Locating Bypassed Reserves in Geologically Complex Mature Fields Environments*

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Abstract

With fewer new oil discoveries, the industry today is turning to maximizing recovery from existing mature oil fields. To exploit trapped bypassed reserves, very complex and thinly laminated reservoirs are being drilled and evaluated. New reservoir management efforts aimed at maximizing production require increasingly sophisticated well placement and formation evaluation capabilities. Recent improvements in well placement and formation evaluation technology, such as azimuthal resistivity, have helped in gaining access to bypassed reserves and to thin bed areas that were originally not thought to be practical development targets.

This paper presents a review of azimuthal resistivity tools and their theory of operation. The planning, execution, and interpretation of this new technology in complex thin sand-shale sequence in mature field are explained. Advanced formation evaluation based on this new azimuthal reading technology is detailed. This system, with multiple depths of investigation and an azimuthal 32-bin measurement around the borehole, creates a system that allows the accurate calculation of the horizontal and vertical resistivity and relative dip angle.

Finally, field examples and multiple case histories that illustrate the use of azimuthal resistivity technology in mature fields to access bypassed reserves are shown. Geologically complex environments are examined from the perspective of using the new measurements to obtain better geological and petrophysical answers. Thin bed environments are examined with these measurements to obtain a better understanding of development possibilities than was previously possible with the use of wave propagation resistivity tools.

Introduction

In today's market, more than half of the world's oil and gas production comes from mature fields, and operators are concerned with boosting production from these declining assets. Increasing ultimate recoveries in these mature assets requires reservoir management efforts through optimal wellbore placement to identify sweet spots. These challenges require increasingly sophisticated geosteering and formation evaluation capabilities.

For this purpose, azimuthal deep reading resistivity tools, which provide directional real-time deep measurements necessary to detect bed boundaries and fluid contacts, are used. These new directional resistivity tools are used to navigate the reservoirs to locate oil and gas sweet-spot accumulations that were left behind after initial production. Drilling through complex reservoirs with traditional technology is difficult because conventional LWD tools lack azimuthal sensitivity that provides the directional information and data necessary for geosteering and evaluating complex reservoirs.

Effective schemes for reservoir drainage to maximize net recovery focus on increased production, optimized production, better reserves estimates, and accessing more reserves. To accomplish these objectives, improving reservoir understanding and creating effective schemes for reservoir drainage are crucial. A new azimuthal, deep resistivity logging-while-drilling sensor accomplishes this objective. The tool is designed to combine deep reading azimuthal (directional) measurements with petrophysical interpretation capabilities. The azimuthal deep resistivity tool provides a deep reading azimuthal (directional) service that greatly enhances geosteering and gives significantly greater control over well placement when drilling horizontal wells. The system also provides important petrophysical parameters, such as true formation resistivity, the horizontal resistivity, Rh, the vertical resistivity, Rv, and the relative dip angle between the wellbore and the bedding planes.

For the geologists and drillers, this system provides the capability to steer the well through the most productive part of the oil or gas reservoir while maintaining a desired distance from the edges of the reservoir. The sensor is based on electromagnetic propagation and can detect boundaries up to 18 ft from the wellbore. This new functionality is a critical factor in many recent successful placements of horizontal well sections in complex mature field reservoirs.

Theory of Operation

The azimuthal deep resistivity sensor, shown in Figure 1, is based on the multi-frequency, multi-spacing, tilted antenna concept. The tool consists of a single 25-ft collar with three upper transmitters, three lower transmitters, and three receivers with transmitter-to-receiver distances that span from 16 in. to 112 in. The sensor operates at three different frequencies (2 MHz, 500 kHz, and 125 kHz) to cover the entire range, from shallow to very deep reading, and generates multiple resistivity measurements and images for boundary detection. The longer spacing and lower frequencies are used to measure the formation properties of the uninvaded zone. With three operating frequencies of 2 MHz, 500 kHz, and 125 kHz, the sensor retains the advantages of high-frequency data, such as greater accuracy in high resistivities and better vertical resolution, while gaining the advantages of the lower frequency measurements, including significantly greater depths of investigation, thus sensing the bed boundaries around the borehole up to 18 ft away (Bittar et al. 2007; Bittar et al. 2010).

As the tool rotates, phase shift and attenuation data are acquired in 32 azimuthally oriented bins referenced to either the high side of the borehole or magnetic north using magnetometers. The phase shift and attenuation measurements are transformed to resistivity to obtain 32 azimuthally oriented phase shift and attenuation resistivities at multiple spacings and frequencies (Figure 2).

Conventional non-azimuthal resistivity identifies an approaching bed boundary using the polarization horns, as shown in Figure 3. The shortcoming of this approach is that the tool has the same signature (Chemali et al. 2008) for a less resistive formation approaching the well from above (right) or from below (left), and the tool is not able to steer in the appropriate direction.

The azimuthal deep resistivity response shown in Figure 4 resolves the ambiguity (Bittar et al. 2007) by measuring resistivity values in all 32 bins around the well axis. In this example, only the resistivity responses for the deeper resistivity measurement at only two azimuth values are shown. As illustrated, the pattern of separation between the case of the well dropping into a lower resistivity interval, shown on the left, is opposite that of the well emerging upward in a lower resistivity interval shown on the right.

For formation evaluation, the resistivity of the formation is essential in the evaluation of water saturation and can provide indications of hydrocarbon concentrations and other information useful to petrophysicists and reservoir engineers. However, the measurements from conventional sensors can exhibit boundary-related artifacts. The azimuthal sensor recognizes when the problem occurs and is able to mitigate it using the many azimuthal measurements performed at every depth level.

Mature Field Case Histories

The first mature field case history is from California, USA. The Wilmington field, in production since 1932, is the largest field in the Los Angeles basin and the third largest oilfield in the United States (Mayuga 1968). The Wilmington structure is a northwest-southeast trending, double plunging asymmetric anticline that is 13 mi long and up to 3 mi wide (Figure 5). A series of transverse, normal faults segment the structure into 10 major productive fault blocks. Throughout the field, seven major producing zones, ranging in age from lower Pliocene to upper Miocene, have produced 2.6 billion bbl of oil and 326 BCF of associated gas from 6,000 wells. The field has an original oil-in-place reserve in excess of 10 billion bbl, with an estimated ultimate recovery of more than 3 billion bbl (Clarke and Henderson 1987).

The Wilmington productive section has a gross thickness of approximately 3,000 ft and comprises an aggradational succession of Miocene- and Pliocene-age confined slope deposits prograding into unconfined basinal-medial to distal-turbidite fan complexes. Medium to thick-bedded hemipelagic mudstones separate successive lower-slope, medial, and distal-fan sand bodies. At the parasequence level, lithofacies comprise indurated mudstones, shales, and siltstones interbedded with semi-consolidated and unconsolidated fine to coarse-grained sandstones.

The optimal positioning of a complex well in a thinly laminated reservoir that has already been produced required careful planning on the part of the asset team. The objective was to use a low angle trajectory to assess the potential for waterflooding in the lower zones of the reservoir that could negatively affect production. The goal was to determine the relative presence or absence of water before fully penetrating the lowest zone, which had the highest risk of waterflood. Figure 6 shows the proposed plan in section.

After entry into the lower zone, the resistivity values from the bottom octant indicated that water was not present in this lower zone up to the detection limit of the tool. As the section was traversed, the measurement continued to indicate the absence of water, enabling the team to confidently drill the section (Figure 7).

Conclusions

Maximum well contact and optimum well placement are key to increasing production from mature fields. Accessing and draining bypassed sweet spots in mature, thin, and complex fields to navigate reservoirs require new directional deep reading well placement technology. Azimuthal deep reading resistivity tools provide real-time deep measurements necessary to detect bed boundaries and fluid contacts, to place the wellbore in the optimum position, and to maximize reservoir contact and production. Proper evaluation of the reservoir is also important in mature field development to minimize the uncertainties in reservoir characterization. Conventional LWD wave propagation resistivity tools are influenced by bed boundary and anisotropy, making it very difficult to determine true formation resistivity necessary for petrophysical interpretation. Directional resistivity measurements offer a resistivity measurement that is free of boundary effects and accurate anisotropy determination to yield accurate water saturations and better determination of oil in place. The case studies in this paper have shown how this technology can assist in the development and evaluation of mature fields.

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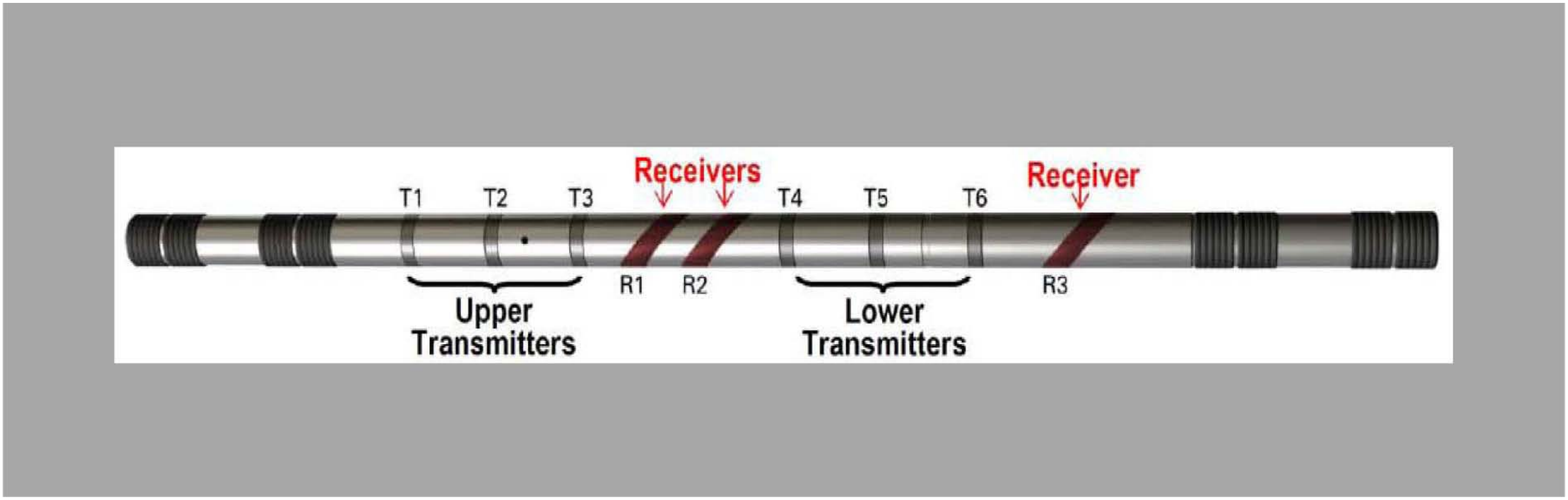

Figure 1. The Azimuthal Deep-resistivity Sensor.

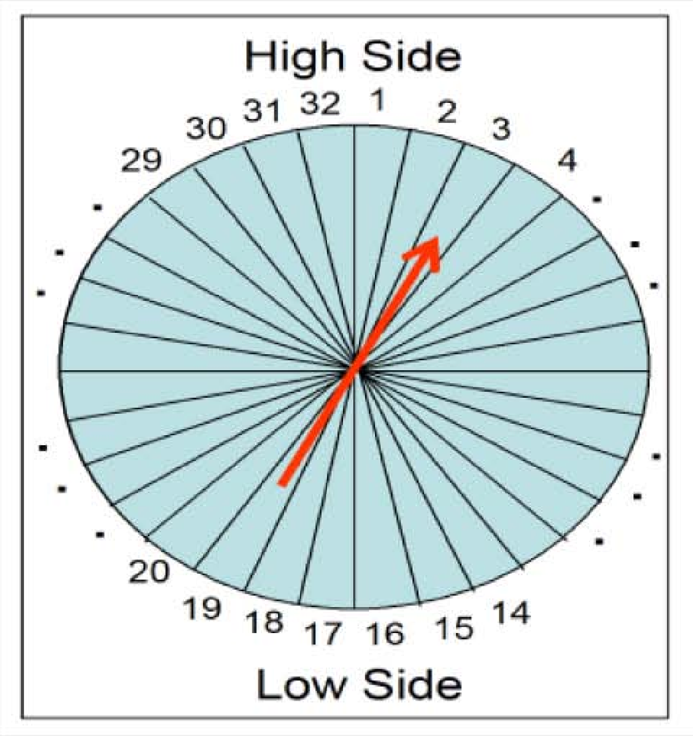

Figure 2. Azimuthal Measurement is acquired in 32 Azimuthal Bins.

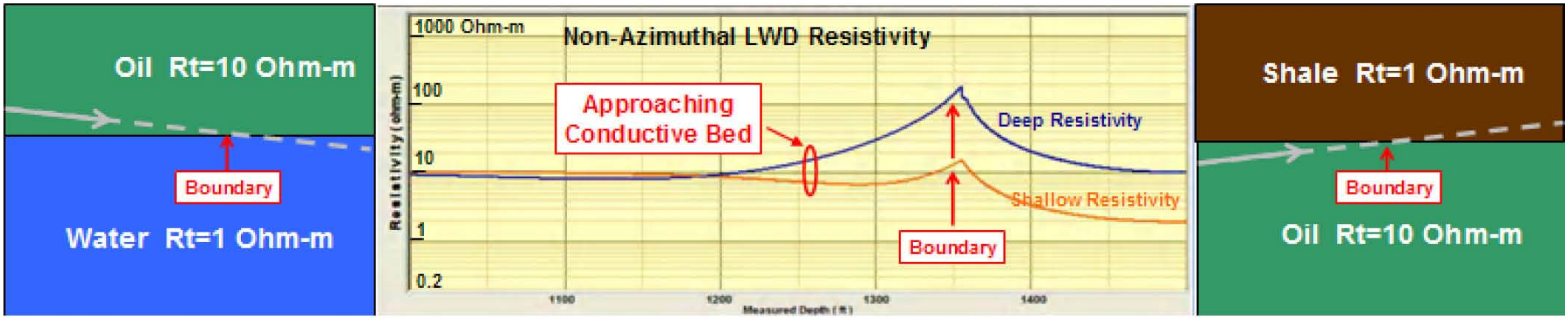

Figure 3. Conventional Non-azimuthal LWD Resistivity Response to Approaching Beds.

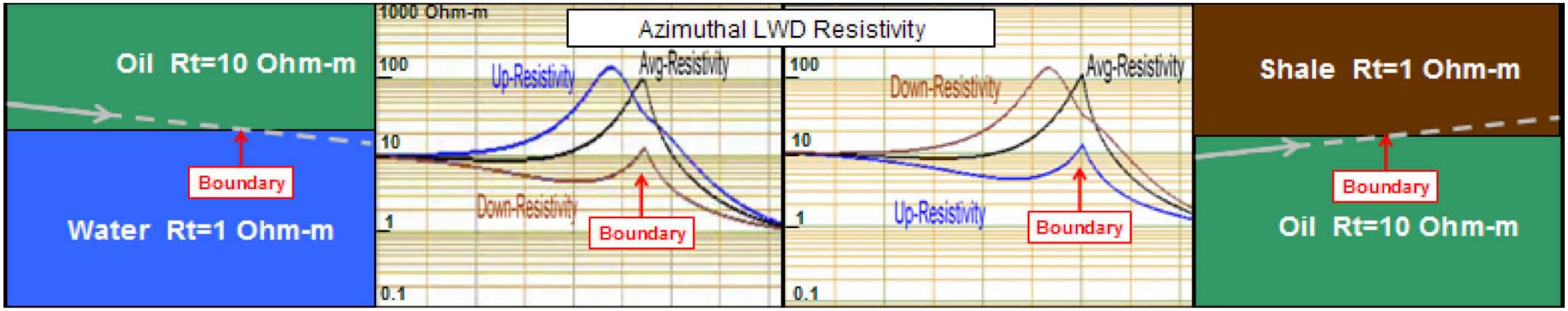

Figure 4. Azimuthal Deep-reading LWD Resistivity Response to Approaching Beds.

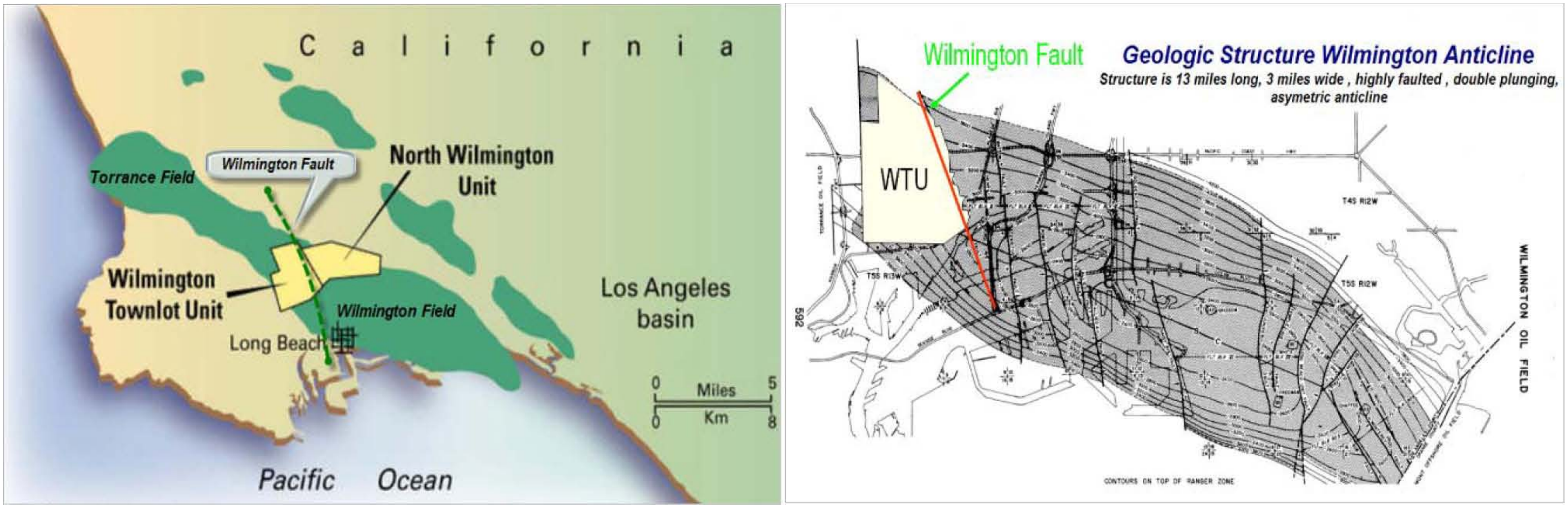

Figure 5. WTU-NWU Location Map and Wilmington Anticline Regional Structure Map (From Pitcher et al. 2009).

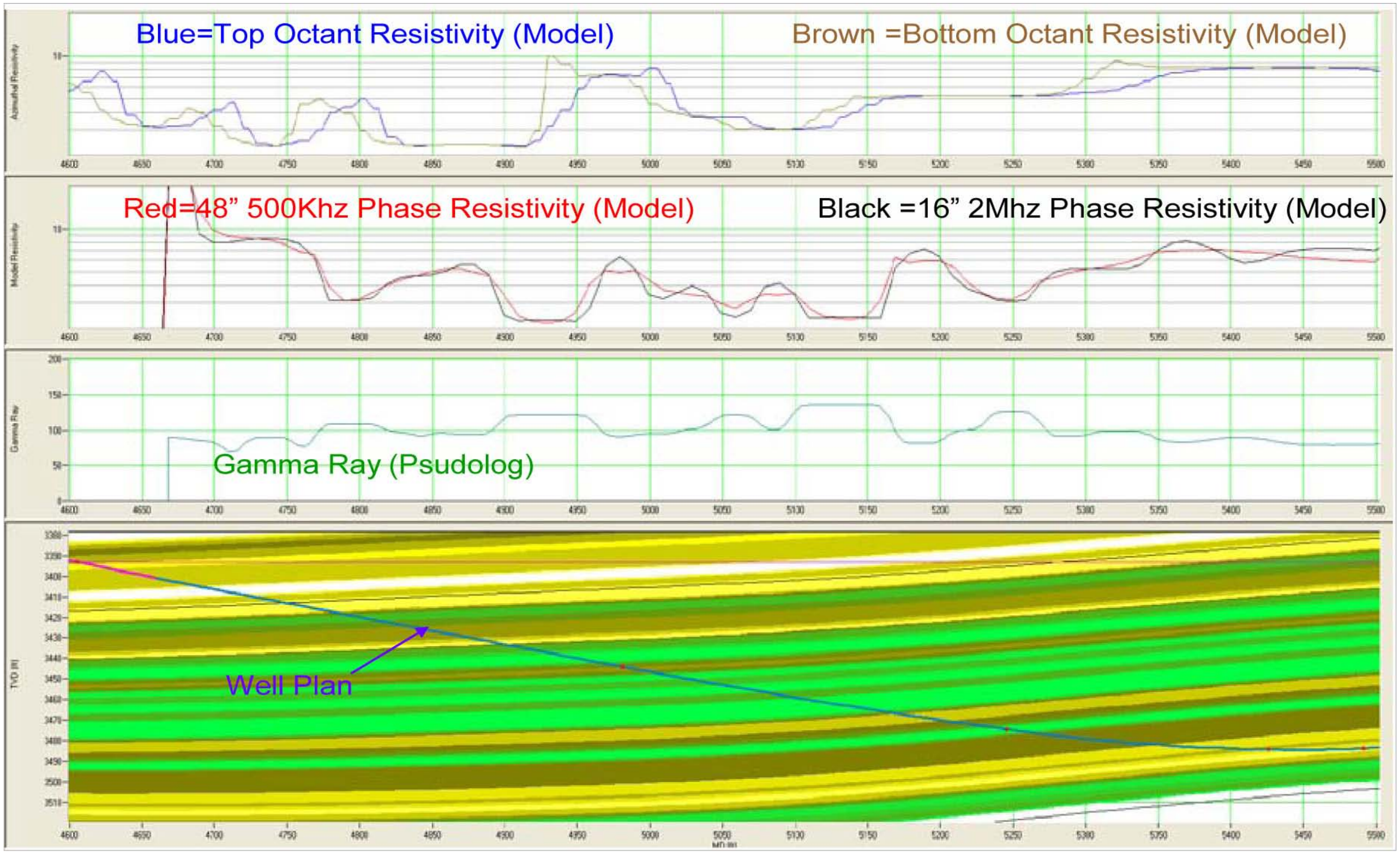

Figure 6. Prewell Proposed Section (From Pitcher et al. 2009).

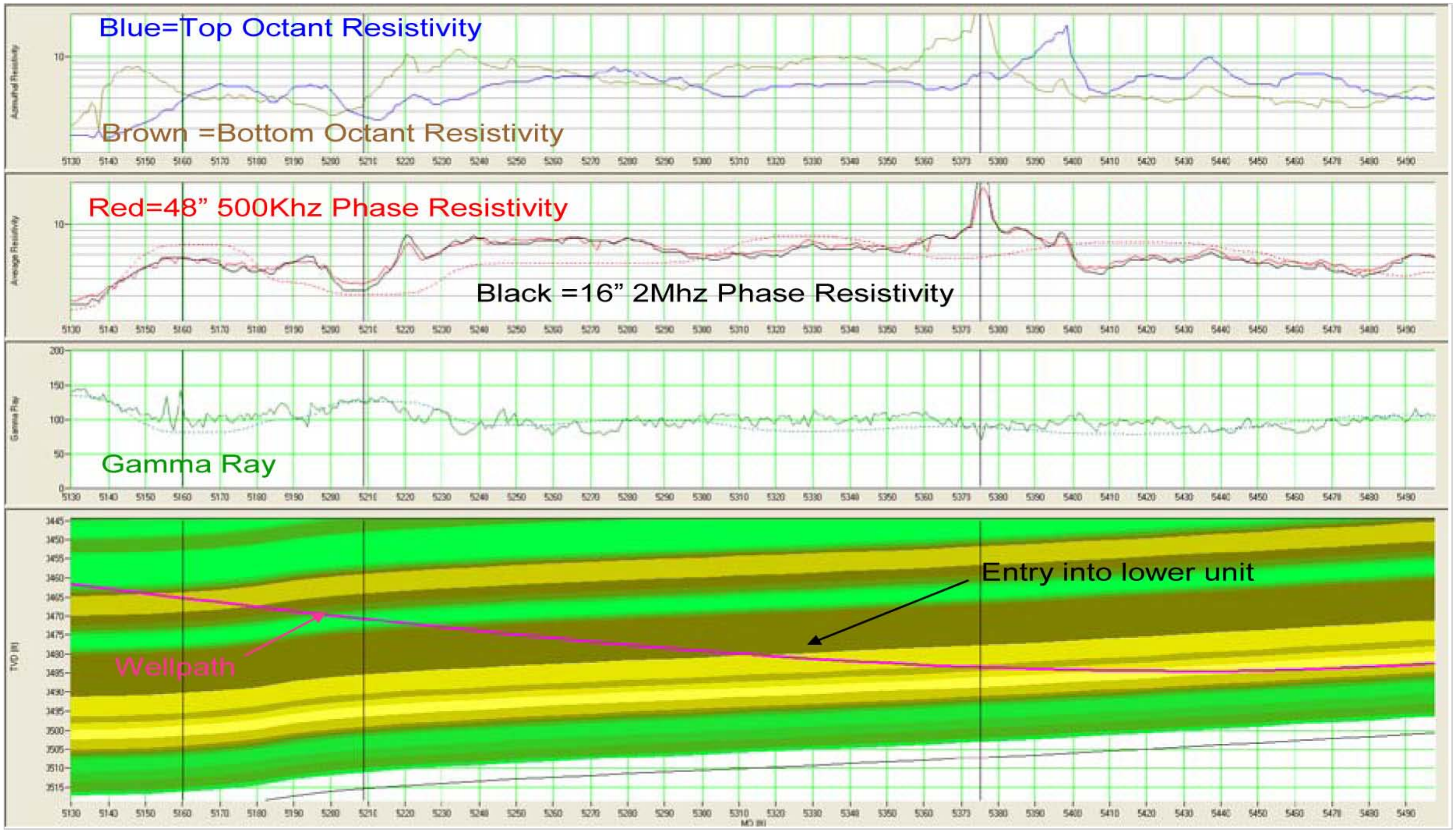

Figure 7. Final Drilled Section (From Pitcher et al. 2009).