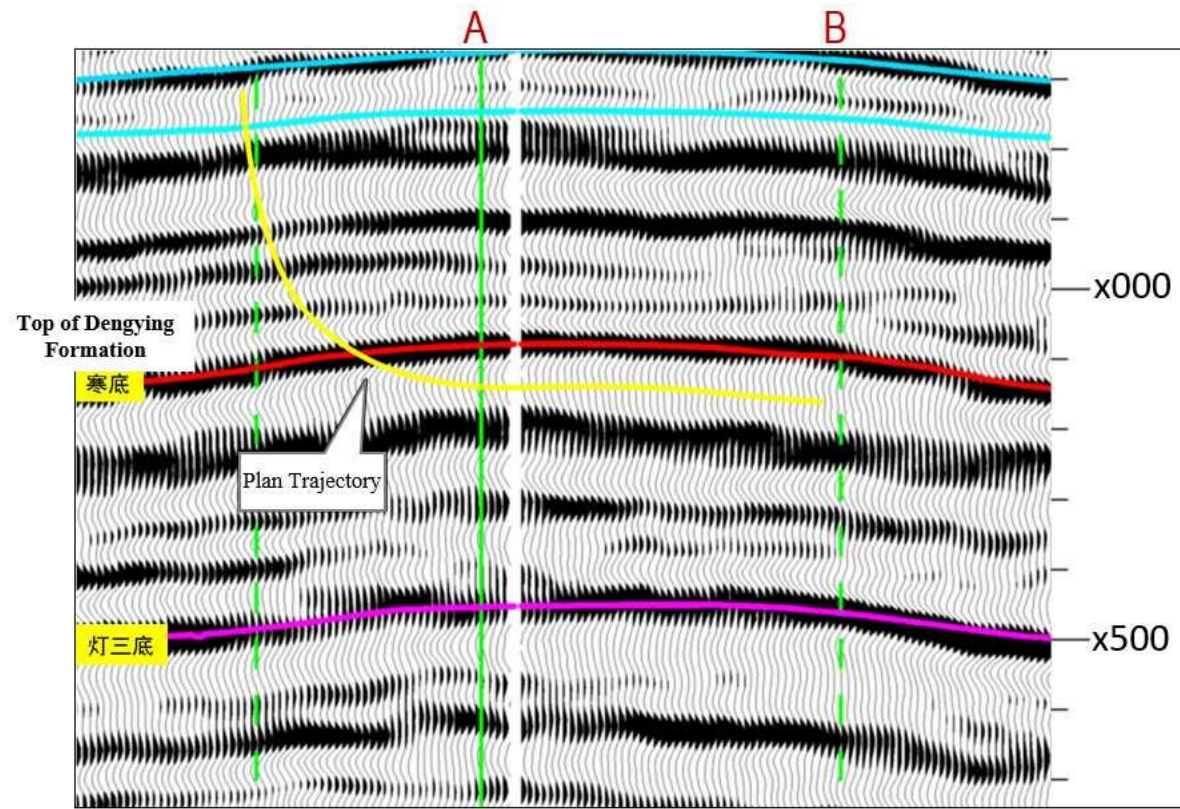


Figure 1. Structural section with plan trajectory from surface seismic data.

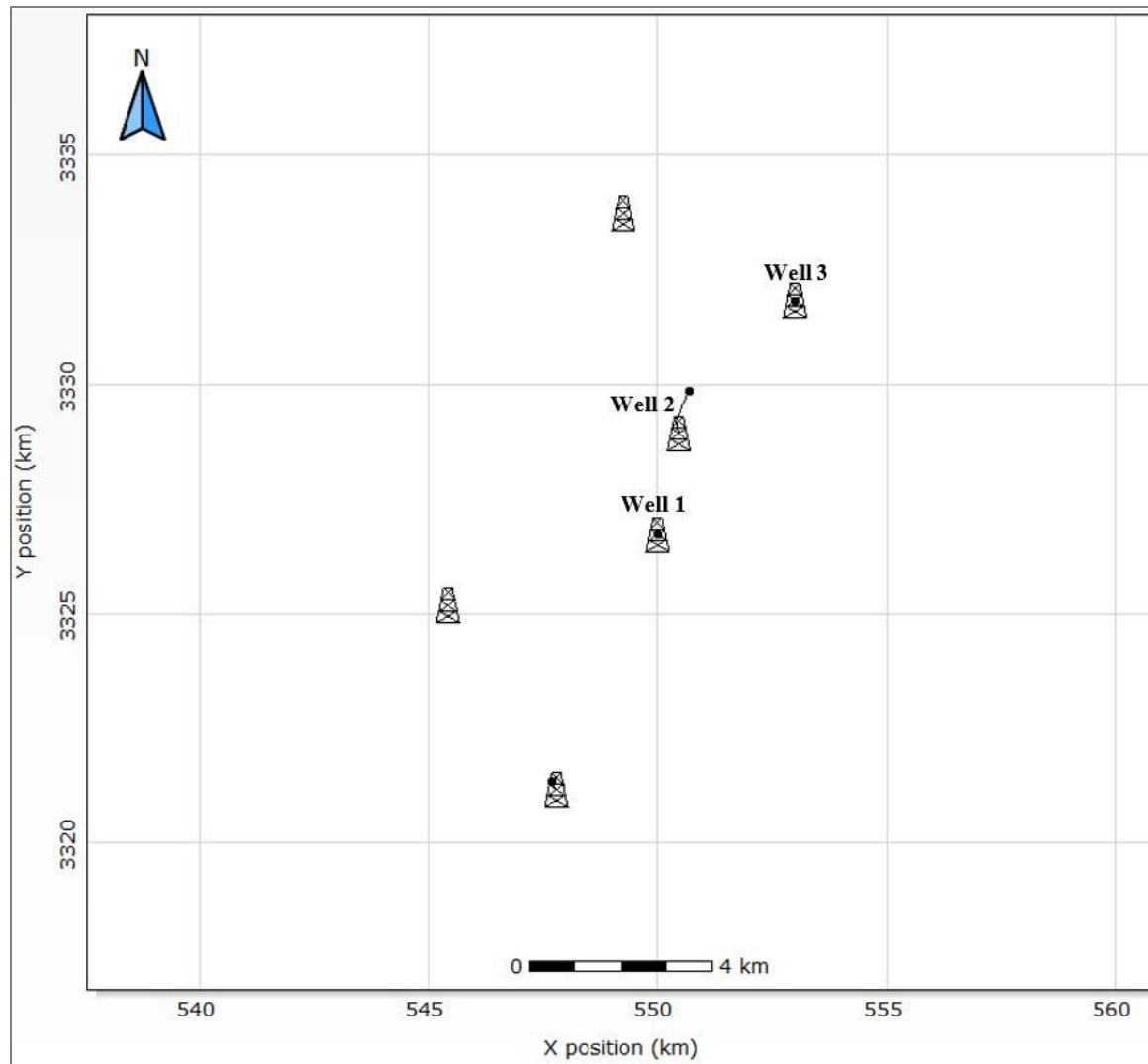


Figure 2. Map of the well locations, including horizontal well 2 and vertical offset wells 1 and 3.



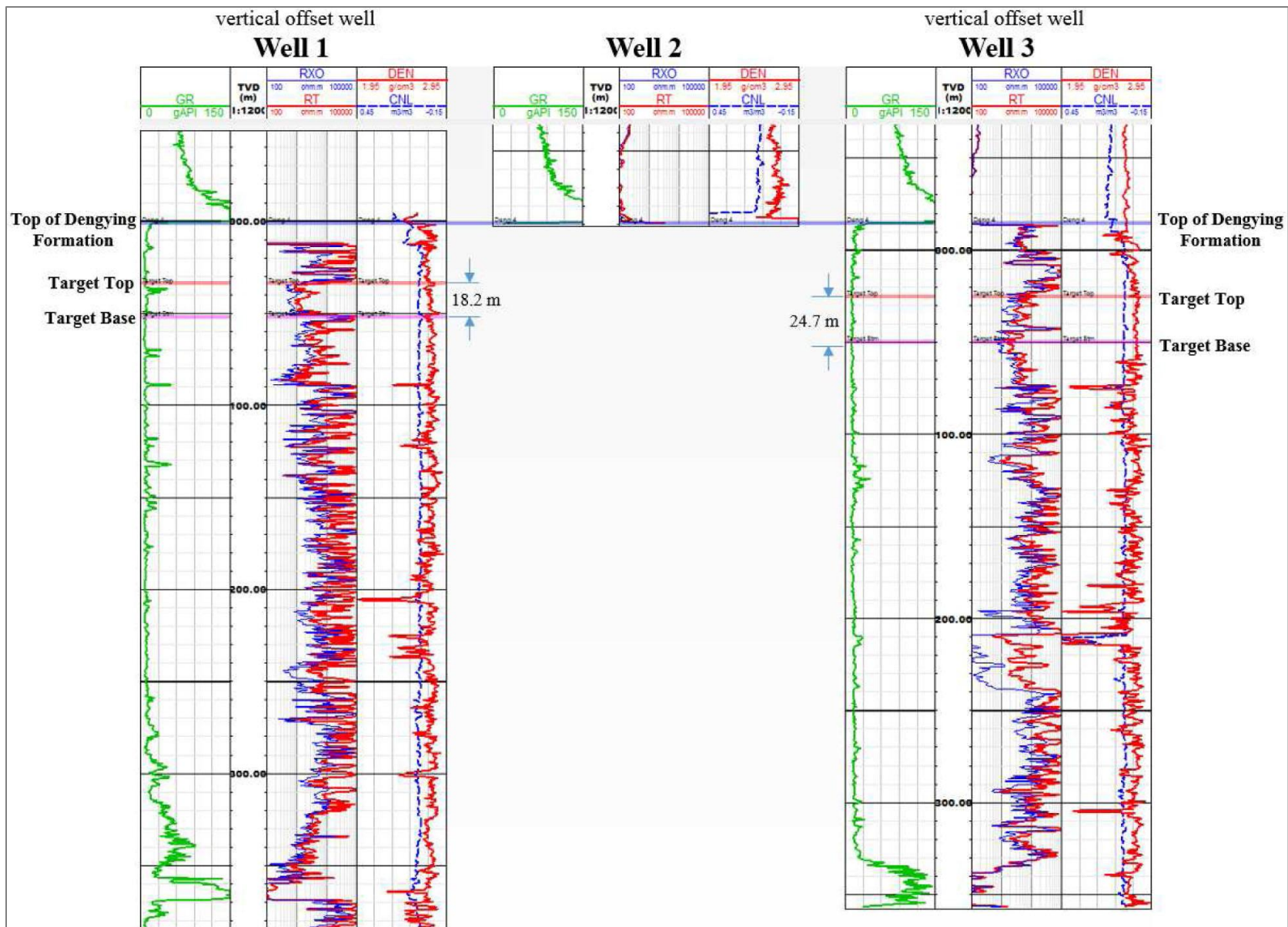


Figure 3. Vertical offset well log correlation.



Figure 4. Photographs of the PDC bit ring out in runs 5 and 6.

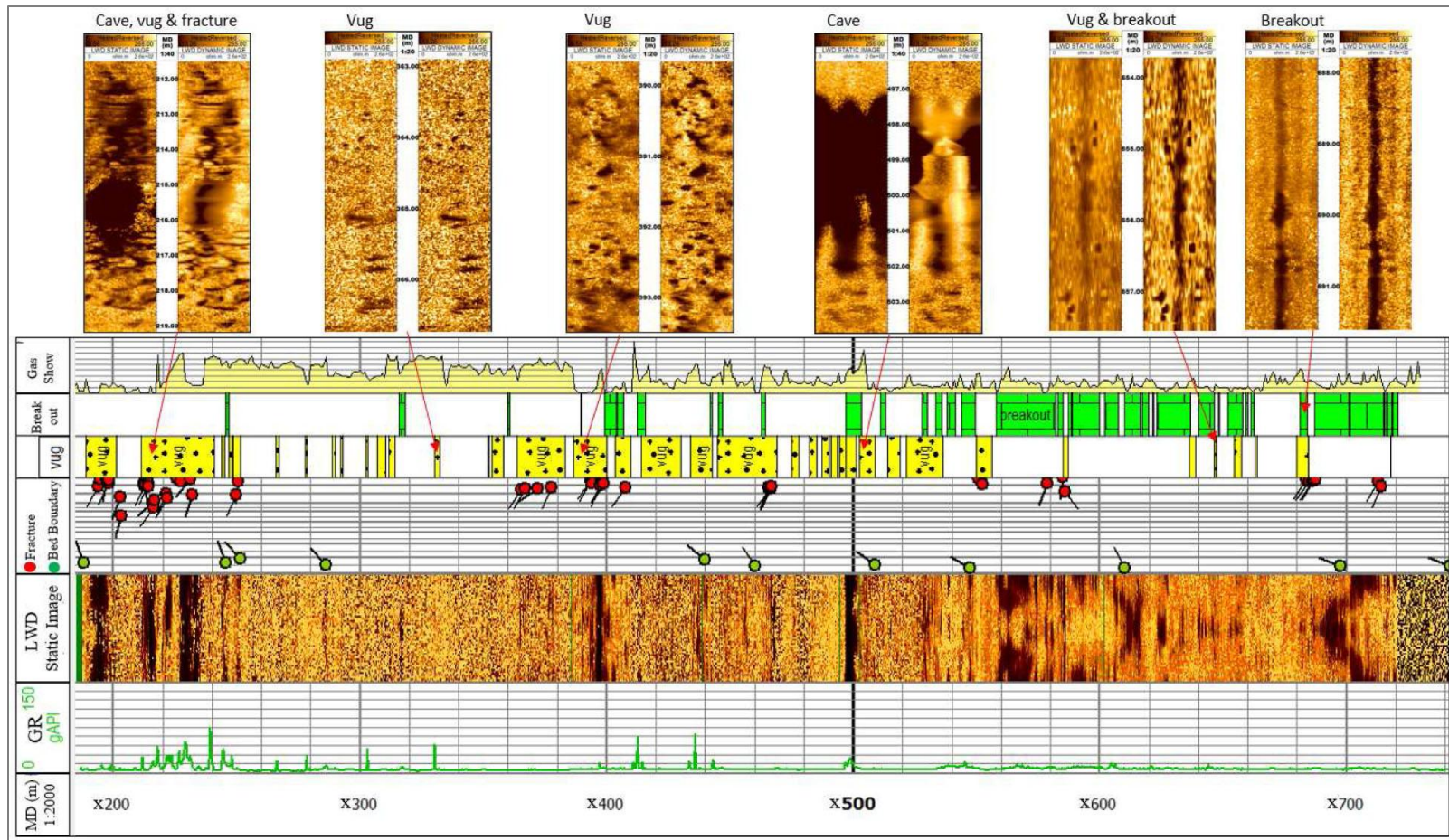


Figure 5. Display of the Quicklook formation evaluation from LWD image logs in the horizontal section of well 2.



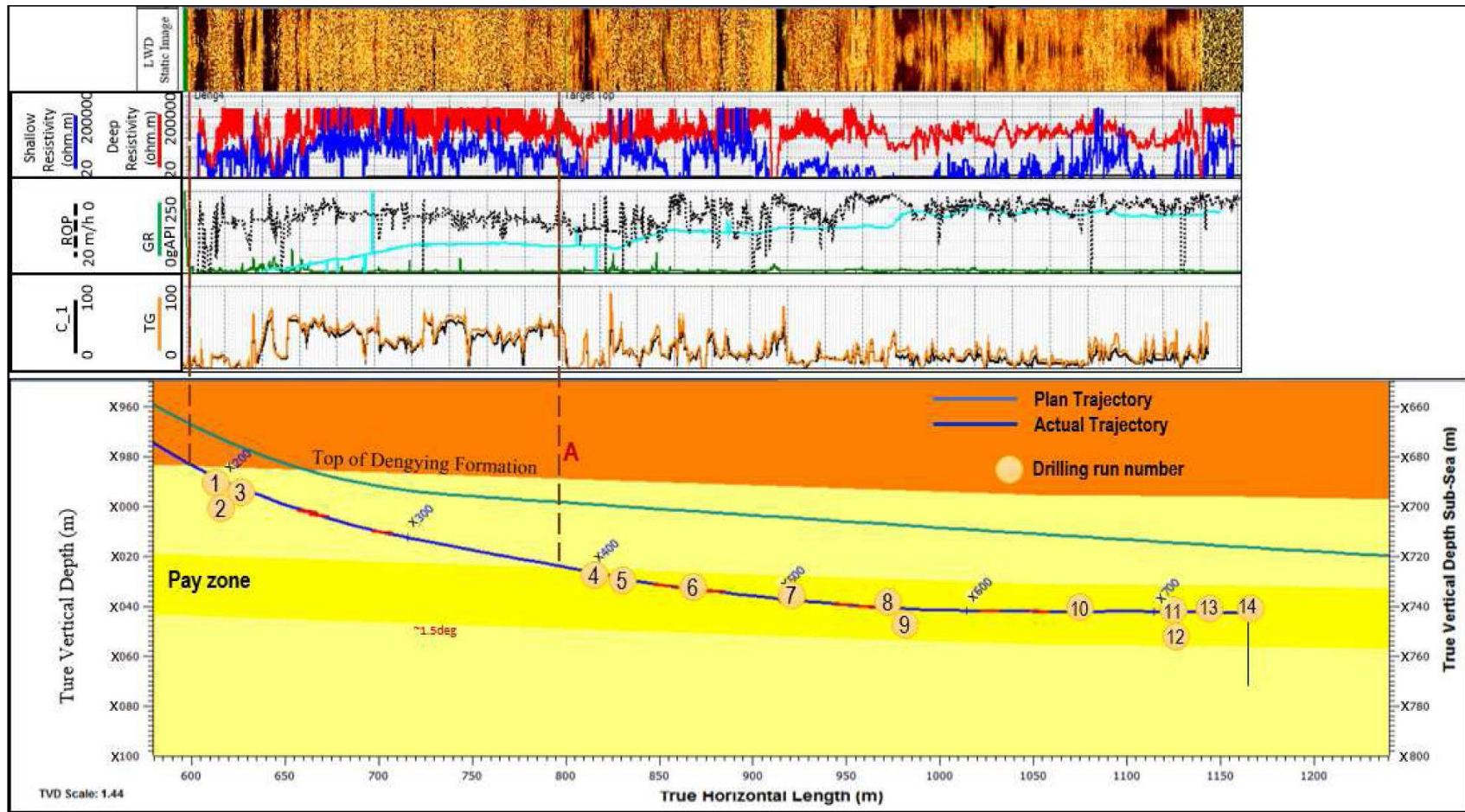


Figure 6. Well placement cross section shows the actual trajectory and drilling run number, associated with the LWD electrical image, shallow lateral resistivity and deep lateral resistivity, ROP, gamma ray, total gas show (TG) and gas component C-1.

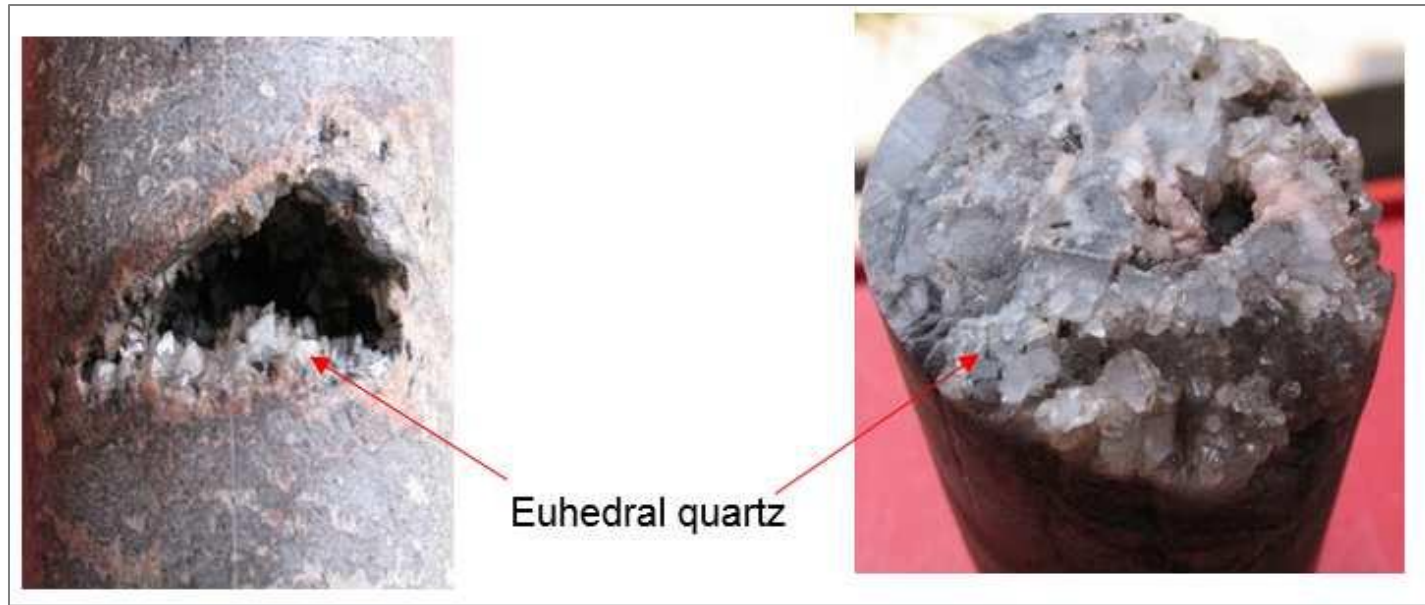


Figure 7. Karst weathering and erosion vugs filled with euhedral quartz in the crystalline dolomite in a core section of the Dengying Formation.

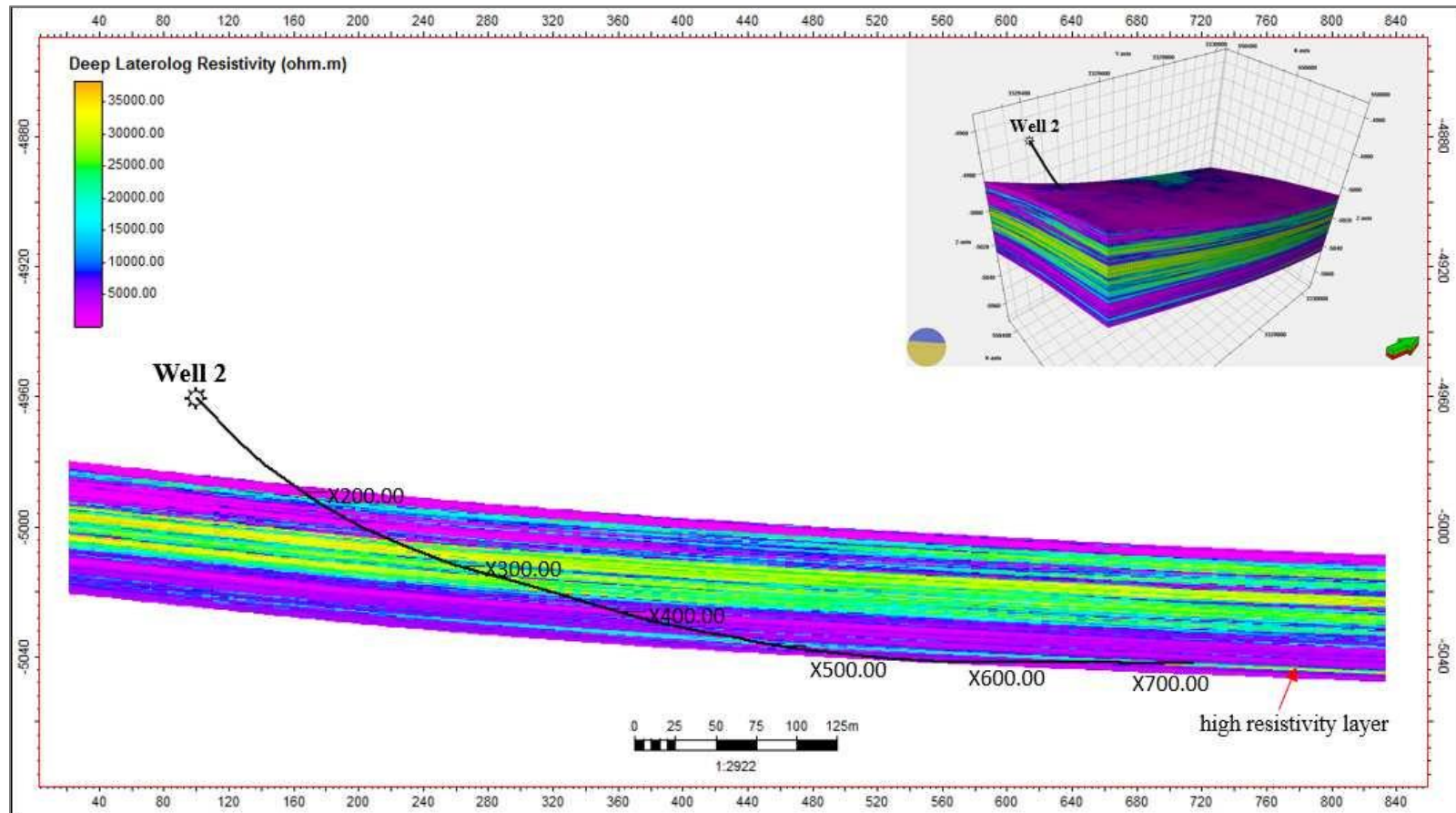


Figure 8. Display of an intersection of the 3-D formation resistivity model showing the structural details and formation resistivity variations along the well trajectory.